Volume 49 • No 2 • April-June 2026
Periodicity: Quarterly • Subject: Multidiciplinary

ISSN 0971-3034

THE INDIAN JOURNAL OF TECHNICAL EDUCATION

Published by
INDIAN SOCIETY FOR TECHNICAL EDUCATION
Near Katwaria Sarai, Shaheed Jeet Singh Marg,
New Delhi - 110 016

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Editorial

Attitude Matters More Than Aptitude: Success is often associated with intelligence, technical knowledge, and academic excellence. While these qualities are undoubtedly important, they alone do not guarantee achievement. In today's rapidly evolving world, organizations seek professionals who are adaptable, resilient, collaborative, and committed to lifelong learning. Many individuals with exceptional academic credentials fail to realize their full potential because they lack perseverance, discipline, or a positive outlook. Conversely, numerous successful entrepreneurs, scientists, and leaders have demonstrated that the right attitude enables ordinary individuals to accomplish extraordinary goals despite limited resources or challenging circumstances.

Aptitude determines how quickly a person can learn or perform a task, but attitude determines whether that person is willing to learn, improve, and persist despite setbacks. A positive attitude transforms failures into valuable learning opportunities, encourages innovation, and strengthens confidence during difficult times. In engineering and technical professions, where technology evolves continuously, the willingness to embrace change, acquire new competencies, and work effectively in teams is often more valuable than existing knowledge alone. Employers consistently value integrity, commitment, adaptability, and problem-solving ability alongside technical competence.

Educational institutions therefore have a vital responsibility to nurture not only intellectual capability but also professional character. Students should be encouraged to develop curiosity, ethical values, emotional intelligence, effective communication, leadership qualities, and a growth mindset. Project-based learning, industry interaction, and community engagement help cultivate these essential attributes. Faculty members, as mentors and role models, play a significant role in shaping students' attitudes toward lifelong learning, responsibility, and innovation.

As we prepare the next generation of engineers and technologists, let us remember that aptitude may open the door to opportunity, but attitude determines how far one progresses. Knowledge and skills can be acquired through education and experience, whereas a positive attitude inspires resilience, creativity, and excellence throughout life. Institutions that foster both competence and character will produce graduates who are not only technically proficient but also capable of leading meaningful change and contributing responsibly to society.

Aptitude may create opportunities, but attitude transforms them into lasting success.

New Delhi **Editor-in-Chief**

30th June 2026

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Evaluating Thermal Comfort of Traditional and Modern Educational Buildings in Chennai

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ABSTRACT

The thermal comfort of the inhabitants of a building depends on the response of the building to the external climatic environment. The traditional principles of built-form architecture have always been prioritized to be relevant to the local ecology, climate, and cultural context. The educational buildings built with traditional building techniques and materials, during the pre-modern period in the coastal region of Chennai, Tamil Nadu in India located in the warm humid zone are thermally comfortable with a climate-responsive design. The traditional and modern educational buildings in the coastal region of Chennai are investigated by comparing the planning design principles and thermal performance within the same microclimatic outdoor conditions. The architectural planning, design strategies, and quantitative thermal performance data are analyzed. The data observed during the peak summer of April 2019, from the fourteen sample rooms of the two buildings of the two construction types are investigated. It is observed that the traditional building is more comfortable than the modern building. The traditional construction of our native region can meet comfort demands through an environment-sensitive design. The appropriate climate-responsive design of traditional buildings can be useful in understanding for application in a modern building.

KEYWORDS: *Educational building, Indian knowledge systems, Indigenous technical knowledge, Traditional architecture, Traditional construction technique.*

INTRODUCTION

The International Energy Agency appraises that the combined sectors of buildings and buildings' construction are responsible for 36% of global final energy consumption [1]. There is a continuous rise in demand for energy from buildings and buildings' construction, driven by enhanced access to energy in developing countries, greater ownership, use of energy-consuming equipment, and rapid growth in global buildings floor area, at nearly 3% per year [2]. The energy crisis worldwide has invoked studies related to performance and energy efficiency. By 2030, India would be one of the leading countries with a 765 million young population [3]. This population includes nearly half the country's population. Children spend nearly 30% of their time and about 20% of their life in schools [4]. Therefore, developing a healthy school and college environment is beginning to be a priority for all stakeholders. The passive approach supports designing buildings that take advantage of the regional environmental conditions such as sun, wind, and daylighting, to create thermally comfortable indoor environments. A review paper on passive design in hot humid climates for thermal comfort, focuses on the problems that differentiate passive design in hot humid climates from that in other climates [5]. The study lists the various passive techniques which apply for buildings in a hot humid climate. The study also insists that more lessons should be learnt from traditional wisdom. Mofidi (2007), synopsizes the outcomes of energy-conscious architectural components and principles in a historically used building [6]. (Dili, Naseer, & Zacharia Varghese, 2011), compared the thermal performance of Kerala's traditional and modern buildings. The chosen

buildings were supervised continuously. Bioclimatic chart and PMV-PPD analysis were used to assess the thermal comfort parameters in the buildings for their performance. The findings show that in Kerala's traditional architecture, an effective passive and natural control system exists to provide a comfortable indoor environment regardless of the outdoor climatic conditions[8]. A study was done for climate-responsive vernacular residential buildings in a hot-humid climate in the Tamil Nadu region of India, to quantify the effect of passive strategies on thermal comfort [9], [10]. According to the census of India 2011, Tamil Nadu, various institutions of professional and technical education were established at the commencement of the 19th century in Chennai. Institutes of higher education had begun in 1820 [11]. It was observed in a field study that these were built in the British colonial construction style (1820-1950), which was climate-responsive. The British colonial buildings were load-bearing structures with walls of over 500mm thick brick in lime mortar and ceiling heights of more than 4.5 to 5.0 m. The ceilings had variations of a flat roof or Madras terrace roof (a traditional construction technique) or the terrace was a pitched roof in steel girder with wooden reapers and tiles. Later these campuses expanded over time due to demand, which had buildings built in a modern style (built post-1960) using modern construction techniques and materials. The modern-style buildings were reinforced cement concrete framed structures with 230mm thick brick walls in cement mortar and ceiling heights of 3.0m to 3.75 m. Traditionally, buildings were climate-responsive. In contrast, the later constructions during the modern period have ignored their sensitivity towards the environment. This has led to increased energy consumption. The architectural design and planning have a considerable effect on the energy consumption of a building. This study examined the thermal performance of the buildings of each of these periods with qualitative and quantitative analysis. The observed data were analysed using thermal comfort tools. The main objective was to formulate the design guidelines in particular for the planning of naturally ventilated educational buildings which were newer additions being built in modern style, in a hot humid climate.

CHARACTERISTICS OF THE CLIMATE AND BUILDINGS SURVEYED

Climatic characteristics

Chennai, being a city on the southeast coast of India, is of warm and humid climate as per the National Building Code of India [12]. As per Indian Society of Heating, Refrigerating, and Air Conditioning Engineers (ISHRAE), climate data for Chennai, annually the temperature ranges from 20.5°C to 37.5°C and is hardly below 20°C or above 40°C. Summer is from April to July, with an average daily temperature of more than 35°C. Winter is from November to mid-February, with an average daily temperature of less than 30°C. The coldest day of the year is around the middle of January, with an average low of 20.5°C and a high of 29.8°C. The monthly mean relative humidity varies from 36% to 96% over the year. The average relative humidity ranges from 68% to 60% from January to July. This average relative humidity increases above 70% from October to December. The highest monthly mean maximum relative humidity of 76% is observed in November. The predominant wind direction is from the southwest, during the monsoon months of June to September. The other monsoon is from October to December which has northeasterly winds. These monsoons bring an annual rainfall of 700mm and above.

Buildings surveyed

General description of case study buildings – traditional building and modern building: A comparative case study of buildings of two different time periods is done. Of the two buildings, one is built in the pre-modern period with traditional construction techniques and another built in the modern period. Two of the sample educational buildings with classrooms oriented in four cardinal directions from two building periods are located within the same campus at Vepery, Chennai. The surveyed buildings are naturally cross-ventilated and provide adaptive controls for the occupants such as opening or closing of windows and doors, control of ventilators, the operation of fan and fan speed regulators, etc. Ceiling fans served the area of occupancy during class hours with speed controllers. For the pre-modern period, St Christopher's college of education henceforth referred to as a traditional building, is selected. For the modern

period, Bentinck higher secondary school, henceforth referred to as modern building is selected for the field study.

Description of architecture and planning features of the traditional building: The study is carried out in the selected naturally ventilated, traditional building (figure 1), on-campus at Vepery, Chennai. The traditional building is a ground plus one storey structure, built in the year 1952. The building primarily accommodated regular academic spaces such as classrooms, physics laboratory, computer laboratory, staff rooms, office, and a library for undergraduate and postgraduate of arts courses. It has a rectangular plan (71.0 x 41.0 m) with the longer side facing north-south, two central large courtyards (18.0 x 21.0 m) which are open grounds with lawn and shrubs. A corridor of 2.40m wide is facing the courtyard, with 6.52m wide classrooms, laboratories, and office spaces all around. The external walls are partially shaded by trees. The building envelope is off white with peach-colored borders. The traditional building is a load-bearing structure with conventional footings. The walls are of 530 mm wide brickwork in lime mortar. The roof is of reinforced cement concrete. The flooring is of cement. The floor-to-floor height is 4.4 m. The floor area to window opening area ranges from 13% to 28% in the building. The ground floor plan, the classroom view, the satellite map, and the building front view of the traditional building are represented in Figure 1.

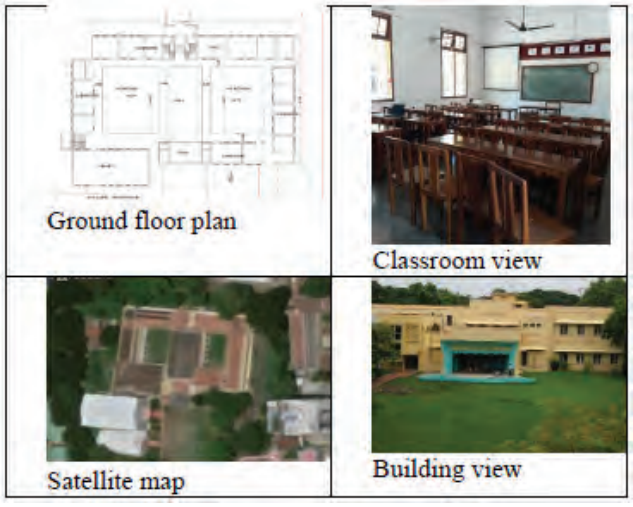

Fig. 1. Traditional Building – Plan, View, Satellite Map and Building View

Description of architecture and planning features of the modern building: The study has been carried out in the selected naturally ventilated, modern building (figure 2), in the campus located at Vepery, Chennai. The modern building primarily accommodated regular academic spaces such as classrooms, laboratories, staff rooms, offices, and a library for a school. The modern building has three blocks around an open playground. The main block is a ground plus one-storey structure, built in the year 1965. It has a linear plan (50.5 x 8.70 m) with the longer side facing north-south. Additionally, there is a vertical west block (36.3 x 8.8m) to the left and a U-shaped block (30.5 x 50.0m) to the right of the main block. The building's envelope is pale green with grey borders. The modern building is a framed structure with isolated column footings. The walls are of 230 mm wide brickwork in cement mortar. The roof is of reinforced cement concrete. The flooring is of cement. The floor-to-floor height is of 3.6m in both storeys. The floor area to window opening area ranges from 12% to 23% in the building. The ground floor plan and classroom view of the modern building is represented in Figure 2.

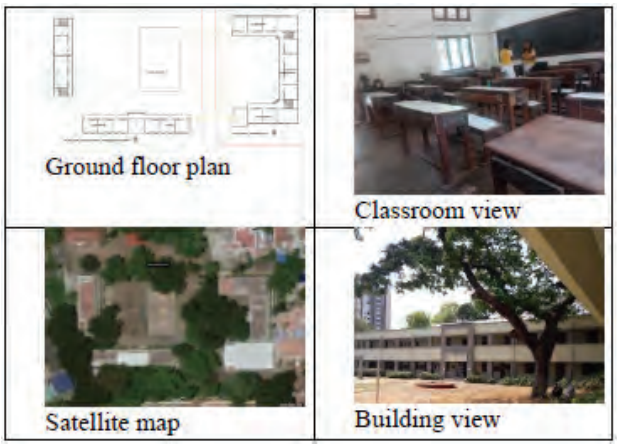

Fig. 2. Modern Building– Plan, View, Satellite Map and Building View

METHODOLOGY

This research intends to investigate the existing climate-responsive strategies adapted in the traditional architecture of educational buildings in the warm humid climate of Chennai in relation to their thermal comfort and thermal performance of the buildings. A comparative case study of buildings of two different periods is done. Of the two buildings, one was built

in the pre-modern period (traditional building), and another was built in the modern period (modern building). The study of the architectural and planning details of the two sample buildings is collected. The observed data of the fourteen classrooms from the two buildings are analyzed using CBE thermal comfort tool. The whole building thermal comfort analysis of the traditional and modern buildings using the CBE Thermal comfort tool ASHRAE 55-PMV method is done [13]. The architecture and planning features of the environmental performance of the different architectural design elements of buildings on campus, concerning the prevailing microclimatic conditions are recorded. The data collection of architectural design features, branches to documenting the building layout, the orientation of the building axis, wall window ratio, the color of the building envelope, and vegetation near the building. The study of building design further branches to study the shape of the building, geometrical configuration, the orientation of openings for winds, and window size.

Quantitative factors influencing passive building design

The quantitative assessment is done by recording in-situ measurements of various climatic parameters, inside the sample buildings, to analyze their thermal performance. The field measurement of ambient temperature (Ta °C), globe temperature (Tg °C), mean radiant temperature (Tr °C), air velocity (Va m/s), and relative humidity (RH %), are recorded during the working hours of the building, in the four orientations, all floor levels of the sample buildings.

Data Collection

The indoor environmental parameters are simultaneously monitored in the summer of April 2019, from 9.30 am to the evening at 5.00 pm in each of the classroom/laboratories of the two sample buildings. Thermal environment variables are recorded for every half hour with the instruments placed at the height of ~1.1 m from the floor level according to the Class-II protocol of ASHRAE 55. The data is continuously monitored to measure the indoor environment. The fourteen sample rooms, in the traditional and modern buildings considered for the studies, are naturally cross-ventilated. Field surveys have been conducted in the rooms along with the four cardinal directions of two levels (ground floor and first/ third floor) of both the buildings. The west orientation rooms on the ground floor of the traditional building are modified into an air-conditioned laboratory. Therefore data is not collected at that location. In the modern building, the third floor of north and east orientation is considered as equivalent to the first floor of the traditional building for data comparison, since the third floor is below the terrace level. In the south and west orientation, the building has only two levels. The floor area of the classrooms surveyed varied between 30-318 sq.m. The details of the surveyed buildings are shown in table 1. The indoor environmental parameters are measured without occupants, without mechanical fans.

Data logging: The indoor environmental parameters of air temperature, relative humidity, and wind, are recorded using the vane anemometer, HTC-AVM-06. Globe temperature is recorded using the instrument HTC DT-1 with a black painted tennis ball. The outdoor climate is recorded from https://www.wunderground.com/ weather/in/Chennai.

RESULTS AND DISCUSSION

Thermal comfort analysis of the traditional building and the modern building

A thermal comfort assessment for fourteen sample rooms of the sample buildings is done with the CBE Thermal Comfort Tool –ASHRAE 55-PMV Method. The thermal sensations are recorded as “Slightly warm”, “Warm” & “Hot” following the inputs provided by the observed data collected at the site. A constant metabolic rate at 1 met (for a classroom) & clothing level as 0.5 clo (for typical summer indoor clothing) has been assumed for the study. It is observed from the thermal comfort analysis, that the modern building is warmer than the traditional building. On the Ground floor, the sensation of the modern building in the north is 25% more, the east is 56.25% more and the south is 68.75% warmer than the traditional building. On the first floor, the sensation of the modern building in the north is 37.5% warmer, east is 93.75% hotter, the south is 25% warmer and west is 43.75% warmer than the traditional building as presented in Figure 3.

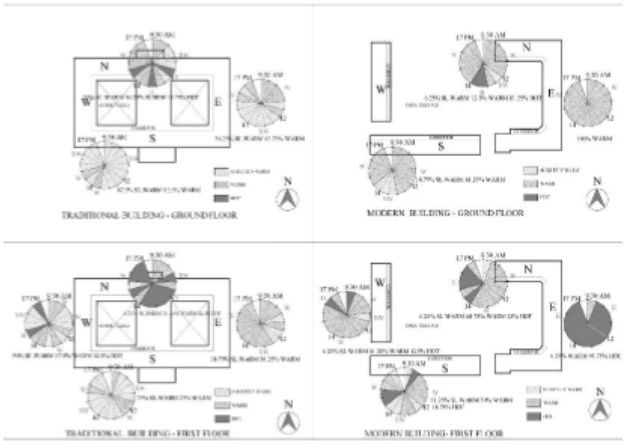

Fig. 3. Thermal Comfort Data Analysis of Fourteen Sample Rooms of Traditional and Modern Buildings

The thermal performance of the traditional building can be attributed to the passive planning and construction period of the pre-modern period as compared to the modern period. The thermal sensation for each orientation has been represented in the pie chart in figure 4. The south orientation shows that the modern building is 9% hotter and 47% warmer than the traditional building. While in the east orientation, the modern building is 47% hotter in sensation than the traditional building. As in the north orientation, the modern building is 31% warmer than the traditional building. The west orientation shows that the modern building is 44% warmer in sensation than the traditional building.

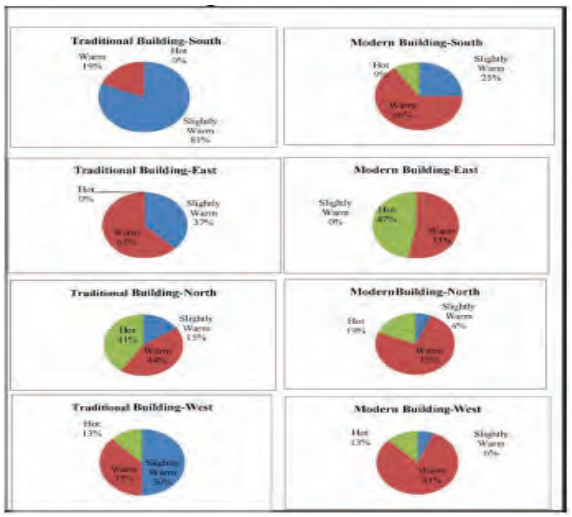

Fig. 4. Thermal Sensations in each Orientation

The whole building thermal comfort analysis of the CBE Thermal comfort tool –ASHRAE 55-PMV method of the traditional and modern buildings is shown in figure 5. Figure 5 also observes that the traditional building is "Slightly Warm" in sensation for 46% of the working hours, while the modern buildings are primarily "Warm" in sensation for 67% of the working hours. Also, the modern building is 25% much warmer and 10% much hotter, for working hours than the traditional building. The most comfortable rooms of all orientations, with zero "hot" sensation, are the traditional building south and east orientation. A similar observation is noted by [14].

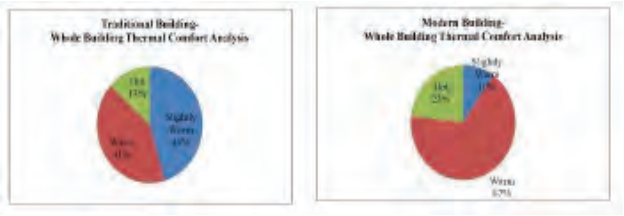

Fig. 5. Whole Building Thermal Comfort Data Analysis

CONCLUSION

To address the high energy demands of modern buildings, this study suggests that passive architectural strategies are potential solutions. The analysis of traditional educational buildings constructed during the pre-modern period in Chennai, India, reveals substantial insights into their climate-responsive features. These buildings utilize passive strategies, including increased ceiling heights, thick lime masonry walls, heavier roofs, and shaded external walls, to achieve thermal comfort. Quantitative analysis using the CBE Thermal Comfort Tool – ASHRAE 55 PMV Method shows that traditional buildings consistently perform better in maintaining thermal comfort compared to modern counterparts. For instance, traditional buildings recorded "Slightly Warm" sensations during 46% of the working hours, whereas modern buildings were "Warm" for 67% of the working hours. Furthermore, modern buildings were observed to be 25% warmer and 10% hotter on average during working hours than traditional buildings.

Key passive features of the traditional design include the greater ceiling height, which increases the time for internal air to warm up; thick lime masonry walls and heavy roofs, which create a time lag in heat

transfer; and large vertical openings that facilitate cross-ventilation and stack effect, enhancing airflow. Additionally, the presence of trees around traditional buildings reduces direct solar heat gain and promotes cooling through shaded walls and cool breezes. These features collectively result in lower thermal sensations across orientations, with the traditional south and east-facing rooms showing zero "Hot" sensations.

The findings demonstrate the critical role of passive architectural strategies in mitigating heat gains and improving thermal comfort. By integrating these traditional design principles, modern buildings can potentially reduce energy consumption and enhance indoor comfort, particularly in warm climates like Chennai. This study underscores the value of learning from climate-responsive traditional architecture to inform sustainable building practices in contemporary design.

REFERENCES

1. IEA (2020), "Tracking Building Envelopes 2020," International Energy Agency Report, June, pp 1-7, [Online]. Available: https://www.iea.org/reports/tracking-buildings-2020
2. IEA (2020), "Sustainable Recovery: World Energy Outlook Special Report," World Energy Outlook, p 185.
3. McKinsey Global Institute, India's urban awakening: Building inclusive cities, sustaining economic growth, Research Report, 2010.
4. IGBC, Green Campus Rating System, Indian Green Building Council, July, 2014.
5. T. Chenvidyakarn (2007), "Review Article: Passive Design for Thermal Comfort in Hot Humid Climates," vol. 5, no. 1, pp 1-28.
6. S. M. Mofidi "Passive architectural cooling principles for arid climates" at 2nd PALENC Conference and 28th AIVC Conference on Building Low Energy Cooling and Advanced Ventilation Technologies in the 21st Century, vol. 2, during September 2007, pp 674–677.
7. A. S. Dili, M. A. Naseer, and T. Zacharia Varghese (2011), "Passive control methods for a comfortable indoor environment: Comparative investigation of traditional and modern architecture of Kerala in summer" Energy Build, vol. 43, no. 2–3, pp 653–664.
8. S. Radhakrishnan, R. S. Priya, S. Nagan, and M. C. Sundarraja (2011), "Climate responsive traditional architecture of Chettinadu housing in Tamilnadu, India - A qualitative and quantitative analysis during summer" International Journal of Ventilation, vol. 10, no. 1, pp 89–97.
9. R. Shanthi Priya, M. C. Sundarraja, and S. Radhakrishnan (2012), "Comparing the thermal performance of traditional and modern building in the coastal region of Nagappattinam, Tamil Nadu" Indian Journal of Traditional Knowledge.
10. Census of India, District Census Handbook Chennai, Census of India 2011, p. 287, 2011.
11. BIS, National Building Code of India, Vol. 2, Bureau of Indian Standards, New Delhi, 2016.
12. F. Tartarini, S. Schiavon, T. Cheung, and T. Hoyt (2020), "CBE Thermal Comfort Tool: Online tool for thermal comfort calculations and visualizations" SoftwareX, vol. 12, Jul. 2020.
13. J. Vijayalaxmi and S. P. Sekar (2013), "Thermal performance of naturally ventilated residential buildings with various room orientations in the hot-humid climate of Chennai, India" J Archit Plann Res.

Analytical Hierarchical Process-derived Weights of Factors Impacting Integration of History of Architecture in Architectural Design Studio

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ABSTRACT

Existing studies indicate a gap between the knowledge-driven history subject and its integration into the design studio. A mixed-method approach was undertaken, including a literature review using the well-established PRISMA framework, is used for the literature and criteria for identification of factors, a physical questionnaire for selection of factors for analysis and pairwise comparison of factors, statistical analysis, and Analytic Hierarchical Process with linear scaling for analysis of weights of factors and ranking of weights. The study aims to evaluate and arrange the factors influencing the integration of the History of Architecture and Architectural Design Studio. Expert responses were collected through pairwise-comparison questionnaires and analysed using the Analytical Hierarchy Process (AHP) to derive the factors' normalised weights and rankings. Teaching methodology (36.49%) emerged as the dominant issue influencing the integration process, followed by student-related issues (26.99%), curriculum-related issues (15.16%), teacher-related issues (11.14%), notional (6.18%), and skill-based communication issues (4.04%). The study demonstrates the effectiveness of a multi-criteria decision-making tool (AHP) in prioritising the issue and identifying solutions through policies and strategies.

KEYWORDS: *AHP, Analytical Hierarchy Process, Integration, History, Architectural Design, Weights of Factors, Factor Ranking.*

INTRODUCTION

History is a continuous conversation between the present and the past, enabling us to assess the historical roots and, through that lens, understand the modern issues (Carr, 1961). Understanding the historical contexts offers new insights, and integrating historical knowledge helps improve the design studio and design curriculum (Wang, 2014; Ferguson & Boyer, 1996) and takes forward the contemporary design practices (Frampton, 2007; Kostof et al., 1995) by enhancing the designer's critical thinking abilities and logical reasoning (Sewell & Johnston, 2019; Bongirwar et al., 2022; Sinha, 2014; Sharma, 2016; Hosagrahar, 2002). Historical knowledge often remains underutilised in design studios due to a gap in the integration of the History of Architecture (HOA) into design (Pawley, 2005).

Assessments of the curricula of higher education institutions that offer architecture education show that the History of Architecture is treated as a parallel or isolated subject rather than an integral component of design education (Salama, 2008; Panwar & Sheoran, 2024). The fragmented approach limits students' ability to contextualise architectural forms, materials, and planning processes within broader cultural and developmental narratives (Frampton, 2007). The absence of meaningful integration between history and design pedagogy creates a gap in the fostering of critical thinking, cultural sensitivity, and contextually rooted innovation (Hosagrahar, 2002; Ockman, 2012). Addressing this gap is essential to reframe history not

as a passive record of the past but as an active resource for contemporary architectural education and its integration in architectural design practice (Till, 2009), which further requires understanding the issues related to the integration of the HOA in Architectural Design (Saghafi, 2021).

Integration of theory subjects into practice-based subjects is of high importance, as theory subjects are taught to implement them in practice (Niu et al., 2022; Gomez-del Rio & Rodriguez, 2022; Zhan & Niu, 2023; Resch et al., 2024). The weights of various factors can be determined by analysing stakeholders' opinions to reach consensus (Christie & Barela, 2005). Limited efforts and studies have identified a comprehensive list of factors that inhibit the integration of history and design, along with their respective weights.

The authors attempted to analyse the weights of barriers to integrating the HOA into the Architectural Design studio by examining the opinions of students, practising architects, and teaching faculty, using sophisticated Structural Equation Modelling. Sheoran & Panwar (2025b) found that simplifying integration across various higher-education institutions requires simpler mathematical tools to support informed decision-making by formulating and testing plausible policies. Hence, simple statistical multicriteria decision-making tools have been employed to facilitate informed decision-making.

Delphi is a process of reaching a conclusion based on the consensus of opinions in cases of lack of agreement or incomplete knowledge concerning the subject, by involving subject-matter experts (Christie & Barela, 2005). There are multiple simple decision-making techniques involving Delphi, such as Simple Additive Weighting, Analytical Hierarchy Process, and Best to Worst Method, which involve experts and Shanon Entropy to avoid expert subjectivity; however, the Analytical Hierarchy Process, due to its simplicity and widespread usage, well-established use across multiple disciplines, is preferred for the study.

The identified issues and barriers towards history and design integration are discussed in existing research only in part, not collectively. A holistic solution to the history-and-design integration issue requires an understanding of all the significant issues and barriers involved. AHP supports the positioning and ordering of the identified issues, helping to grade each issue, thereby leading to a stepwise distinction of which issues need to be addressed more significantly than others. So, in academics, issues can be addressed sequentially, in due time, depending on their importance. This also helps categorise and identify problem areas more efficiently, thereby improving problem resolution towards history and design integration. A comprehensive solution is an appropriate approach to integrating history and design, thereby justifying the research study. The present investigation attempts to identify the most appropriate history and design integration barriers; to organise the issues and barriers into specific categories; to identify and organise the normalised geometric weights of the identified issues and barriers for history and design integration; and to position and order the integration issues.

LITERATURE REVIEW

PRISMA Framework for Literature Review

The literature review consisted of three steps: identification, screening, and inclusion (Figure 1). Literature was searched using the keywords 'architectural history and the studio' and 'integration of history in the architectural design studio' in the Science Direct and Google Scholar databases, resulting in 352 articles. Duplicate research papers were removed (n=34). Title screening led to the exclusion of research papers (n=166), and the rest of the 152 research papers were screened for abstracts. Abstracts were excluded for being out of scope (n=67), inaccessible (n=8), language barriers (n=3), or limited rigour (n=16). The research papers were assessed for full-text eligibility (n=58). Research papers were excluded due to the unavailability of full texts (n=26). A total of (n=32) research papers were included in the study.

All 32 papers (100%) suggested integrating history with the design studio. The issues of teaching methodology-based issues (72%), curriculum (56%), and student-based issues (56%) were discussed in the maximum number of papers, followed in decreasing order by notion-based issues (28%), teacher-based issues (9%), and skill-based issues (6%). Discussions on teaching methodology, curriculum, and student-based

psychological issues suggest that these issues have been recurring themes in the context of history and design. The largest proportion of studies (56%) was qualitative, with the case study method (38%) and qualitative theoretical analysis appearing to be the preferred choices. A total of 13% studies used quantitative methods, reflecting a dearth of concrete evidence. Teaching methodology- and curriculum-related issues are the most discussed, while skill-, teacher-, student-, and notional-related issues are among the least discussed in the integration of theory subjects with practical subjects (Sheoran & Panwar, 2025).

Literature on Methods for Analysis of Criterion

The Simple Additive Weighting Method is one of the most widely used multi-criteria decision-making (MCDM) methods due to its simplicity, but it has many associated limitations (Taherdoost, 2023; Panwar & Fandian, 2025). The Analytic Hierarchy Process (AHP), developed by Saaty (1980) and its subsequent developments, is another widely used MCDM technique known for its simplicity and ability to consistently handle up to 10 attributes (Saaty & Vargas, 2012; Stofkova et al., 2022; Tavana et al., 2023). Best Worst Method (BWM) yields consistent results and requires fewer comparisons, reducing cognitive load, and is less prone to rank reversal in comparison to AHP (Rezaei, 2016; Bafail & Abdulaal, 2022); however, it fails to capture complex problem structure and is less used in solving scientific problems as compared to AHP. Shannon Entropy is another widely used and simple MCDM method based on entropy of decision matrix data from the criteria values of alternatives, reducing the subjective biases of the experts; however, the results are sensitive to outliers and correlated criteria, and the weights might not align with the practical importance (Ahmad et al., 2023; Milošević et al., 2023).

The decision-making problem in integrating the History of Architecture into Architectural Design is a related problem with six criteria; hence, AHP, due to its computational simplicity and strong ability to handle six criteria, is selected for decision-making. The Eigenvector Method (EVM) and Row Geometric Mean Method (RGMM) are widely used methods for deriving priorities in the Analytic Hierarchy Process (Saaty & Vargas, 2012). The Eigenvector Method is sensitive to inconsistent matrices and sometimes leads to rank reversals when alternatives are added or removed (Budescu et al., 1986) (Saaty, 1987). RGMM, which is aligned with geometric mean's statistical properties, is computationally simpler and, due to its less sensitivity to small perturbations, yields more consistent results (Saaty & Vargas, 2012; Tavana et al., 2023). The use of the geometric mean in AHP yields the most accurate results for ranking criteria and is easy to execute (Stofkova et al., 2022). It is suggested to check the Standard Deviation of Ranks in addition to the Consistency Ratio proposed by Saaty (Kuo, 2021). RGMM is the only method that strictly satisfies the reciprocity condition when aggregating group judgements without compromising the mathematical integrity of judgements (Xu & Xu, 2020).

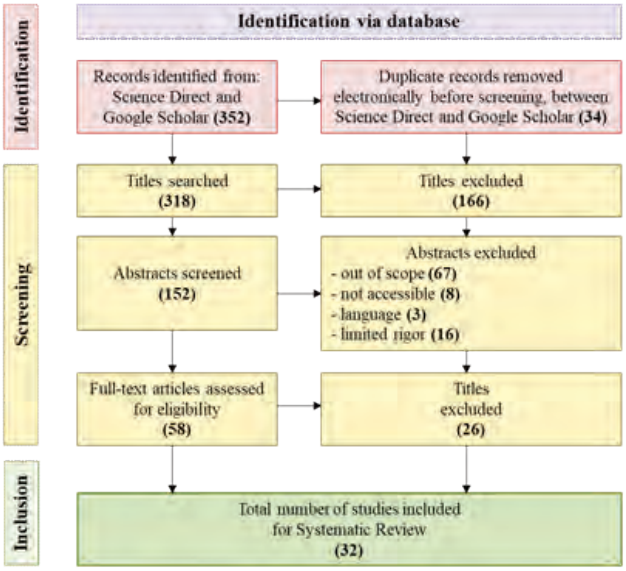

Fig. 1. PRISMA Diagram for Research Suggesting History Integration with Design Studio and Pertinent Issues (Source: Authors)

The criteria matrix [A] will be consistent only if SDR [A] = 0; however, a threshold using SDR [A] ≤ $\delta\sigma_{(1\sim n)}$, where $0 \leq \delta \leq 1$, is also acceptable (Kuo, 2021). Although the Consistency Ratio threshold is sufficient for checking, another check, the Geometric Consistency Index in Geometric means-based analysis, further strengthens the validity of the results (Aguaroon & Moreno-Jimeenez, 2003). A consistency ratio variation of less than 10% is acceptable and can be assessed using online software tools or by revising

the comparison matrix (Goepel, 2018; Frish et al., 2025), thereby avoiding the need to revisit experts. The authors used the RGMM of AHP, with geometric mean aggregation of experts' opinions and linear scaling, to analyse the weights of the various criteria in the present investigation.

METHODOLOGY

A mixed-method approach, including literature review using the well-established PRISMA framework, is used for the literature and criteria for identification of factors; expert Delphi survey, a physical questionnaire for selection of factors for analysis and pairwise comparison of factors; statistical analysis; and Analytic Hierarchical Process with linear scaling for analysis of weights of factors and ranking of weights. The authors used an empirical approach to analyse the weights of factors related to integrating architectural history into the architectural design studio.

Definitions

Definitions of some key terms were elaborated to bring clarity to their meaning, understanding and use in the study.

a) Notion-based issues: a common perception that something is boring, uninteresting, and insignificant, and therefore irrelevant to design, in the present or the future.

b) Communication skill-based issues: challenges arising from limitations in language proficiency, comprehension, reading habits, and visual representation skills, which affect the communication and understanding of knowledge.

c) Teacher-based issues: aspects of a teacher's knowledge, motivation, enthusiasm, and ability to engage and inspire students in the learning process.

d) Teaching Pedagogy-based issues: barriers arising from inadequate teaching approaches that limit and restrict experiential, visual, and hands-on methods that facilitate deeper learning, such as sketching, model-making, presentations, and site visits.

e) Student-based psychological issues: issues arising from a lack of motivation, interest, or relevance, and from reluctance to engage with new or demanding learning experiences, which hamper inspiration and enthusiasm towards new learning discoveries.

f) Curriculum-based issues: issues in the curriculum having limitations on explanations, setting the context both in design and theory subjects, lack of mentions of integration methods and absence of evaluation rubrics for checking the integration.

Identification of Experts

The architectural profession in India is governed by the Council of Architecture (COA), New Delhi. For the selection of experts, only experts working in COA-recognised architecture institutes were selected.

Definition of Experts

An 'expert' was defined as a person holding a minimum of an undergraduate degree in architecture, along with at least one of the following attributes:

Teaching the history of architecture theory course and leading as coordinator of the architectural design studio for a minimum of 10 years, and providing discourse on the integration of history/theory subjects in the design studio.

Or

Having more than 10 years of experience engaged in both professional practice and teaching, with engagement in architectural design studio, offering a history of architecture theory courses, and providing discourse on the integration of history/theory subjects in design studio/practice.

Or

A person with an undergraduate degree engaged in professional practice or leading an architectural firm for more than 20 years, with experience in applying historical precedents in a minimum of medium to large-scale 5 architectural projects.

Profile of Delphi Expert Panel (N=20)

The twenty experts comprised eminent teaching faculty from various parts of India, specialising in architectural design and HOA, as well as practising architects. The comprehensive ideation process identified gaps in the existing body of knowledge, which in turn led to the formulation of research questions. The details of

the educational qualifications, work experience, and institutional character are presented graphically in Figure 2.

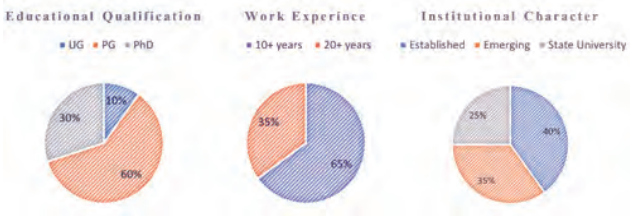

Fig. 2. The Demographic Characteristics of the Delphi Experts (source: authors)

The Delphi survey provided the face and content validity for the survey items. Through unstructured interviews and discussions, further insights were gained that informed the framing of the survey instrument and led to the expansion of the scope of the issues and barriers. The academic seniority of holding a postgraduate or PhD in Architecture or a related field of heritage conservation / architectural history, pedagogical experience of at least 10 years of teaching experience in both lecturing theory courses (history of architecture) and supervising architectural design studios, and evidence of expertise through peer-reviewed publications focusing on curriculum development, architectural education or the intersection of history and design.

Research Framework

Developing the research framework involved identifying the key factors through a systematic literature review. Based on the findings, a questionnaire was prepared to collect responses from the identified Delphi experts. The process followed a 7-step comprehensive process as described below:

Step 1: Identification of factors related to the integration of the HOA in the architectural design studio through literature review.

Step 2: Identification of experts with awareness of questionnaire development, history of architecture and its integration in the architectural design studio

Step 3: Expert's opinion on inclusion and exclusion of factors identified from literature and rating using AHP

Step 4: Development of a questionnaire for pairwise comparison on the Saaty scale (1-9) and the content analysis of the questionnaire

Step 5: Collection of expert opinion

Step 6: Analysis of individual expert opinion by using the AHP consistency ratio and the Geometric Consistency Index

Step 7: The individual pairwise comparison matrices are then consolidated using the weighted geometric mean (in this case, all weights are considered the same), and the resulting matrix is used to calculate the weights in step 6 mentioned above.

The population of architects engaged in professional practice and higher education is limited and can be approached using personal connections. The authors also used similar personal connections to approach the identified experts and to secure time for a personal discussion about the importance of the HOA theory course in architectural design. After a discussion of the importance of the HOA in architectural design, the experts were presented with a list of factors affecting its integration into architectural design and studio courses at higher education institutions.

The analysis of the discussion led to the identification of factors, which were then presented to experts for rating their importance on a scale of 0-10. These marks are then statistically analysed in aggregate to list the final factors to be considered for pairwise comparison by the same experts in a second meeting / telephonic conversation.

Level one Delphi helped in the finalisation of a total of six criteria by using the rating on a scale of 0 to 10.

Data Collection, Preparation and Analysis

The data collected from individual expert opinions were analysed using the AHP consistency ratio and the Geometric Consistency Index. The following steps were followed for the same:

The pairwise comparison matrix [A1] was developed for all the individual experts

The geometric mean of rows of an n x n matrix was calculated by using equation [1]:

$$GM_i = \left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}} \quad (1)$$

n is the number of criteria (in the present investigation, n = 6)

The sum of the geometric mean of the column was calculated by using equation [2]

Sum of Geometric Mean

$$(\sum GM) = \sum_{i=1}^{n} GM_i \quad (2)$$

The GM_i values were normalised, and the weights were found [A2] by using equation [3]

$$W_i = \frac{GM_i}{\sum_{i=1}^{n} GM_i} \quad (3)$$

The consistency check was performed using the measurement of inconsistency

Generate [A3] = [A1] x [A2]

Generate [A4] = [A3]/[A2]

Calculate λ_{max}=Average [A4]

Calculate

$$Consistency\ Index\ (CI) = \frac{\lambda_{max} - n}{n-1} \quad (4)$$

The Random Index for n=6 from Table 1 is 1.24, which was used to calculate the consistency ratio.

Table 1: Random Index

N	3	4	5	6	7	8	9	10	11	12
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

Source: (Saaty, 1987)

The Consistency Ratio (CR) was checked by using

$$Consistency\ Ratio = \frac{Consistency\ Index}{Regular\ Index}$$

(Acceptable<0.1); (5)

The Geometric Consistency Index was analysed by using the reciprocal property of errors in the log of errors and the log of unity

$$GCI = \frac{2}{(n-1)(n-2)} \sum_{i<j} (\log e_{ij} - \log 1)^2 \quad (6)$$

GCI≤0.3147 for n=3, GCI≤0.3526 for n=4, and GCI≤0.370 for n>4 is acceptable.

If the Consistency Ratio < 0.1 is observed for any expert, the value is accepted; otherwise, the variation is revisited with the expert for a recheck and to refill the pairwise comparison matrix, with guidance on which values to consider to improve consistency. This method is consistent with the original proposed by Saaty (1980). Experts with an observed consistency index>0.1 are to be dropped. This method does not interfere with experts' consistent initial judgments. The individual pairwise comparison matrices were then consolidated using the weighted geometric mean (all weights considered the same).

RESULTS AND DISCUSSION

The Saaty scale is used in the pairwise comparison matrix, where experts compare one factor against another based on their perceived relative importance. The scale value of one means equal importance, three denotes moderate importance, five implies strong importance, seven denotes very strong importance, and nine suggests extreme importance.

The individual pairwise comparison matrices from 20 experts were combined into a single consolidated matrix using the weighted geometric mean method. This approach is commonly used in AHP to aggregate multiple expert judgements while maintaining the reciprocal properties of the matrix (Saaty, 1980). The study consisted of 6 factors. Each expert provided their pairwise comparison, and these values were aggregated using the weighted geometric mean to derive a collective decision. The method ensured that all expert opinions were proportionately represented and that extreme values would not influence the final matrix. Hence, a balanced group consensus is represented with reduced variability and improved consistency. The consolidated results show greater consistency and provide a strong basis for further calculation of weights and ranking of the factors.

The pairwise comparison matrix for all 20 experts was used to analyse the consistency ratio individually and then at the group level. The results of the analysis are presented in Figures 3 and 4.

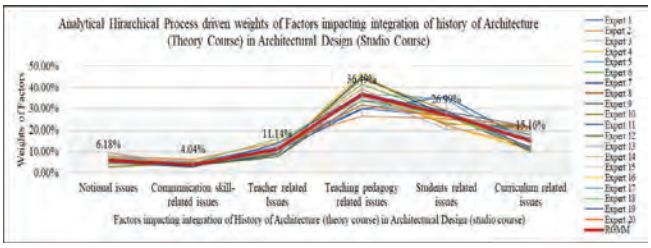

Fig. 3. Analytical Hierarchical Process derived weights (in percentage) by 20 respondent experts and their collective weights for identified factors impacting integration of HOA in the Architectural Design Studio

The Box-and-Whisker Plot of AHP-derived weights illustrates the distribution and variability of expert opinions for each factor. While the AHP weights provide average priorities, the box plot helps interpret consistency among experts, consensus or disagreements, the spread of decisions, and the presence of outliers. A median line represents central tendency, the box itself denotes the interquartile range (Q1-Q3), the whiskers indicate the minimum and maximum non-outlier values, and the outliers are simply the unusual expert judgements.

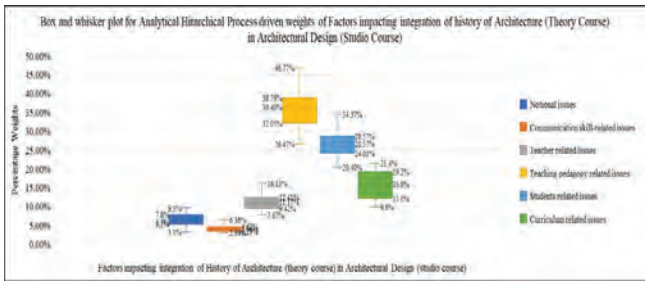

Fig. 4. Box and Whisker variations in Analytical Hierarchical Process derived weights (in percentage) by 20 respondent experts and their collective weights for identified factors impacting integration of HOA in Architectural Design Studio

The median weight for the Teaching pedagogy-based issues is the highest (36.40%), indicating that most experts consistently ranked this issue as the most important criterion. The narrow width of a box indicates high consensus. Experts showed larger variability in the issues of Curriculum-based issues (IQR= 19.2-12.0= 7.2%), followed in decreasing order by Teaching pedagogy-based issues (IQR= 38.79-32.05= 6.74%), Student-based psychological issues (IQR= 28.57-24.01= 4.56%), Teacher-based issues (IQR= 12.41-9.42= 2.99%), Notion-based issues (IQR= 7.8-5.2= 2.6%), and Communication skill-based issues (IQR= 4.62-3.29= 1.33%). IQR values indicate differing expert perspectives on the relative significance of the issues.

Whiskers show the overall range and indicate the amount of variance among the experts. The issues follow a decreasing order of variance from Teaching pedagogy-based issues (26.47 to 46.77), followed by Student-based psychological issues (20.40 to 34.37), Curriculum-based issues (9.8 to 21.4), Teacher-based issues (7.67 to 16.13), Notion-based issues (3.1 to 9.5), and Communication skill-based issues (2.99 to 6.36). The priority of the AHP weights is hence additionally supported by the Box plots.

The initial Consistency Ratio (CR) assessment of the pairwise comparison matrices indicates that the judgements provided by the individual experts are within the range of 4% (0.04) and 13% (0.13). The acceptable threshold for the CR is 10% (0.10). The CR values for Experts 8, 11, 12, 14, and 16 exceeded the acceptable limit of 10%. The CR values are 11% (0.11) for Experts 8, 11, and 12, and 13% (0.13) for Experts 14 and 16. Hence, these 5 experts were dropped from further analysis. The CR values for the remaining fifteen experts ranged from 4% (0.04) to 9% (0.09). Since all values were below the acceptable limit of 0.1, the comparisons were considered reliable for further analysis.

The Mean Consistency Ratio of 4.80% of all twenty experts and 4.29% of the total fifteen experts (after the exclusion) indicates that the overall level of consistency among experts is acceptable and within the permissible limit (Saaty, 1980). The Geometric Consistency Index (GCI) values range from 0.16 to 0.35, indicating moderate variability in the expert judgements. Lower GCI values correspond to higher consistency. The GCI mean value of 0.16 for the fifteen experts suggests that the overall level of agreement among the experts is highly consistent (Aguaron & Moreno-Jimenez, 2003). This confirms the overall reliability of the pairwise comparison results. The results for the consistency ratio and GCI, generated from the respective pairwise comparison matrices of experts at two stages, are presented in Table 2.

Table 2: Initial computed Consistency Ratio for individual experts for two stages

Sr. No	Expert	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	GM
1	CR(%)	5	4	9	0	0	5	9	11	5	9	11	11	5	13	9	13	9	6	9	5	4.80
2	GCI	.18	.16	.31	.23	.21	.30	.30	.39	.17	.31	.29	.372	.35	.39	0.30	0.44	.34	.23	.34	.25	0.18
3	CR(%)	5	4	9	0	0	5	9		5	9			5		9		9	6	9	5	4.29
4	GCI	.18	.16	.31	.23	.21	.30	.30		.17	.31			.35		0.30		.34	.23	.34	.25	0.16

Table 3: Consolidated matrix using the weighted geometric mean of 15 respondent experts for the identified six factors impacting the integration of the HOA in the Architectural Design Studio

Consolidated Matrix = Weighted geometric mean of respondent experts Number of experts = 15 Number of factors = 06		Notion-based Issues	Communication Skill-based Issues	Teacher-based Issues	Teaching Pedagogy-based Issues	Student-based Issues	Curriculum-based Issues	Normalized Geometric Weights
Factors	Code	C1	C2	C3	C4	C5	C6	
Notion-based Issues	C1	1.0000	5.9988	0.4825	4.3022	5.8275	0.9057	6.18%
Communication Skill-based Issues	C2	0.1667	1.0000	0.1542	0.4826	1.0000	0.2477	4.04%
Teacher-based Issues	C3	2.0727	6.4866	1.0000	6.4791	6.6041	1.0000	11.14%
Teaching Pedagogy-based Issues	C4	0.2324	2.3116	0.1543	1.0000	2.5076	0.2612	36.49%
Students-based Issues	C5	0.1716	1.0000	0.1514	0.3988	1.0000	0.1994	26.99%
Curriculum-based Issues	C6	1.1041	4.0365	1.0000	3.8281	5.0158	1.0000	15.16%

The individual pairwise comparison matrices were then consolidated using the weighted geometric mean (in this case, all weights are considered the same), and the consolidated pairwise results and the normalised Geometric Weights obtained using AHP with linear scaling, as proposed by Saaty, are presented in Table 3.

The AHP weight analysis indicates that the teaching pedagogy-based issues (36.49%) are the most important and influential among the six identified factors. Student-based psychological issues (26.99%) are the second-most influential factor. Curriculum-based issues (15.16%) were placed as the next significant factor. Teacher-based issues (11.18%) came next, followed by notion-based issues (6.18%), while communication skill-based issues (4.04%) were placed lowest. The findings suggest that the panel of 15 experts strongly prioritise pedagogy as a factor affecting the integration of the HOA into the Architectural Design Studio.

The final weights and ranks of the criteria under consideration are presented in Table 4 to support the further ranking of factors affecting the integration of the HOA into the Architectural Design Studio.

Table 4: Analytical Hierarchical Process derived weights and ranks of factors impacting integration of HOA in the Architectural Design Studio using linear scaling

Sr. No.	Criterion	Weights	Final Rank
1	Teaching methodology-related issues	36.49%	1
2	Students related issues	26.99%	2
3	Curriculum-related issues	15.16%	3
4	Teacher-related issues	11.14%	4
5	Notional issues	6.18%	5
6	Skill-related issues	4.04%	6

The derived weights indicate the comparative priority of each factor, and the ranks reflect the order of the factor's significance. The weights indicate that Teaching Methodology-based issues carry the highest weightage (36.49%), have the greatest impact on the integration of History and Architectural Design, and are therefore ranked first. This suggests that improvements in teaching methodology will have the greatest impact. The highest rank indicates a strong collective prominence regarding teaching methodology-related issues. The student-based psychological issues carry the second-highest weight (26.99%) and are hence ranked second. Although considered important, the lower weight suggests that this was perceived as secondary to teaching methodology. This was followed by Curriculum-based issues (15.16%), ranked third, implying that curriculum was considered significant, albeit lesser than teaching methodology and student-based psychological issues, but a focused curriculum of both the history of architecture and integration check-based curriculum of architectural design can help in stronger integration and adaptability to learnings of theory subjects in architectural design. Teacher-based issues (11.14%), ranked fourth, reflecting their significance in the overall factors. Notion-based issues (6.18%) ranked fifth, and Skill-based communication issues (4.04%) ranked sixth.

The proportional variations among the weights are significant in AHP because the weights are normalised and their sum equals 1.00. The difference between the values reflects the relative dominance of one factor over the other. The weights indicate a strong preference hierarchy among the factors.

CONCLUSION

Integrating theory subjects into the architectural design studio is important. The integration of theoretical

subjects into architectural design is being evaluated informally and subjectively, but not formally defined. The HOA theory subject has been given due importance in the formulation of syllabi at different institutions, but the practice of integration is very limited. The practice of measuring the integration of theory subjects, such as structural design and services, is available, but measurements of HOA integration are missing. This work identified basic issues that favour a lack of integration, determined their respective weights, and ranked them using a well-established Analytical Hierarchy Process. Teaching methodology-related issues (36.49%) and student-related issues (26.99%) were major roadblocks, accounting for more than 60% of the overall integration issues, followed by curriculum-related issues (15.16%) and teacher-related issues (11.14%). The notional issues (6.18%) and skill-related issues (4.04%) remain restricted to around 10% of the issues and can be tackled only when resolutions to other issues don't work. The results of AHP are robust with a consistency ratio (<0.10) and a Geometric Consistency Index (0.16). The derived weights and corresponding ranks provided a systematic understanding of the relative importance of each factor. The AHP-derived ranking is significant for prioritising areas to address integration barriers and would lead to relevant and appropriate interventions in these areas, as well as to the substantial integration of history and architectural design.

Future Scope: A detailed investigation on the subfactors of the identified factor can be done. The use of other multicriteria decision-making tools, such as TOPSIS, Best-Worst Method, VIKOR, and Structural Equation Modelling, can be attempted to strengthen the validation of the weights and ranks of the identified factors. Similar AHP-driven studies on integrating other subjects into architectural design in the Indian context could be undertaken.

ACKNOWLEDGEMENT

The authors have no acknowledgements to declare.

REFERENCES

1. Aguaroon, J., & Moreno-Jimeenez, J. M. (2003). The geometric consistency index: Approximated thresholds. European Journal of Operational Research 147, 147, 137–145.
2. Ahmad, M., Haq, A. U., Raina, S. H., Pala, S. M., & Khan, A. I. (2023, July 19). Students' Perception and Gender Differences in Digital Learning During COVID-19: A consensus Based Approach. https://doi.org/10.21203/RS.3.RS-3091677/V1
3. Bafail, O. A., & Abdulaal, R. M. S. (2022). A Combined BWM-TOPSIS Approach Versus AHP-TOPSIS Approach: An Application to Solid Waste Management. ACM International Conference Proceeding Series, (January 2022), 27–33. https://doi.org/10.1145/3524338.3524343
4. Budescu, D. V., Zwick, R., & Rapoport, A. (1986). A Comparison of the Eigenvalue Method and The Geometric Mean Procedure for Ratio Scaling. Applied Psychological Measurement, 10(1), 69–78. https://doi.org/10.1177/014662168601000106
5. Carr, E. H. (1961). What Is History? (First). Vintage.
6. Christie, C. A., & Barela, E. (2005). The Delphi technique as a method for increasing inclusion in the evaluation process. Canadian Journal of Program Evaluation, 20(1), 105–122. https://doi.org/10.3138/cjpe.020.005
7. Frampton, K. (2007). Modern Architecture: A Critical History (World of Art) (Fourth). Thames & Hudson (World of Art imprint).
8. Frish, S., Talmor, I., Hadar, O., Shoshany, M., & Shapira, A. (2025). Enhancing consistency of AHP-based expert judgements : A new approach and its implementation in an interactive tool. MethodsX, 14(February), 103341. https://doi.org/10.1016/j.mex.2025.103341
9. Goepel, K. (2018). Implementation of an Online software tool for the Analytic Hierarchy Process (AHP-OS). International Journal of the Analytic Hierarchy Process, 10(3), 469–487. https://doi.org/10.13033/ijahp.v10i3.590
10. Gomez-del Rio, T., & Rodriguez, J. (2022). Design and assessment of a project-based learning in a laboratory for integrating knowledge and improving engineering design skills. Education for Chemical Engineers, 40, 17–28. https://doi.org/10.1016/J.ECE.2022.04.002
11. Hosagrahar, J. (2002). Looking Back, Moving Ahead-History and Modernization Institutional Context: The Birth and Development of Architecture Schools.
12. Kostof, S., Castillo, G., & Tobias, R. (1995). The Popes as Planners: Rome, 1450-1650. In The History of Architecture: Settings and Rituals (pp. 485–510).

Oxford University Press New York, NY. https://doi.org/10.1093/oso/9780195083781.003.0022

13. Kuo, T. (2021). An Ordinal Consistency Indicator for Pairwise Comparison Matrix. Symmetry, 13(2183), 1–11.

14. Milošević, I., Arsić, S., & Stojanović, A. (2023). Corporate Social Responsibility, Circular Economy and Sustainable Development: Business Changes and Implications in Project-Oriented Companies. In Sustainable Business Change: Project Management toward Circular Economy (pp. 111–143). Springer, Cham. https://doi.org/10.1007/978-3-031-23543-6_5

15. Niu, H., Fan, J., & Yan, H. (2022). Research on the Integration of Subject Competition and Professional Course Teaching Mode Based on OBE Concept. Frontiers in Educational Research, 5(16), 21–25. https://doi.org/10.25236/fer.2022.051604

16. Ockman, J. (2012). Architecture School: Three Centuries of Educating Architects in North America (J. Ockman, Ed.; First). The MIT Press.

17. Panwar, M., & Fandian, S. (2025). Influence of the Mass Rapid Transit System on Plotted Residential Property Prices : A Case Study of Gurugram , India. Journal of Contemporary Urban Affairs, 9(2), 387–401. https://doi.org/10.25034/ijcua.2025.v9n2-4

18. Panwar, M., & Sheoran, S. (2024). Analysing the state of Integration of History of Architecture with the Architectural Design in India. In Innovative Approaches to Cultural Heritage and Sustainable Urban Development: Integrating Tradition and Modernity (pp. 55–67). Cinius Yayınları. https://doi.org/10.38027/N5ICCAUA2024IN0399

19. Resch, K., Schrittesser, I., & Knapp, M. (2024). Overcoming the theory-practice divide in teacher education with the 'Partner School Programme'. A conceptual mapping. European Journal of Teacher Education, 47(3), 564–580. https://doi.org/10.1080/02619768.2022.2058928

20. Rezaei, J. (2016). Best-worst multi-criteria decision-making method: Some properties and a linear model. Omega The International Journal of Management Science, 64, 126–130. https://doi.org/10.1016/j.omega.2015.12.001

21. Saaty, T. L. (1987). Concepts, theory and techniques: rank generation, preservation, and reversal in the analytic hierarchy decision process. Decision Sciences, 18(2), 157–177.

22. Saaty, T. L., & Vargas, L. G. (2012). Models, methods, concepts & applications of the analytic hierarchy process. Springer. https://doi.org/10.1007/978-1-4614-3597-6

23. Saghafi, M. R. (2021). Teaching strategies for linking knowledge acquisition and application in the architectural design studio. Archnet-IJAR: International Journal of Architectural Research, 15(2), 401–415. https://doi.org/10.1108/ARCH-01-2020-0005

24. Salama. (2008). A Theory for Integrating Knowledge in Architectural Design Education. Archnet-IJAR: International Journal of Architectural Research, 2.

25. Sewell, J. E., & Johnston, A. S. (2019). Rethinking history in design education through the history of materials. Part - 1. https://www.platformspace.net/home/rethinking-history-in-design-education-through-the-history-of-materials-part-1

26. Sheoran, S., & Panwar, M. (2025). The Role of History in Architecture Design : An Analytical Research Study. In A. Nikoofam, M., & Mobaraki (Ed.), Resilient Urbanism: Architecture, Equity & Innovation (pp. 33–46). Cinius Yayınları. https://doi.org/10.38027/N3ICCAUA2025EN0246

27. Stofkova, J., Krejnus, M., Stofkova, K. R., & Malega, P. (2022). Use of the Analytic Hierarchy Process and Selected Methods in the Managerial Decision-Making Process in the Context of Sustainable Development. Sustainability, 14(11546), 1–20. https://doi.org/https://doi.org/10.3390/su141811546

28. Tavana, M., Soltanifar, M., & Santos-Arteaga, F. J. (2023). Analytical hierarchy process: revolution and evolution. Annals of Operations Research, 326(2), 879–907. https://doi.org/10.1007/S10479-021-04432-2

29. Till, J. (2009). Architecture depends (Vol. 55). MIT Press.

30. Xu, K., & Xu, J. (2020). A direct consistency test and improvement method for the analytic hierarchy process. Fuzzy Optimization and Decision Making, 19(3), 359–388. https://doi.org/10.1007/s10700-020-09323-y

31. Zhan, Z., & Niu, S. (2023). Subject integration and theme evolution of STEM education in K-12 and higher education research. Humanities and Social Sciences Communications 2023 10:1, 10(1), 781-. https://doi.org/10.1057/s41599-023-02303-8

Mechanical Properties of Recycled Aggregate Concrete made with 100% Recycled Concrete Aggregates

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ABSTRACT

Utilisation of 100% Recycled Concrete Aggregate (RCA) for sustainable construction using Recycled Aggregate concrete (RAC) will lead to economic development and reduce the overexploitation of natural resources. It enhances the Green technology in Construction development. This study investigates the physical properties and mechanical properties of the recycled concrete aggregate and recycled aggregate concrete, respectively. The RCA is produced from the different sources of construction and Demolition (C&D) waste recycling plants in Hyderabad. This study has considered 100% replacement of virgin aggregates with the recycled concrete aggregate (RCA) to produce the recycled aggregate concrete. The properties of the materials used in the production of recycled aggregate concrete had been evaluated as per the IS Code. The experimental outcomes highlight the significant potential for maximising the recycling of construction and demolition waste, if it is properly processed.

KEYWORDS: *Recycled concrete aggregate (RCA), Virgin aggregate, and recycled aggregate concrete (RAC), Mechanical properties.*

INTRODUCTION

With rapid urbanisation, construction and demolition (C&D) waste has significantly increased, contributing to environmental concerns. The use of recycled coarse aggregate (RCA) in concrete production can mitigate these issues by reducing landfill waste and natural resource depletion [1], [2]. However, concerns regarding strength, durability, and performance limit the widespread adoption of 100% RAC. This study provides a detailed assessment of RAC's mechanical properties, durability, and economic feasibility, along with strategies for enhancing performance.

The global construction industry generates an estimated 3.57 billion tonnes of Construction and Demolition (C&D) waste annually [3]. The recycling of this waste into Recycled Concrete Aggregate (RCA) and other sustainable materials is gaining importance worldwide to avoid depletion of natural resources. However, the adoption rate, production capacity, and policy frameworks differ significantly across countries [1], [4]. This paper presents a comparative analysis of recycled aggregate production from C&D waste in Hyderabad, Telangana, India.

The recycling percentage of C&D in India is noticeably very low compared to the generation of the waste. A comparative recycling percentages are shown in Table 1, such that India has to move further ahead in the sustainability of recycling the C&D waste produced.

Construction and demolition waste in India

At present, there are 34 operational plants for the recycling of C&D waste in India[15]. In Hyderabad, there are four recycling plants for collecting C&D waste, as shown in Fig. 1. These recycling units are working as per the guidelines of Greater Hyderabad Municipal Corporation (GHMC)[16]. Table 1 explains the four recycling units mentioned in Fig. 1, their capacities, power consumption, percentage of recycling and working hours of the plant they run for. The GHMC will pay charges to the recycling plants based on the quantity of C&D waste collected.

Table 1 Recycling of Construction and Demolition (C&D) waste

Country / Region	Year of Estimate	C&D Waste (Mt/year)	Share of Total Waste (%)	Recycling (%)	Key Reference Nos	Implementation
China	2014–2020	1000–2300	30–40	5–40	[5], [6]	Strict regulations, advanced recycling plants
European Union	2018–2020	400–850	25–30	70–88	[5], [7]	Mandates minimum RCA content in public projects
United States	2018	~600	25–30	55–60	[8], [9]	Voluntary adoption, state-wise policies
Japan	2018–2019	~200	20–25	75–95	[6], [10]	Strong government policies, innovative reuse strategies
Germany	2018–2019	200–230	30–35	85–90	[5], [7]	Advanced sorting and recycling facilities, strict regulations
South Korea	2020–2023	60–70	20–25	90–95	[10]	High recycling efficiency, strong waste management laws
Netherlands	2018–2020	20–30	25–30	90–95	[5], [7]	Circular economy approach, strict waste separation policies
India	2016–2023	150–500	25–30 (est.)	1–10	[11], [12]	Limited adoption, major potential for growth
Australia	2015–2019	20–30	~40	60–70	[9], [13]	High adoption in infrastructure projects
Brazil	2018–2020	80–100	50–60	40–60	[14]	Growing recycling initiatives

The case study of Hyderabad, like other developed cities, highlights a pressing issue: the growing challenge of landfills. This scenario is evident in Hyderabad, where the dumping of C&D waste is projected to become a significant problem by 2040, as shown in Fig. 2, based on urban population growth estimates[7], [8] and [9]. This will lead to the reduction of water bodies and, in turn, lead to the scarcity of potable water. The loss of green areas would decrease the air quality due to air pollution. The development of infrastructure would lead to scarcity of open land, and it may lead to falling short of achieving consistent sustainable climate conditions. This paper discusses the material properties of natural aggregates/virgin aggregate (NA), RCA and RAC, which are very much needed for the upcoming development of infrastructure that should use sustainable materials for a better tomorrow.

Power consumption for recycling of C&D waste represents the energy demand for processing operations such as crushing and screening. It is widely used as an indicator of process efficiency, operational cost, and environmental impact in life cycle assessment studies [16], [20].

Fig. 1. Location of C&D collections in Hyderabad

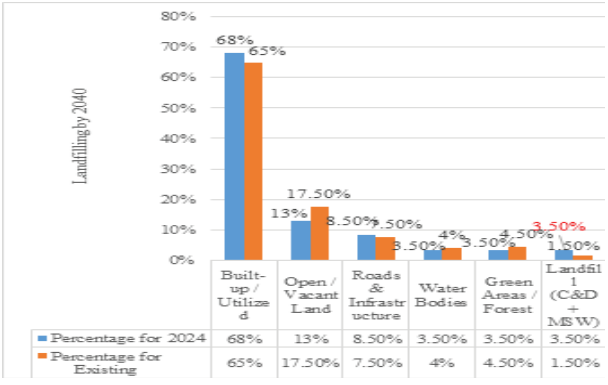


Fig. 2. Estimated landfilling of Hyderabad by 2040

Higher power consumption leads to considerable magnitudes of CO_2 emissions, especially in India, where electricity is also generated using coal. Hence, the power consumption should be minimised as much as possible for sustainable recycling of C & D waste.

Table 2: Details of the C&D Waste recycling plants in Hyderabad

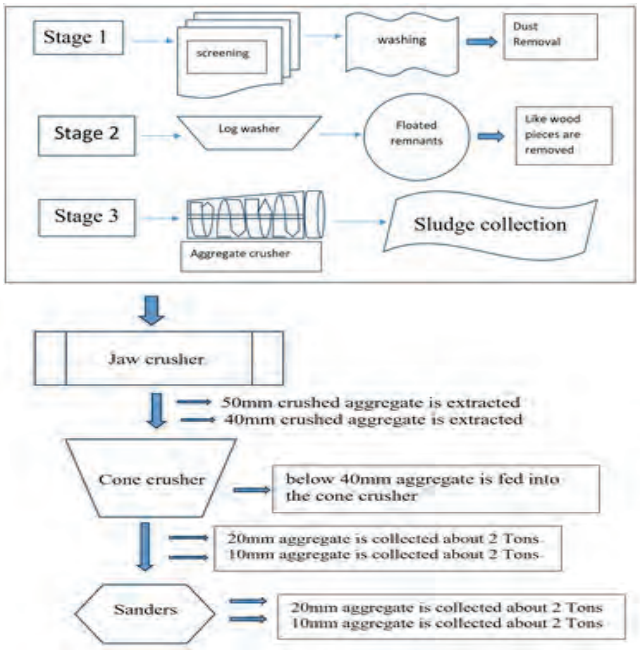
S.No	Recycling plant in Hyderabad	Capacity of the plant	Working hours of the plant	Output % from waste	Cost of sales	Power consumption
1	Thumikunta	150 to 200 Tons/hr	8hr	60%	400 - 450 Rs/Ton	4.06kW/h
2	Fathullaguda	80 Tons/hr	24 hours in 3 shifts	50-60%	400 Rs/Ton	2000-2500kW/day
3	Shamshabad	60 Tons/hr	8hr	60%	400 - 450 Rs/Ton	4.06kW/h
4	Jeedimetla	40 Tons/hr	24 hours in 3 shifts	50-60%	400 Rs/Ton	2000-2500kW/day

METHODOLOGY

The C&D waste collected from the different zones of Hyderabad is transferred to the recycling units. The first quantitative breakdown of C&D waste in India was provided in 2001[21]. Indian C&D waste consists of approximately 36% soil, sand and gravel, 31% brick and masonry, 23% concrete, 5% metals, 2% wood, and 3% other materials[22].

The C&D waste is cleaned in three stages prior to feeding it to a jaw crusher.

Flow chart for the recycling process of Construction and Demolition waste



After completing three stages of cleaning the feed, the main construction material, recycled coarse aggregates of different sizes, are extracted and collected along with sand and fine paste of dust called sludge. The recycled aggregate now contains small chunks of cement matrix, aggregate with adhered mortar, which is called the interfacial transition zone (ITZ) of aggregate, along with brick bats, wood, plastic, glass etc.

TEST ON RECYCLED CONCRETE AGGREGATE

The materials collected from the two different sources have been designated as Source 1 (S1) and Source 2 (S2).

The bulk densities of the RCA

The bulk density of recycled concrete aggregate has relatively lower values compared to the virgin aggregate; this is because of the Interfacial Transition Zone (ITZ) [23], [24], [25], [26], [27], on the RCA as shown in Fig. 5. From Fig. 3 and 4, the S1 has relatively higher bulk density than the S2 because of less adhered motor, or it can be conveyed as a smaller ITZ zone[28], [29], [30], [31] and because of microcracks in them[4]. Treating of the recycled aggregate will enhance its properties; there is little research has been done on treating the recycled aggregate, including thermal treatment, slurry treatment and chemical treatment [4] [32].

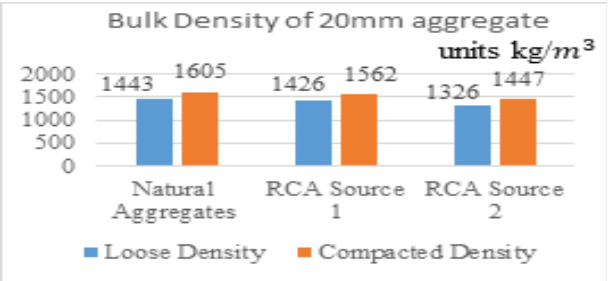


Fig. 3: Bulk density of 20mm size aggregate

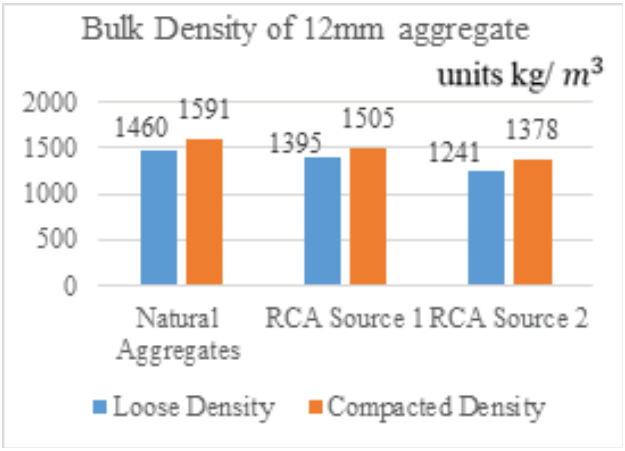


Fig. 4: Bulk density of 10mm size aggregate

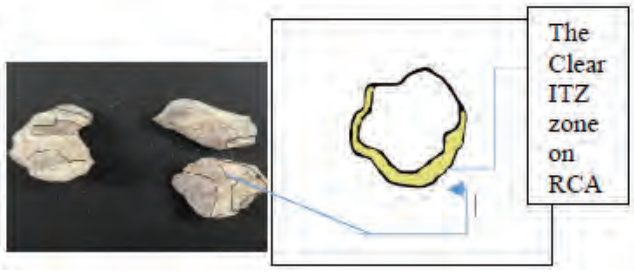


Fig. 5: The ITZ zone on the recycled concrete aggregate

The specific gravity test on RCA

The test was performed as per IS 2386 (Part 3):(1963). The specific gravity of recycled aggregates of sources S1 and S2 have significantly lower values than that of virgin aggregates, because of the high porosity of the residue mortar on the recycled aggregates [4] which leads to lower bulk densities and strength reduction of RAC[27], [30], [33]. This influences the water absorption [29].

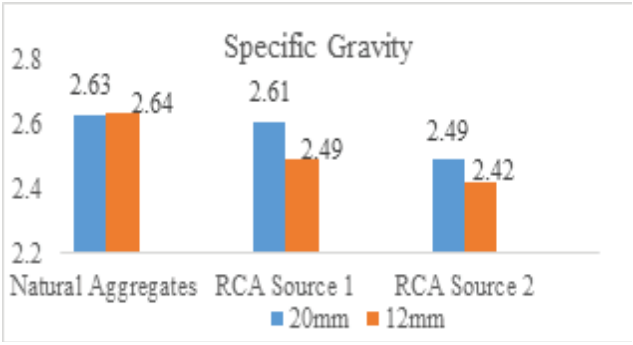


Fig. 6 Specific gravity of natural and recycled concrete aggregate (S1 & S2)

Test on Water Absorption on RCA

The study on water absorption on recycled aggregate can be up to 12%[4], [24], [28], [33], [34]. According to IS 383:2016, the water absorption of natural aggregate will be less than 2%. The higher the adhesion content on aggregate, the higher the water absorption of RCA[29], [30]. The higher the water absorption, the greater the effect on the workability of concrete [35]. The 20 mm recycled coarse aggregate from the two sources has a lower water absorption value compared to the 10 mm recycled aggregate from the respective sources, as shown in Fig. 7.

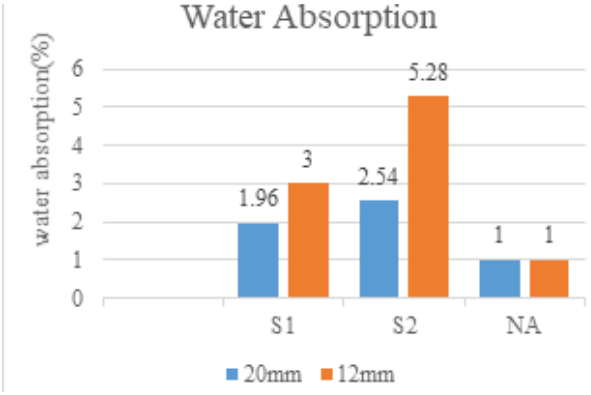


Fig. 7. Water absorption for natural and recycled aggregates

The aggregate crushing value of the RCA

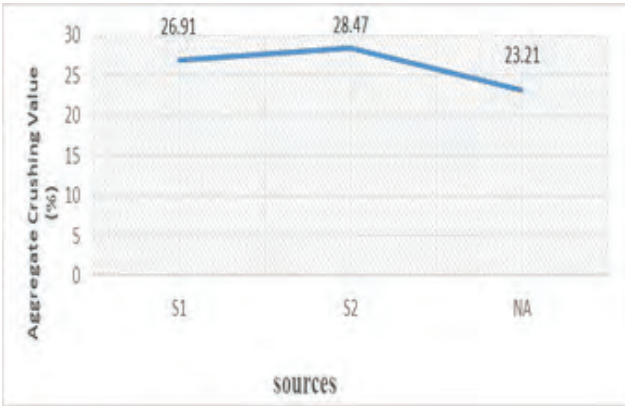


Fig. 8 The crushing strength test results for natural and recycled concrete aggregate

As per IS 2386 (Part 4), the Aggregate Crushing Value (ACV) test is carried out to assess the resistance of aggregates to crushing under a gradually applied compressive load. The permissible ACV is generally

limited to 30% for pavements, while values up to 45% for base courses. Lower ACV values indicate stronger aggregates, whereas the values exceeding 45% represent weak aggregates unsuitable for structural applications.

The recycled coarse aggregate collected from source 2 (S2) has a higher aggregate crushing value compared to the recycled coarse aggregate collected from source 1 (S1), as shown in Fig 8, indicating the weak ITZ on the aggregate[4], [27], [31], [36].

The aggregate Impact test on RCA:

The toughness of aggregates, which reflects their resistance to sudden impact or shock loading, is commonly evaluated using the Aggregate Impact Value (AIV) test as specified in IS 2386 (Part 4):2016. The AIV represents the percentage of fines generated under standardised impact conditions and serves as an indicator of aggregate quality. The quality of aggregate decreases in case of considerble quantity of adhered motar to the recycled aggregate. The source 2 has relatively higher adhered mortar and thus they have the higher AIV when compared with source 1 as shown in Fig. 9. The suitability of aggregates for various construction applications is assessed by comparing the obtained AIV with the acceptance limits prescribed in IS 383:2016. According to these provisions, aggregates with Aggregate Impact Values not exceeding 30% are considered suitable for wearing surfaces such as pavements, while values up to 45% are acceptable for general concrete works. Aggregates exhibiting higher values (AIV) are generally regarded as weak and unsuitable for structural applications. Lower values (AIV) indicate superior resistance to impact loads, thereby contributing to enhanced durability and mechanical performance of concrete.

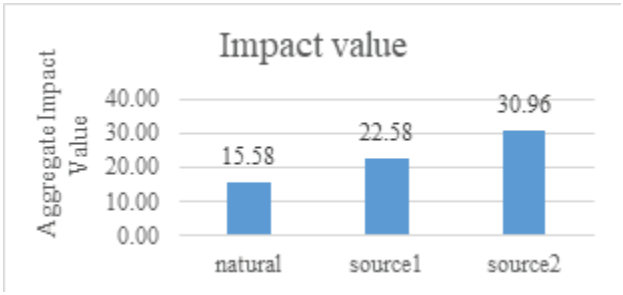


Fig. 9 The aggregate impact value for natural and recycled concrete aggregate

THE TEST ON FINE AGGREGATE

Fine aggregate used in concrete was tested in accordance with IS 2386 to evaluate its suitability. Sieve analysis was conducted as per IS 2386 (Part 1):1963 to determine the particle size distribution and grading zone as per IS 383:2016. Specific gravity and water absorption tests were performed following IS 2386 (Part 3):1963. The bulking of sand was determined to account for volume changes due to moisture content. Additionally, silt content and deleterious materials were assessed to ensure compliance with permissible limits as shown in Table 3. These tests are essential to ensure proper mix design, workability, and strength characteristics of concrete

According to IS 383:2016, the grading of the aggregate in Fig. 10 corresponds to Zone II, which is the most commonly used category for general concrete works.

Table 3: Physical properties of fine aggregate

S. No	Experiments done	Results	IS Code permissible values
1.	Specific Gravity	2.59	2.5 – 3.0
2.	Loose Bulk Density	1664 kg/m3	1200 – 1750 kg/m³
3.	Compacted Bulk Density	1780 kg/m3	1400 – 1900 kg/m³
4.	Water absorption	1	≤ 2%
5.	Bulking of sand	36.18% (at 4% moisture content)	5% – 40% (depends on moisture content)
6.	Fineness modulus	2.68 (Zone II)	2.2 – 3.2 (Zone I–IV sand)

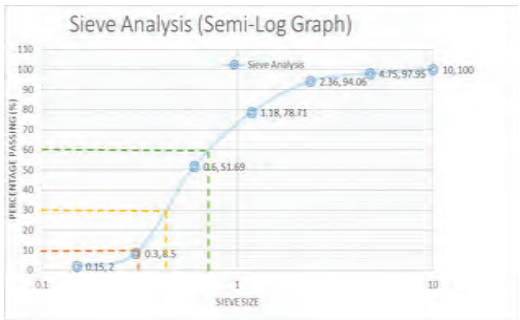


Fig. 10: Sieve analysis of fine aggregate (river sand)

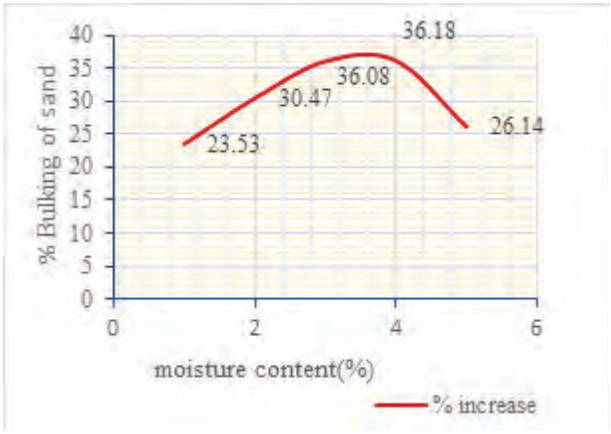


Fig. 11: Bulking of fine aggregate (river sand)

Bulking of sand is the apparent increase in volume of fine aggregate as shown in Fig. 11 due to the presence of moisture, which forms a thin film around the particles, causing separation due to surface tension. The repulsion takes place between the sand particles and moves apart. This phenomenon is more significant in finer aggregates due to their higher surface area and decreases with increasing moisture content until saturation is reached. The determination of bulking is essential for accurate volumetric batching of concrete and is carried out as per IS 2386 (Part 3):1963. In the case of recycled aggregates, higher porosity and water absorption characteristics influence moisture distribution and volumetric behaviour, thereby affecting the bulking and workability of concrete[37], [38]. Therefore, proper assessment of bulking is crucial for ensuring mix design accuracy and performance of recycled aggregate concrete.

THE TEST ON CEMENT

As per IS 1489 (Portland Pozzolana Cement), the recycled aggregate concrete is tested. The normal consistency of cement is defined as the percentage of water required to prepare a standard cement paste such that the Vicat plunger penetrates to a depth of 5–7 mm from the bottom of the mould. This test is conducted in accordance with IS 4031 (Part 4):1988 using a Vicat apparatus. The normal consistency provides a measure of the water requirement of cement and serves as a reference for determining setting time and soundness characteristics. Table 4 shows the results in permissible limits as per IS Codal provisions.

Table 4: Experiments done to determine the Physical properties of Portland Pozzolana Cement(PPC)

S.No	Experiments done	Results	IS Code permissible values
1.	Specific Gravity	3.101	3-3.15
2.	Fineness	3.6%	<10%
3.	Normal consistency	33%	5–7 mm from the bottom using the Vicat plunger
4.	soundness	3mm	<10mm
5.	Initial setting time	70 min	>30 min

TEST ON CONCRETE

This paper discusses about the comparative studies for M25, M35 and M45 grades using recycled concrete aggregate (RCA) called Recycled Aggregate Concrete (RAC) and concrete from natural aggregate (NAC). The superplasticiser, which is an additive to increase the workability and flowability, used for the mix design was a polycarboxylate-based (PCE) of 0.4%[39]. Major types include Polycarboxylate Ethers (PCE), Sulfonated Naphthalene Formaldehyde (SNF), and Sulfonated Melamine Formaldehyde (SMF). PCE is preferred for superior slump retention and environmental benefits[40].

Slump

The slump test is carried out for M25R, M35R, M45R, M25N, M35N and M45N, where M represents the Mix, R represents Recycled aggregate, and N represents Natural aggregates. The slump values of the higher grades of concrete were relatively lower than those of the lower grades. It's because of the lower water-cement ratios for the higher grade of mix design[41], [42]. And also, the recycled aggregate concrete shows much lower values because of the debris tiles, which lead to weak bonding, and microcracks develop because of it [43]. Figure 12 clearly explains that the lower workability of the recycled aggregate concrete decreases gradually as the grade decreases and the water-cement ratio decreases, as mentioned in Table 5 of the mix designs as per IS 10262:2019. The main drawback of using recycled concrete aggregate is its very low workability, which in turn makes it difficult to use in real-time, as it is hard to transport, place, and compact.

The slump achieved from recycled aggregate concrete is medium to high. By this, it can improve the recycled aggregate strength.

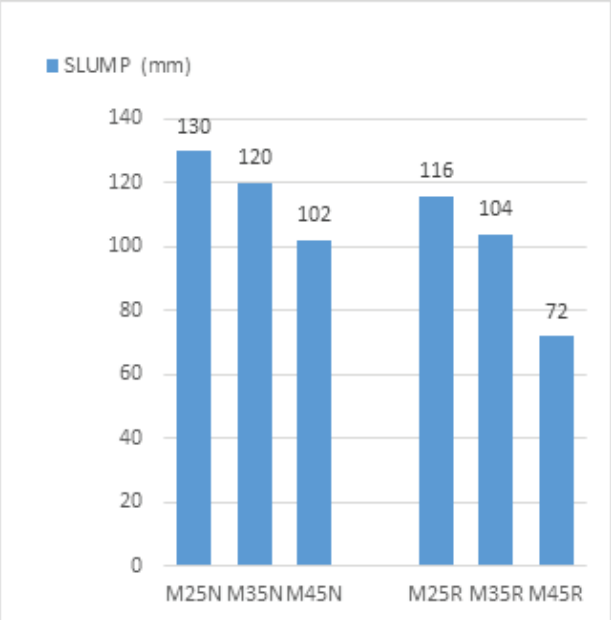


Fig. 12: The slump cone test results for the M25, M35, and M45 for both the natural aggregates and recycled concrete aggregate, respectively

Compaction factor

The compaction factor measures the more accurate workability than that of the slump cone test. It is the ratio of partial compaction to complete compaction. The results of the compaction, as shown in Fig. 13, show that the workability is medium to low for recycled aggregate concrete, whereas the natural aggregate concrete has high workability to medium.

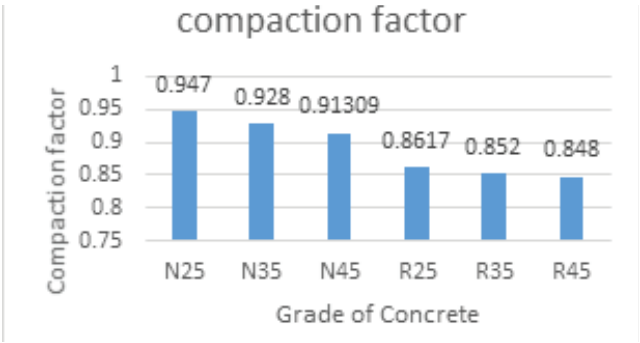


Fig. 13: The compaction factor test results for the M25, M35, and M45 for both the natural aggregates and recycled concrete aggregate, respectively

Compressive Strength

The 28-day compressive strength of M25N, M35N, M45N, M25R, M35R and M45R is tested to evaluate the comparative strength results between the grades of mix design as shown in Fig. 14. Several studies are carried out to determine the compressive strength by the replacement of recycled aggregate. This study was carried out with 100% replacement of the recycled aggregate to compare the trends of change in compressive strength for 28 days.

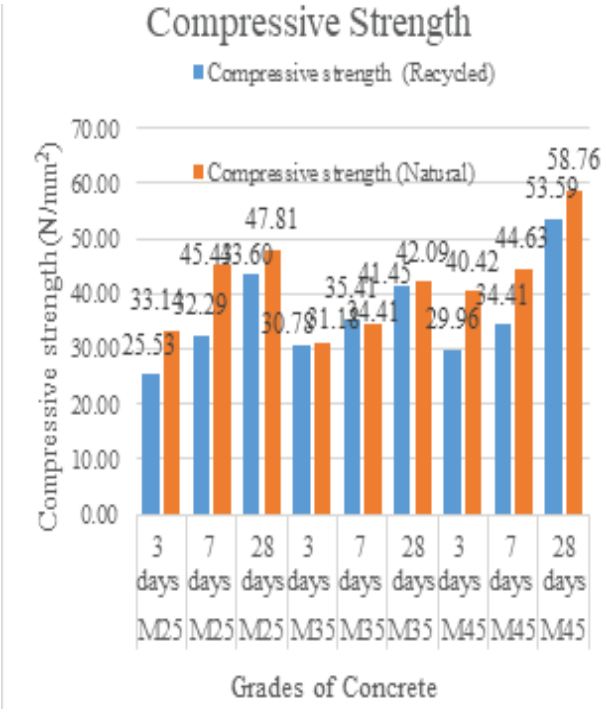


Fig. 14: The compressive strength test result for different grades of concrete using natural aggregate and recycled aggregate

Flexural Strength

The tensile strength of concrete is calculated for all grades M25N, M35N, M45N, M25R, M35R and M45R. The flexural strength is low for the recycled aggregate concrete compared to the natural aggregate concrete, as shown in Figure 15. As the grade increases, the flexural strength also increases. The flexural strength as per IS 456 is $0.7\times \sqrt{(}$ fck) , where fck is the compressive strength of the concrete. The flexural strength results, as shown in Figure 15, satisfy the $0.7\times \sqrt{(}$ fck).

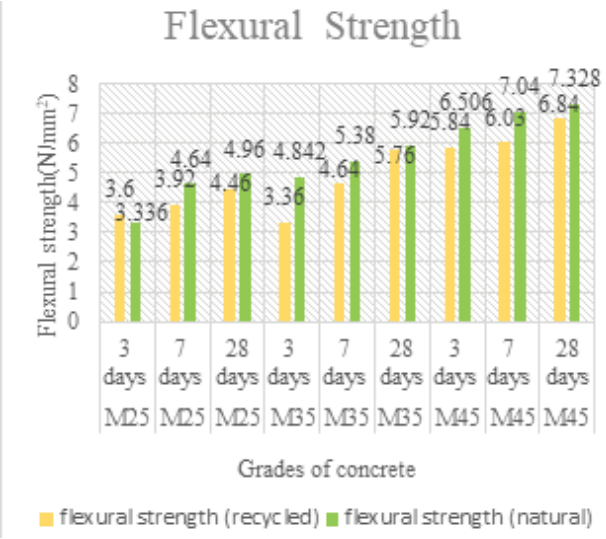


Fig. 15: The flexural strength test result for different grades of concrete using natural aggregate and recycled aggregate.

Splitting Tensile strength

The improvement in strength in RAC can be attributed to the rougher surface texture of RCA compared to NCA, and the compositional similarity between the old mortar and the new paste, which reduces stress concentrations at the interfacial transition zone (ITZ).

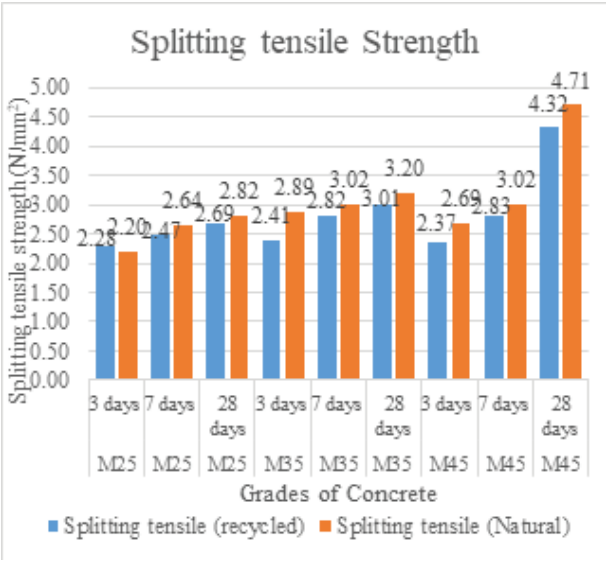


Fig. 16: The Splitting strength test result for different grades of concrete using natural aggregate and recycled aggregate

Table 5: Mix Proportions

Grade	Cement	Water	Sand	Coarse aggregate (10mm)	Coarse aggregate (20mm)	Super plasticizer (%)
M25R	1(360)	0.45	2.06	1.198	1.82	0.004
M35R	1(410)	0.4	1.741	1.02	1.541	0.004
M45R	1(420)	0.35	1.741	1.02	1.541	0.004
M25N	1(340)	0.45	2.12	1.4	2.1	0.004
M35N	1(390)	0.4	1.892	1.15	1.73	0.004
M45N	1(400)	0.35	1.892	1.15	1.73	0.004

CONCLUSIONS

The aggregate crushing value and impact value of the recycled aggregates are relatively lower than that of natural aggregates. Hence, the compressive strength of recycled aggregate concrete is lower than that of natural aggregate concrete. This is mainly due to the weak ITZ. The strength can be improved by adding a relatively higher quantity of cement than with the usage of natural aggregate. Though there is a higher demand for cement to achieve the target strength of concrete, there will be savings in the recycled aggregate concrete, as recycled aggregates are relatively cheaper than natural aggregates. Though the recycled aggregate concrete satisfies the target strength, the recycled aggregate concrete of grades M25, M35 and M45 has a relatively lower strength by 8.8%, 1.5% and 8.7%, respectively, in comparison with concrete made using natural aggregate for the same grades. The splitting tensile strength of all grades of recycled aggregate concrete has satisfied the theoretical values as per the IS 456. But, the M25, M35 and M45 grades of recycled aggregate concrete have a lower splitting tensile strength by 4.6%, 5.9% and 8.1% respectively, with respect to natural aggregate concrete. The flexural strength of M25, M35 and M45 of recycled aggregate concrete has lower values by 10%, 2.7% and

6.6% respectively, with respect to natural aggregate concrete. The overall variation in compressive strength, splitting tensile strength, and flexural strength is not more than 10% with respect to natural aggregate concrete. The strength of RCA concrete can be enhanced by treating the recycled aggregate, that is, the removal of the adhered cement matrix. There are several studies carried out on the treatment of recycled aggregate, including thermal beneficiation[44] and chemical treatment[45]. The thermal beneficiation would remove the previously adhered mortar layer and could remove weak zones and reduce the microcracks. The physical properties will be improved, resulting in better strength of recycled aggregates. The workability of recycled aggregate concrete grades of M25, M35 and M45 is medium, and it is achieved by using chemical admixture. It is observed that it is difficult to achieve the desired workability without adding chemical admixture for recycled aggregate concrete when it used without any treatment. The strength of recycled aggregate concrete (RAC) with proper mix design and treatment of recycled concrete aggregate (RCA) can achieve the desired properties of concrete. 100% replacements of natural aggregates with recycled aggregate will utilise landfill waste and avoid degradation of natural resources. The water absorption for the recycled aggregate is relatively high by 30% and 50% for source 1 and 2 respectively, for the concrete chunks having 12mm aggregates when compared with concrete chunks having 20mm aggregates. It is observed that water absorption is higher by 96% and 154% for 20mm size recycled concrete aggregate from source 1 and source 2, respectively compared with natural aggregate of 20mm size. For 12mm aggregate, sources 1 and 2 have relatively higher water absorption by 200% and 428%, respectively compared with natural aggregate. If the mortar chunks of size equivalent to that of coarse aggregate can be separated from the processed recycled aggregates, the strength of recycled aggregate concrete can be improved.

Design of a Flood Control System

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ABSTRACT

Panaji, a coastal city facing increasing vulnerability to flooding due to projected sea level rise, rapid urbanisation, and rapidly increasing tourism, confronts imminent challenges exacerbated by climate change. As a designated smart city by the Government of India, addressing these issues necessitates a proactive and dynamic approach. This study focuses on Patto, a pivotal area in Panaji, to conduct a comprehensive assessment of flood-prone zones, analyse the underlying technical causes of drainage congestion within the existing infrastructure, and quantify the extent of flooding. By identifying these critical areas, the study aims to propose effective strategies to mitigate waterlogging and strengthen the area`s drainage system.

INTRODUCTION

Panaji, which lies on the estuary of the Mandovi river is the capital city of Goa and has been identified as a coastal city vulnerable to flooding due to projected sea level rise, rapid urbanisation, increasing pressure from tourism on city infrastructure, and future risks from climate change. Contributing factors include the loss of green spaces due to illegal construction, inadequate infrastructure, and unplanned development. Over the years, several key areas have been submerged due to heavy rains affecting Panaji. Residents frequently encounter traffic congestion and blockages at Miramar Circle Road, 18 June Road, Patto Complex, etc, forcing commuters to navigate through floodwaters and disrupting daily activities. Issues of raw sewage flowing on roads at Patto-Panjim have become the new normal and the CCP and Imagine Panaji Smart City Development Corporation Limited (IPSCDL) are at the receiving end of the general public given the flood-like situation. As urbanisation continues, the city's infrastructure is under significant strain. To tackle these challenges, it is imperative to take a proactive and dynamic approach. A comprehensive plan would incorporate modern engineering solutions and sustainable practices, such as regular maintenance of drainage systems, stricter waste management policies, and community awareness programs. Patto in the city of Panaji has been selected as the study area for this project.

Before becoming Goa's capital in 1843, much of today`s Panaji city consisted of low-lying marshlands along the floodplains of the Mandovi River. From the latter half of the nineteenth century, these marshlands were gradually reclaimed to expand the city, with careful consideration of flood risks. Conversely, recent urban development has not prioritised environmental awareness. This expansion has predictably reduced the city's green spaces, with former Khazan farmlands on the outskirts being converted into urbanised zones along major roads leading into the city. Consequently, there is a higher risk of increased stormwater runoff from impermeable surfaces, potentially resulting in localised flooding.

The Patto area is no exception to this trend. Like the rest of Panaji, Patto too was once low-lying reclaimed marshland, bordered to the west by the Ourem creek, as depicted in the following image.

Fig. 1: Bird's eye-view of Patto in Panaji, as seen in 1950

Over the span of three decades, Economic Development Corporation (EDC) has undertaken the development of approximately 177,000 square metres of land in Patto. The land was reclaimed by infilling, levelled, and subdivided into different plots, which have subsequently been allocated to various lessees on a perpetual lease basis over time. The development of the Patto Plaza has been instrumental in relieving the congestion in Panjim, providing a location where about 30,000 individuals are currently employed. In 2009, significant upgrading works were approved, which involved connecting drains from the majority of plots to the main drainage system. But, because of the area`s low-lying topography and proximity to the Mandovi River, it is still prone to waterlogging and inundation and its vulnerability presents significant challenges, causing considerable inconvenience not only to the employees of the different offices housed within the Plaza but also to the commuters who depend on its roads for their daily travels.

MATERIALS AND METHODOLOGY

The focus of this project centred around Patto Plaza in Panjim, a crucial urban area now managed by the Corporation of the City of Panjim (CCP). The drainage map of Patto Plaza, which was last updated in 2009 and provided by the CCP was analysed. This map detailed the slopes of the base of drains, their depths at various points and junctions, and the Reduced Levels (RLs) of the drain bases, essential for understanding the drainage infrastructure in the area.

From what was observed, there are 3 major reasons for the flooding of the Patto Plaza: the difference between RLs of the base of drains, the peak tide levels and the heavy rainfall that Goa receives and to tackle the problem, the following was carried out. Firstly, different zones in Patto were categorised based on the occurrence of flooding. The area of each zone was then found by using CAD. Next, the RLs of the drains in flood prone zones were cross checked and visual checks to confirm their connectivity were carried out. Lastly, the discharge into the drains based on the maximum rainfall received were calculated.

To understand the effects of tides on Patto, tidal charts had to be referred to. Tidal charts are used for tidal prediction and show the daily times and levels of high and low tides. The charts were obtained from the Captain of the Ports Department. The highest tide having a level of 2.71m occurred on the 12th of February at around . The next highest value from the chart was 2.61 m which occurred on the 13th of march, 2024, with the tide level reaching its peak at approximately 1 am.

To ascertain the occurrence of flooding due to the levels of tides, a visual check was carried out on the night of the 12th of march, 2024. As the tide began to increase, brackish water entered the drains from the creek due to the low reduced levels of the drain bases. The Reduced levels at the discharge points, as indicated on the drainage map of Patto are 100.00 m which is much below the peak tide level. As per the tidal chart, for the reading of 2.61m, the RL of the tide was found to be 100.88m. This meant that for a reading of 2.71m, the RL should be 100.98m, nearly an entire metre above the RL of the drain bases at the discharge points. Hence, for tidal readings greater than 2.51m, brackish water would flow onto the surface of the roads, while readings between 1.73m and 2.51m mean reversal of flow of water has occurred and brackish water is entering the drains. The same is entirely held within the drains and does not reach the road surface level.

A high flood level (HFL) is the maximum level to which the water could rise due to rain water and runoff during a flooding event. In this case, considering storm water of about 30 cm during storms, the reduced level due to the combination of peak tide and high flood (RL of HFL) would be 101.28 m (100.98m + 0.3m). The major contributor to flooding in such cases would be the reverse flow of water into the drains during high-tide. The entry of brackish water into the drains can be

prevented by providing sluices at the discharge points where runoff water normally exits the drain into the creek. The provision of sluice gates would thus ensure that only the rainfall runoff from the area is being dealt with.

Fig. 2: River water on streets of Patto during peak tide (13 March 2024, at 01:40 am)

Another issue that arises due to the reverse flow of water is that debris and sewage that are discharged into the river and creek flow into the drains and get trapped in them. This not only leads to bad odour , but also leads to the clogging of drains because of collection of silt and debris flowing from the creek which decreases the depth of flow of the drains, thus resulting in the reduction of their discharge capacities.

To ascertain the difference between the reduced levels of the base of drains, the same 2 stretches of the drains were surveyed, the first from the walking Patto bridge to the Patto circle and the second from the Patto circle to the central library. These two stretches were selected on observing that they were tidally affected (road included) during peak high tide.

To begin, the reduced level of 100 m was considered as the temporary benchmark (TBM) at the base of the drain at outfall 1. An Auto-level was used to find the Levels. This also helped ascertain the slopes of the drains that were surveyed. The same was plotted on autoCAD, using green lines to indicate the drains and blue arrows to indicate the direction of flow within the drains. A staff was inserted at the beginning and end of each drain. The drains have been numbered 1-14 to break them down into smaller sections and understand the problem better.

As can be seen in the drawing, drains 1-3 contribute to outfall 1, while drains 4-14 lead to outfall 2.

One of the major issues encountered during this process was the presence of silt and debris in the drains. Certain points in the drains had up to 20 cm of silt and debris collected in them which would naturally result in a massive reduction in the capacity, while also reducing the slope of the drain over such sections. Through the survey, a number of execution errors on site were also found. The slope of 430 mm that was supposed to be provided along DRAIN 3 is 580 mm on site. Similarly, DRAIN 11 has a slope of 850 mm instead of the 150 mm that was supposed to be provided as per the drainage plan from 2009. These errors have been recorded and indicated in the following drawing and the corrected readings have been mentioned in the boxes.

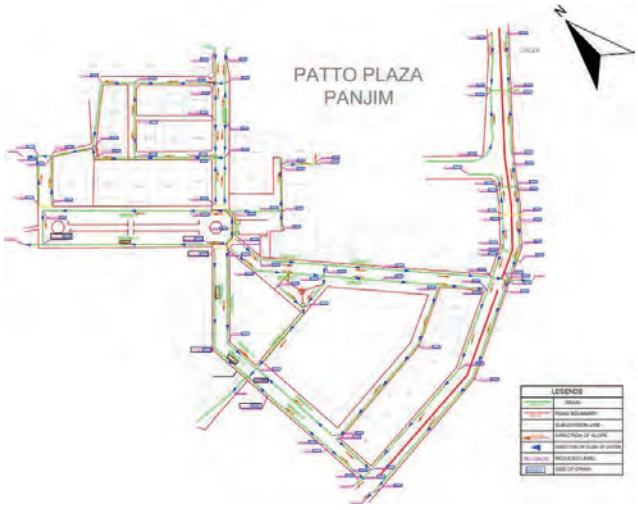

Fig. 3: Updated drainage map of Patto Plaza with corrected readings

After dividing the area into distinct zones based on flood occurrences and topographical features, the boundaries and dimensions of each zone were mapped out. Using AutoCAD, the areas serviced by each drain were plotted and marked accordingly. These areas were shaded to distinguish them visually, and the directions of runoff into the drains were indicated using red arrows. This process allowed the visualisation and quantification of the extent of each drainage catchment area within Patto Plaza. By accurately delineating and quantifying these catchment areas using AutoCAD, a comprehensive understanding of the drainage dynamics in Patto Plaza

was gained.

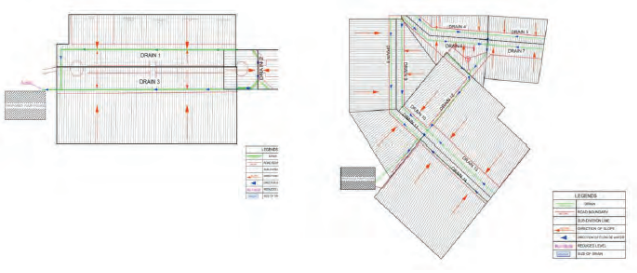

Fig. 4: Area demarcation for drains 1-3 and 4-14

3. RESULTS AND DISCUSSION

Through the analysis, it was determined that the total catchment area for outfall 1 measured approximately 26,674 square metres, while outfall 2 encompassed a total catchment area of 51,134 square metres. These calculations were crucial in assessing the capacity and efficiency of the drainage system, providing valuable insights into the volume of water each outfall is expected to manage during rainfall events. Runoff peak discharge was determined using the rational method formula Q=C·I·A. To simplify the process, an Excel sheet was developed which included inputting the three parameters to calculate the discharge. This discharge value was then used in another equation within the same sheet to determine the required depth of flow and the base width of the drain, based on the formula for the most economical section i.e. Q= A*C*(mi)^½.

This Excel sheet allowed verification of the adequacy of the drains by just adjusting the parameters.

DRAIN NO	C	I (x10^-6 m/s)	A (m^2)	Q=C*I*A (m^3/s)	L (length) m	h (height) m	slope (i)	constant	Depth (y) m	width (b=2*y) m
1	0.95	1.27	10136	0.012229084	200	0.43	0.00215	70.7	0.106832186	0.213664371
2	0.95	1.27	1515.8	0.001828813	38.15	0.15	0.0039318	70.7	0.044277244	0.088554488
3	0.95	1.27	15348.5	0.018517965	200	0.43	0.00215	70.7	0.126119386	0.252238772
4	0.95	1.27	2600.26	0.003137214	114.76	0.2	0.0017428	70.7	0.06465498	0.129309961
5	0.95	1.27	2400.728	0.002896478	68.21	0.1	0.0014661	70.7	0.064826109	0.129652219
6	0.95	1.27	3504.94	0.00422871	123.41	0.2	0.0016206	70.7	0.073922981	0.147845962
7	0.95	1.27	3664.35	0.004421038	68.14	0.1	0.0014676	70.7	0.076757774	0.153515548
8	0.95	1.27	7508.4	0.009058885	118	0.2	0.0016949	70.7	0.099364792	0.198729584
9	0.95	1.27	3428.48	0.004136461	111.59	0.2	0.0017923	70.7	0.071812967	0.143625934
10	0.95	1.27	2524.65	0.00304599	45.25	0.15	0.0033149	70.7	0.056186128	0.112372255
11	0.95	1.27	4306.55	0.005195853	52.2	0.15	0.0028736	70.7	0.071583151	0.143166302
12	0.95	1.27	8729.1	0.010531659	84.5	0.1	0.0011834	70.7	0.11339719	0.226794381
13	0.95	1.27	9548	0.011519662	118.86	0.25	0.0021033	70.7	0.104767667	0.209535334
14	0.95	1.27	12913.85	0.01558056	120	0.25	0.0020833	70.7	0.118444175	0.23688835

Fig. 5: Required dimensions of all 14 drains for ½ inch rainfall intensity

Upon doing this, it was discovered that the required dimensions of the drains were smaller than the dimensions provided as per the drainage plan. However, it is observed as per survey levels and chart datum for tides during the year 2023-2024, that peak tide water enters the drains and hence, they are tidally affected. Ideally, the Patto Plaza should have been formed above the high flood level for the natural drainage above the highest tides and floods. As per the present levels, the plaza is susceptible to tidal fluctuation and thus requires mitigation of water logging through mechanical pumping and redesign of drains, most importantly, considering tidal effects. To improve the drainage system, it is better to have more width for the drains than depth, thus increasing the holding capacity, use gates to control the entry of water during high tides and release water naturally during low tides and use pumps to discharge rainwater during peak tides, during monsoons.

Due to tidal influences, it is ideal for the depth of drains, or their inverts, not to fall below the HTL or HFL, ensuring that drainage occurs above these levels. Achieving this however, is impractical due to the minimum required drainage slope of 1 in 1000 (1 cm per 10 m). For drains affected by tides, it is recommended to increase their width. This adjustment facilitates drainage discharge before the peak of high tide, addressing tidal impacts effectively. Consider drains of clear size 900mm width and 400mm depth. Slope for drainage 1 cm every 10 m, i.e. 1 in 1000. Drains that end into outfall connecting or a jackwell of clear diameter 5.00 m and depth 5.00 m (below ground level). The bottom 1.00 m is to be concreted. The well should hold a maximum 4.00 m depth of water and minimum depth of 2.00 m depth for

the purpose of pumping. A pump house is proposed at each outfall for mechanical pumping of water: one near the walking Patto bridge and the other near the Central Library, as indicated on the drainage plan.

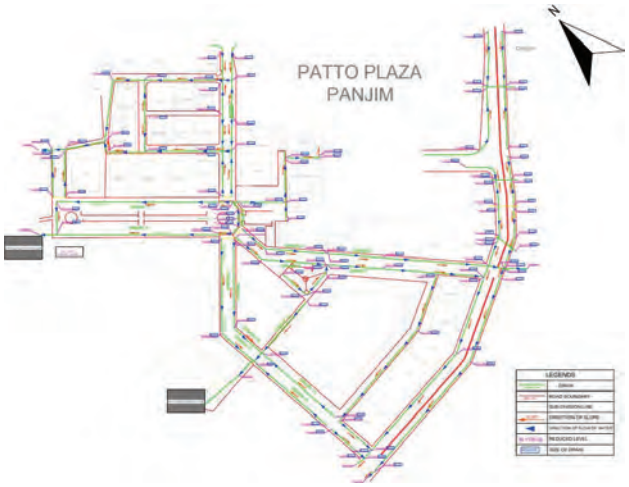

Fig. 6: Plan showing Proposed dimensions and proposed Pumping Stations

The pumping system is designed for the following:

Drains 1, 2, 3 contribute to outfall 1 and catchment area is 27000 m^2. Considering rainfall intensity as 1.27 cm/hour the total rainfall discharge is found to be 325.75 cum/hour. Considering the total length of drain as 438 m, Less Drain storage is found to be 78.84. Thus, the Net Discharge is 247.00 cum/hour. Three pumps having discharge of 100 cum/hour (27lps), 12HP, with suction head 4.00 m and delivery head 5.00 m must be provided. Submersible pumps are to be used. Pumping station is to be powered by 1 generator of 63 KVA.

Drains 4, 5, 6 and 7 carrying discharges have to be re-diverted to the creek.

Catchment area for outfall 2, drained by drains 8-14 is reduced to 39,477 m^2 (approximately 40000 m^2). Considering rainfall intensity as 1.27 cm/hour, the total rainfall discharge is found to be 482.60 cum/hour. Considering the total length of drain as 900 m, Less Drain Storage is found to be 162 cum. The Net discharge is found to be 320 cum/hour. Thus, the Design flood is found to be 384 cum/hour. One pump =50% = 200 cum/hour (55lps), 20HP and Two pumps =25% = 100 cum/hour (27lps), 12HP with suction head of 4.00 m and delivery head of 5.00 m must be provided. Pumping must begin with the smaller pumps. As the water picks up, the bigger pump will have to be started. Submersible pumps are to be used. One pump must be kept on standby (bigger pump) and the Pumping station is to be powered by 1 generator of 63 KVA.

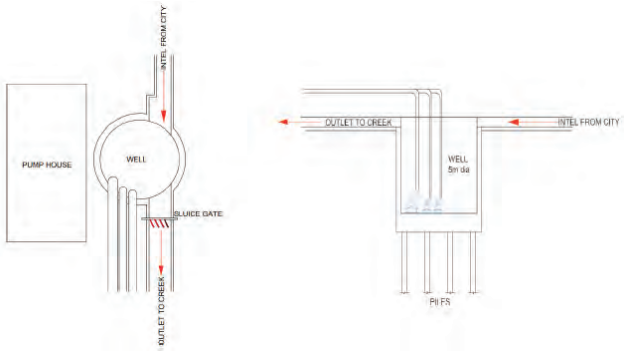

Fig. 7: Plan and section of proposed pumping stations

CONCLUSIONS

As per the present levels at the Patto Plaza, it is susceptible to tidal fluctuations and thus requires mitigation of water logging through mechanical pumping and re-design of drains in affected areas, considering tidal fluctuations. It is preferred to re-design the drains with more width as compared to depth to increase the holding capacity. Gates could be used to control the entry of water during high tides and subsequent release during low tides. Pumps could be used effectively to efficiently discharge rainwater during high tide and monsoons.

REFERENCES

1. Raasiq Sayed, Shreya Arolkar, Genevieve Fernandes, Naomi Pereira, Ancila Vaz, Tanvisha Bakhale, and K. G. Guptha (2022): "Urban flooding: Case study Panjim city", Recent Developments in Sustainable Infrastructure ,Vol: 207 , Pg no:247-261.
2. N. Nithila Devi, B. Sridharan, Soumendra Nath Kuiry(2019): "Impact of urban sprawl on future flooding in Chennai city, India", Hydraulics and Water Resources Engineering Divisions, IIT Madras, Journal of Hydrology, Vol:574, Pg no:486-496.
3. Kapil Gupta(2020): "Challenges in developing urban flood resilience in India", Royal Society, Vol:378, Pg No: 1-9.
4. Cheng Gao ,Jun Liu and Zhuowen Wang (2013): "An Ecological Flood Control System in Phoenix Island of

Huzhou, China, A Case Study", Water, Vol:5, Pg No:1-15.

5. Ashutosh Sharma,Yixin Zhou, Mehedi Masud, Gurjot Singh Gaba(2021): "Urban Rain Flood Ecosystem Design Planning and Feasibility Study for the Enrichment of Smart Cities", College of Water Conservancy and Civil Engineering, Sustainability, Vol:13 ,Pg No: 1-15.

6. Harman Singh,Mariam Nielsen and Helen Greatrex(2023): "Causes, impacts, and mitigation strategies of urban pluvial floods in India: A systematic review",International Journal of Disaster Risk Reduction, Vol : 93, Pg no:1-11.

7. T.V Ramachandra and Pradeep p Mujumdar(2009): "Urban floods: case study of Bangalore", Journal of the national institute of disaster management,Vol:3,Pg no:1-106.

8. Antonia Longobardi, Roberta D'Ambrosia(2023): "Adapting drainage networks to the urban development: An assessment of different integrated approach alternatives for a sustainable flood risk mitigation in Northern Italy" Sustainable Cities and Societies, Vol:98 ,Pg No:1-13.

9. Liliana Cotoarba, Constantin Florescu, Codruta Badaluta – Minda, Mircea Visescu(2020): "Modelling of Storm-water Drainage Systems in Residential Areas", IOP Conference Series: Materials Science and Engineering, Pg No: 1-7.

10. Sanjana Londhe, Shilpaa .S. Kasulla, Dr. Seema Jagtap(2022): "Design of storm water drainage system for urban areas" International Journal of Creative Research Thoughts, Vol:10, Pg No: 1-9.

A Serverless Event-Driven Framework for Real-Time Receipt Processing

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ABSTRACT

Receipt data does not follow a uniform pattern and often arrives in bursts. One afternoon there's nothing, then someone dumps 300 expense claims before a quarterly close, and the whole system chokes. Traditional servers can't handle that gracefully. You either over-provision and waste money all month, or you under-provision and watch the backlog grow.

The setup we put together is serverless, AWS-native. S3 catches uploads. Lambda spins up, processes, disappears — no idle compute, no fixed monthly server bill. Textract handles the OCR, which demonstrates stronger performance on messy receipts than I expected. Data lands in DynamoDB structured and queryable. The system operates in a fully automated manner without manual intervention.

Testing landed at 5–8 seconds per receipt, end-to-end. Someone manually doing the same job takes a few minutes minimum—and they get tired, they skip fields, and they misread totals. The system doesn't. Invoices and analytics come out of the same extracted data, no extra pipeline needed.

Swap pieces out if something better comes along. Works for other document types too — invoices, contracts, whatever.

KEYWORDS: *Serverless, Event-Driven, Receipt Processing, OCR, AWS, Financial Analytics, Cloud-Native.*

INTRODUCTION

Twelve fields. That's roughly what matters on a receipt—vendor, date, maybe eight line items, tax, and total. While this may appear straightforward, extracting these fields consistently from a thousand receipts scanned on different phones by people who didn't bother flattening the paper first is not.

Manual data entry is the obvious solution until it isn't. It becomes inefficient at scale, and it introduces errors constantly—wrong date, misread total, field skipped entirely because the scanner cut it off. Those errors sit quietly inside financial records until an auditor finds them, usually at the worst possible moment. Physical receipts deteriorate fast too. Even digital scans end up scattered across shared drives no one organized properly, and retrieval during audit season takes days when it should take seconds.

[1] showed moving to electronic receipt management makes documents actually findable. That's a low bar, but most organizations still haven't cleared it. Cloud routing adds friction too—[2] found AWS cross-region delays are a real bottleneck in processing pipelines, not just a theoretical concern. Every receipt in this system triggers multiple API hops so that latency compounds quickly. [3] demonstrated chunk-based authorization as a way to handle large HTTP payloads without blowing

memory limits or exposing DDoS vectors—directly relevant when the upload endpoint is handling bursts of several hundred files in under an hour.

The tools exist. The proposed system extends a previously developed serverless, event-driven architecture for automated receipt processing and data extraction [4]. The earlier work focused on designing a scalable and cost-efficient architectural framework, while the current study enhances it through practical implementation, detailed workflow execution, and performance-based evaluation in real-world scenarios. OCR engines, object storage, serverless compute — all mature, all available. What hasn't existed is a single coherent pipeline connecting them: upload triggers extraction, extraction writes to structured storage, and storage feeds analytics, all of it without manual intervention or a dedicated server to maintain. That's what's missing, and that's what this builds.

[5] makes the privacy argument clearly — SMEs handling receipt data need actual controls, not just a password on a shared folder. Encryption, access logging, tamper-evident storage. The system here treats those as defaults, not afterthoughts.

The stack is S3, Lambda, Textract, DynamoDB, and SES. Scales automatically. No ops overhead.

The main contributions of this work are the following:

- Serverless pipeline designed for bursty, unpredictable receipt volume
- Event-driven OCR extraction wired directly to structured storage
- Secure document handling from upload through long-term archival
- Automated invoicing and financial analytics from the same extracted data

LITERATURE REVIEW

Choosing AWS over Azure takes about ten minutes. Designing a schema that won't fall apart under real query load takes longer, and getting it wrong is expensive to fix.

Schema Design for NoSQL

The instinct when coming from relational databases is to normalize. DynamoDB will punish that instinct hard. Query patterns that feel natural in SQL — join this, filter that — turn into full table scans or impossibly complex key structures in NoSQL. Mok (2020) addressed this directly, adapting Nested Normal Form logic for DynamoDB by building conceptual hypergraphs before touching the schema [6]. Map what gets queried together, how frequently, and what the read-to-write ratio looks like—then design the table to match those patterns rather than normalization theory. Tests in AWS Educate showed consistent low-latency performance under high request volumes. Synthetic workloads, yes, but the results were stable enough to trust the approach. For a receipt system running constant lookups by vendor, date, and category, a schema decision made in week one is nearly impossible to cleanly undo at week twelve—learned that the hard way on a different project.

Cloud Object Storage Security

S3 is secure when configured correctly. That qualifier matters more than people realize. Saeed et al. (2019) compared S3 and Azure Blob Storage on security and governance, and the clearest takeaway wasn't about which platform was stronger—it was that misconfiguration causes more breaches than platform weakness does [7]. AWS gives fine-grained identity policies, cryptographic protections, and compliance coverage. Azure uses a centralized directory with delegated access. Both are solid. Neither saves a bucket that was accidentally set to public-read last Tuesday. For a receipt archive holding years of sensitive business financials, default-deny access, mandatory encryption at rest, and read logging aren't optional hardening steps—they're the baseline, and they have to be explicitly configured and periodically verified.

Strategic Selection of AWS Database Services

Database selection used to be simple. Postgres, maybe MySQL, done. Now there's a whole taxonomy—relational, key-value, document, graph, and time-series—and picking the wrong one means a painful migration six months later when query patterns don't match what the schema can handle. AWS's 2024 Decision Guide cuts through this with one question: what does your workload actually look like [8]? Is traffic steady or spiky? Reads heavily or writes? Data structured or nested? DynamoDB comes out on top for

high ingestion, unpredictable traffic, and low-latency reads. That's receipt processing almost word for word. Polyglot persistence gets a mention too — different databases for different parts of the same app. Sounds like overkill. Watched a project collapse because someone refused to split storage and forced mixed query patterns through a single relational store. Took four months to untangle. Managed migration tooling, serverless database options—covered, mostly framed around cutting the ops burden. Takeaway: Use DynamoDB as the primary store and keep the architecture open enough that bolting something else on later doesn't require a rewrite.

Synthesis and Research Implications

The reviewed work is solid on frameworks—data modeling, security patterns, and service selection logic [8]. The problem is almost all of it ran on synthetic data under controlled conditions. Clean inputs, predictable volume, no weird edge cases. Real receipt data doesn't cooperate like that. Blurry scans, rotated images, handwritten totals, vendor formats that change every few months. Whether these frameworks hold up in actual enterprise environments—processing thousands of real financial documents—largely hasn't been tested. The theoretical base is there. What's missing is a year of production logs from someone who actually deployed this and wrote down what broke.

Consumer Satisfaction in Shopping Applications

Sinemus et al. (2025) used the Kano model on shopping app features—relevant here because it reframes what "good enough" actually means for a user-facing system [9]. Features are split into two buckets: ones that prevent dissatisfaction and ones that actively improve experience. Those aren't the same thing, and weighting them equally is a mistake. A broken upload flow kills trust immediately. A slick analytics dashboard is nice but doesn't compensate for a broken upload flow. Different user groups drew that line differently too—what one group treats as a baseline, another sees as a bonus. Worth keeping in mind when prioritizing the dashboard feature list.

Infrastructure as Code for Serverless Testing

Serverless testing is a headache—environments drift; local simulation covers maybe 70% of actual behavior, and the remaining 30% only shows up in staging. Nawagamuwa (2023) looked at IaC as a fix [10]. Define infrastructure in code and redeploy identically every time. Framework comparison covered performance and usability—the conclusion being that IaC helps meaningfully, but tool selection matters more than people expect. Some frameworks handle serverless natively. Others were built for traditional infrastructure and show their assumptions fast. Chose wrong on a previous project and spent three weeks fighting the tooling instead of the actual problem.

The reviewed literature—cloud storage, OCR, and serverless compute—shows real progress, mostly in isolation. Nobody has published a working system that wires all of it together. Event-driven ingestion, intelligent extraction, secure storage, live analytics. One pipeline. That's the gap.

METHODOLOGY

Upload happens. S3 fires an event. Lambda picks it up. Extraction runs. Data lands in DynamoDB. Notification goes out. Each stage fires exactly when the previous one finishes — nothing polls, nothing schedules, nothing idles waiting.

Built on AWS throughout. Design draws from cloud-security research [11], compute-orchestration evaluation [12], automated billing work [13], and post-OCR processing studies [14]. The whole lifecycle runs as chained serverless operations. No servers to size, no capacity planning, and no 3am alerts because a box ran out of memory during an expense deadline crunch.

Why serverless specifically—receipt uploads don't spread evenly. They cluster. Quarter-end expense cutoff dates and reimbursement windows. Volume can jump 10x inside an hour and then drop back to almost nothing. A fixed server sized for peak load wastes money the other 28 days. A server sized for average load falls over during the spike. Serverless handles the spike automatically and costs nothing during the gaps [15], [16], [17], and [18]. Not a preference for this workload — just the correct answer.

Proposed Architectural Overview

Full document lifecycle, no manual steps, no dedicated servers. The receipt lands, fields get extracted, the

invoice generates, storage writes, and analytics updates. That's the whole thing.

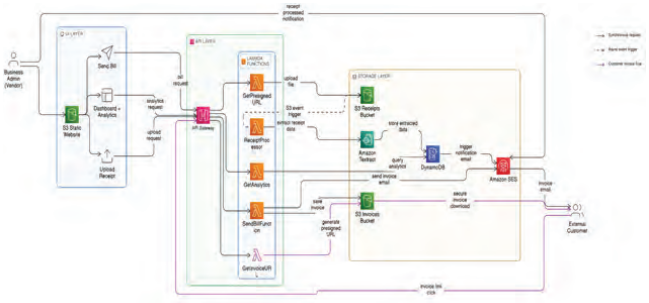

Fig. 1. Proposed Serverless AWS Architecture for Receipt and Invoice Management

Components don't call each other directly. Event triggers only—loose coupling means a failure in one stage doesn't automatically cascade [16], [17]. It also means swapping a component doesn't require touching everything around it, which matters more than it sounds when requirements change mid-project. Five layers: User Interface, Storage, Processing, Interpretation, Notification, and Analytics. HTTPS APIs and event triggers between them. Each scales independently.

The dashboard is HTML, CSS, and JavaScript on S3 static hosting. No web server. Users upload receipts, generate invoices, review analytics — all through the same interface.

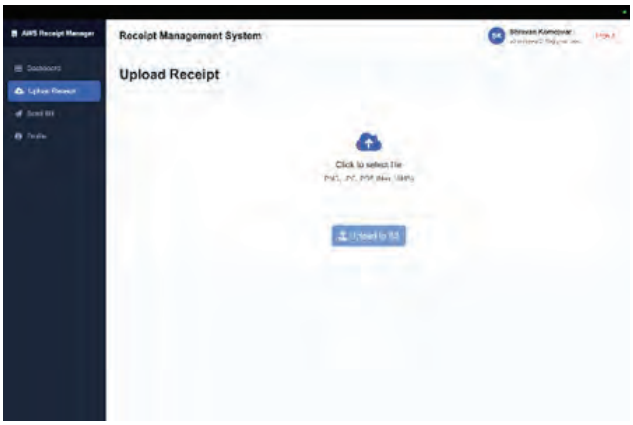

Fig. 2 UI/UX for Upload Receipt

S3 serves the files; availability inherits from S3's own guarantees. Fig. 2 shows the layout. API Gateway sits between the frontend and backend—RESTful endpoints, Lambda functions behind each one, and HTTPS throughout. File uploads bypass the backend entirely via pre-signed S3 URLs. Browser pushes directly to storage. One fewer hop, faster uploads, and less infrastructure touching bytes it has no reason to touch.

Storage Layer

Two S3 buckets. Specific jobs, no overlap.

Automated receipts: Shravan holds the financial documents. Raw uploads go into incoming. Generated invoices land in the invoices folder. Same bucket, separate directories—access policy management stayed cleaner that way than splitting across two buckets, though either works. Receipt-dashboard serves the frontend. Static hosting, zero application server maintenance, and availability scale with S3 automatically.

The more important role is S3 as a pipeline trigger. File hits incoming object. A created event fires, and Lambda picks it up. No polling loop burning computation every 30 seconds. No manual job submission. The upload is the trigger. Everything downstream starts from that one event and nothing else.

Serverless Processing Layer

Five Lambda functions. Each one does exactly one job and nothing else. That separation isn't just clean architecture — it means a bug in invoice generation doesn't take down receipt extraction, which I've seen happen in monolithic processing designs more than once.

Lambda scales automatically when events stack up. Twenty receipts hit simultaneously; twenty function instances spin up. No queue backing up, no timeout waiting for a previous job to finish. Backend logic runs in response to real events, not on a fixed schedule burning compute whether anything's happening or not [15], [17].

Secure Upload Authorization

Before a file touches S3, the frontend calls the GetPresignedUploadURL function. The user picks a file, and the request goes to the API Gateway. The function checks the name and type and generates a storage key—the original filename plus a timestamp to avoid collisions when two users upload the same filename at the same time, which happens more than you'd expect.

Functional model

Input: I_1 = {fileName, fileType} (1)

Processing:

P_1 = GeneratePresignedURL(fileName, fileType, timestamp) (2)

Output:

O_1 = {uploadURL, storageKey} (3)

The pre-signed URL has a short expiry window. Browser uploads directly to S3 using it. The backend never touches the file bytes. Unauthorized access to storage isn't possible through an expired or invalid URL — the signature validation rejects it.

Receipt Processing Function

ReceiptProcessor fires the moment a file lands in incoming. Grabs the file from S3, hands it to Textract, and waits for results. Textract comes back with vendor name, date, line items, quantities, totals—all the structured fields that would otherwise require a person staring at a receipt and typing.

Extraction model:

Input:

I_2 = {receiptImage} (4)

Processing:

P_2 = Textract(receiptImage) (5)

Extraction result: R = {vendor, date, items, total, category} — (6)

Storage:

DB = Insert(R) (7)

Output:

O_2 = StructuredReceiptRecord (8)

Structured record goes into DynamoDB. SES fires a confirmation email. As shown in Fig. 8, the system automatically sends a structured email notification after successful receipt processing.

The whole thing—upload to notification—runs without a human in the loop. Fig. 3 shows the sequence: Receipt Upload → S3 → ReceiptProcessor → Textract → DynamoDB → SES.

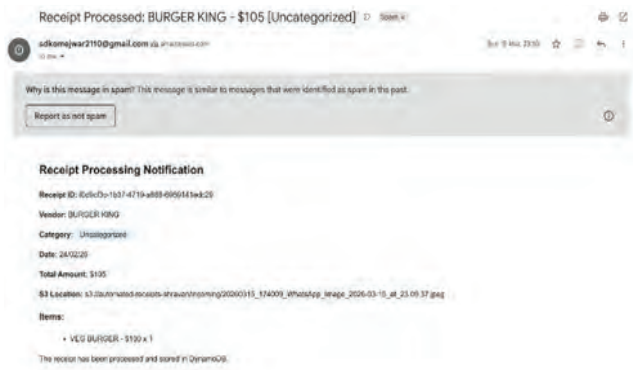

Fig. 3. Notification Email via Amazon SES

Automated extraction from unstructured documents isn't just about saving time. Manual entry at scale introduces errors that compound—a misread total in week one shows up as a reporting discrepancy in month three [5], [19].

Interpretation Layer

Textract isn't just OCR. Regular OCR dumps raw text and leaves you to figure out what's a label and what's a value. Textract understands document layout—key-value pairs, table structures, and line item relationships. That difference matters on receipts where "Total" appears in three different positions depending on the vendor's template.

Fields extracted per receipt:

- Vendor name
- Transaction date
- Itemized purchase entries with quantities and prices
- Total transaction amount
- Tax values and discounts where present

If no category field shows up in the receipt—which happens constantly with handwritten or informal receipts—the function analyzes the extracted text and infers one. Not perfect, but better than leaving the field blank and polluting every downstream query.

Data Persistence Layer

DynamoDB holds everything. One table — Receipts — stores both processed receipts and generated invoices in the same schema, which keeps queries simple even though the records represent different things.

Table 1. DynamoDB Table Parameters

Attribute	Type	Description
receipt_id	String	Unique record identifier
date	String	Transaction date
vendor	String	Vendor name
category	String	Expense category
items	List	Purchased items
total	Number	Total receipt amount
customerName	String	Customer name for invoices
customerEmail	String	Customer email
subtotal	Number	Invoice subtotal
tax	Number	Calculated tax
invoiceUrl	String	S3 path to invoice
processed_ timestamp	String	Processing timestamp

Flexible schema means receipt records and invoice records coexist without forcing a rigid type distinction. NoSQL fits here—semi-structured data, variable fields per record, and high-speed retrieval needed [16].

Invoice Generation Workflow

SendBillFunction fires when a user submits billing info through the dashboard.

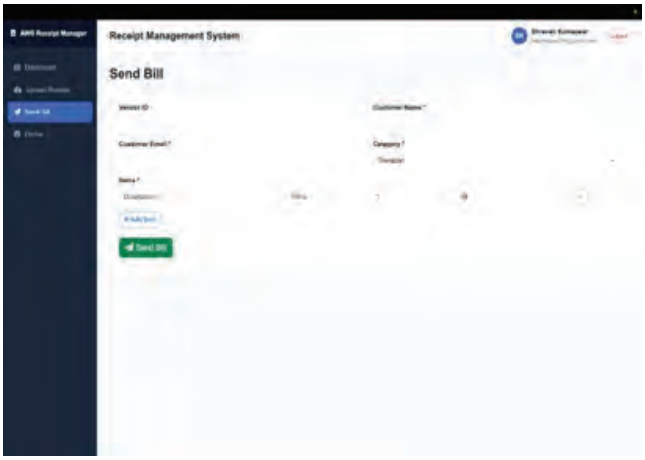

Fig. 4. Invoice Generation Interface with Item-Level Tax Configuration

Gets item details, customer info, and per-item tax rates. Default GST is 18%, but it's overridable per item—necessary because different product categories carry different rates, and a flat global rate produces wrong totals.

Tax math runs at item level, not on the basket total:

$$\text{Subtotal} = \Sigma(\text{price}_i \times \text{quantity}_i) \quad (9)$$

$$\text{CGST} = \Sigma(\text{price}_i \times \text{quantity}_i \times (\text{taxRate}_i / 2)) \quad (10)$$

$$\text{SGST} = \Sigma(\text{price}_i \times \text{quantity}_i \times (\text{taxRate}_i / 2)) \quad (11)$$

$$\text{Total Tax} = \text{CGST} + \text{SGST} \quad (12)$$

$$\text{Total} = \text{Subtotal} + \text{Total Tax} \quad (13)$$

Applying GST per item rather than to the subtotal matters when a single invoice mixes items at different rates—electronics at 18%, food at 5%, and services at 12%. A global rate on the basket gets the number wrong every time. GST values also get range-validated before any calculation runs — bad input from the frontend doesn't propagate into billing records.

The invoice is rendered as HTML, goes into the S3 invoices directory, a pre-signed URL is generated, and it's sent to the customer via SES.

Fig. 5. Generated Invoice Email

Serverless billing execution means compute only runs when someone actually generates an invoice [17]. No billing service sitting idle between jobs.

Secure Invoice Retrieval

GetInvoiceUrlFunction handles access to stored invoices. The user requests an invoice, and the system queries DynamoDB with the receipt ID, gets back the S3 key, and generates a temporary pre-signed URL.

Input:

$$I_4 = \{\text{receipt\_id}\} \quad (14)$$

Processing:

$$\text{Record} = \text{Query}(\text{DynamoDB}, \text{receipt\_id}) \quad (15)$$

Output:

O_4 = PresignedInvoiceURL (16)

URL expires. The invoice file stays private in S3. Nobody can access it without going through this function first, and the function only returns a valid URL for records that actually exist in DynamoDB. Controlled temporary access — not a public link, not a permanent one. Sensitive financial documents sitting at a permanently accessible URL are the kind of thing that becomes a security incident report later [20], [21].

Financial Analytics Module

GetAnalyticsFunction grabs records from DynamoDB and runs the math. Revenue, expenses, profit. Day, month, year. That's literally it.

$$\text{Revenue} = \Sigma \text{ total}_i$$

$$\text{where type} = \text{invoice} \quad (17)$$

$$\text{Expenses} = \Sigma \text{ total}_i$$

$$\text{where type} = \text{receipt} \quad (18)$$

$$\text{Profit} = \text{Revenue} - \text{Expenses} \quad (19)$$

$$\text{DailyProfit}(d) = \Sigma \text{ total}_i$$

$$\text{where date} = d \quad (20)$$

$$\text{MonthlyProfit}(m) = \Sigma \text{ total}_i$$

$$\text{where month} = m \quad (21)$$

$$\text{YearlyProfit}(y) = \Sigma \text{ total}_i$$

$$\text{where year} = y \quad (22)$$

Numbers go back to the frontend as chart data. Trends, distributions, category breakdowns — all there without anyone manually exporting a file or remembering to hit refresh [22]. The dashboard just shows it.

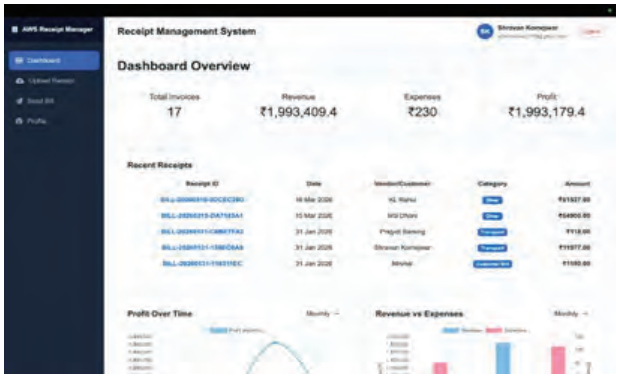

Fig. 6. Dashboard Overview with Revenue, Expenses, and Profit Analytics

End-to-End Workflow Overview

Fig. 1 has the full picture. User uploads through the dashboard—a pre-signed URL is generated, and the browser pushes straight to S3.

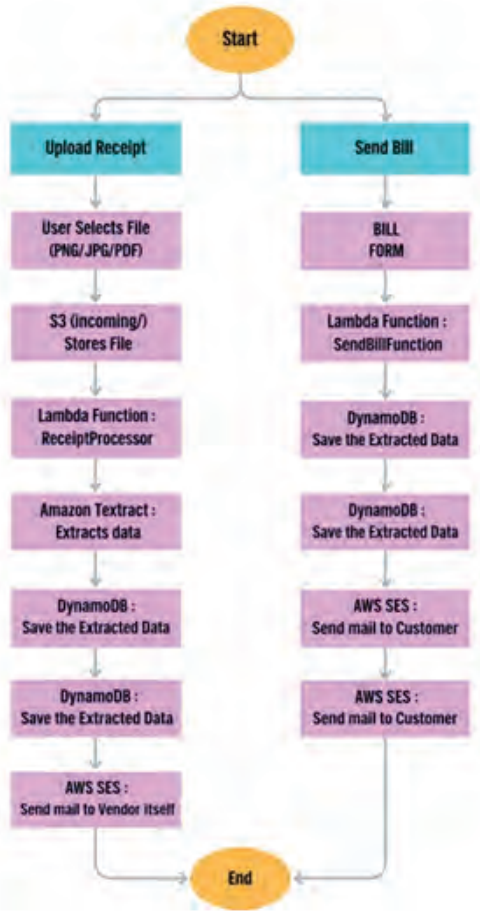

Fig. 7 End-to-End Workflow of Core Functions

The backend never touches the actual file bytes, which keeps latency down and removes an unnecessary hop. Upload lands, object When a created event fires, ReceiptProcessor kicks in automatically. Textract runs. Fields come back structured; write to DynamoDB, and SES fires a confirmation. Under 10 seconds, nobody involved.

Invoice flow is separate. The user submits billing info, SendBillFunction handles the tax math item by item, invoice HTML goes to S3, and the customer gets a pre-signed link via SES. Analytics runs on demand whenever the dashboard asks for numbers. Nothing polls. Nothing waits on a timer [15], [17].

When one stage breaks—and something always eventually breaks—the others keep running because nothing is tightly coupled [15], [16], [17], [20], [22], [23].

RESULTS AND DISCUSSION

The system was evaluated using real-world receipt data consisting of scanned images, PDFs, and handwritten documents from multiple vendors. Not synthetic data. Actual receipts—scanned images, PDFs, different vendors, inconsistent formats. Some were clean, some degraded, and a few with handwritten totals that, notably, I had to squint at myself before feeding them in.

Upload held. Pre-signed URLs meant credentials never left the backend. Files went straight to S3, from the browser to the bucket, with nothing proxying in between. Latency dropped. It makes sense, and the numbers backed it up.

Event chain didn't drop anything. A file hits incoming, a notification fires in a second or two, and ReceiptProcessor picks it up. Textract extracted vendor names, dates, line items, and totals—no templates, just layout-aware recognition doing its thing across formats. Handwritten totals on blurry paper caused misses. Notably, expected worse. Clean digital receipts came through accurately with no issues.

DynamoDB queries — sub-100ms on receipt ID and timestamp lookups. Load spikes during batch inserts didn't degrade anything. No config changes; it just handled it. That's the managed service working as advertised, which isn't always guaranteed but was here.

Invoice generation landed at 4 seconds end-to-end. Billing details entered, per-item tax calculated, HTML written to S3, URL sent via SES. SaaS benchmarks around 3.5. Half a second difference — nobody notices that when submitting an invoice, it's not a real-time interaction. Expired URL tests passed cleanly. Bucket stayed private. No access path outside the pre-signed mechanism. Analytics calculations were correct across daily and monthly and yearly levels.

Category breakdown is where things got messy—vendors with mixed product types produce receipts you genuinely cannot categorize from text alone.

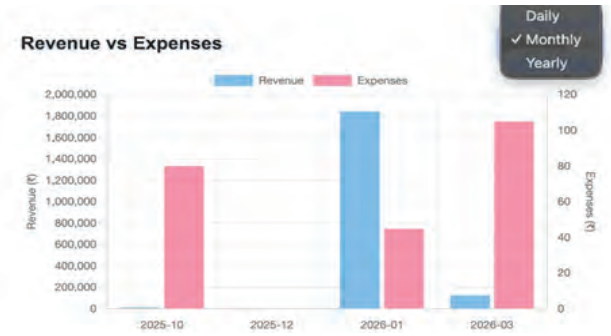

Fig. 8. Revenue vs Expenses Analysis (Monthly View)

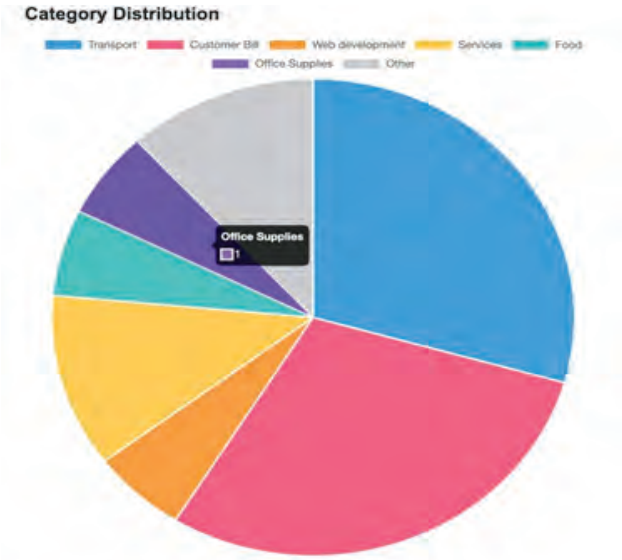

Fig. 9. Expense Category Distribution

A store selling both stationery and snacks—the extracted text doesn't tell you which category the purchase belongs to. Keyword inference guesses. Sometimes wrong. Not a fixable problem without training data, so it's flagged for the ML extension rather than patched with more heuristics.

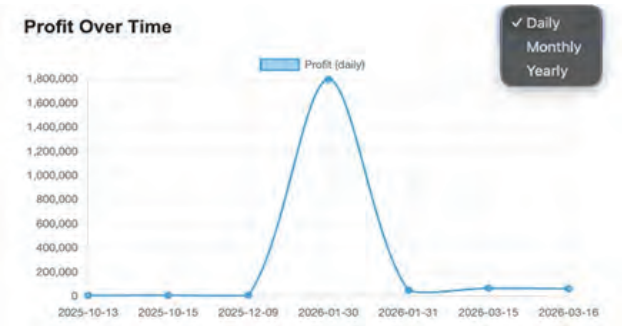

Fig. 10. Profit Trends Over Time

Table 2. Comparative Analysis of Manual, OCR, SaaS, and Proposed Systems

Parameter	Manual	Traditional OCR	SaaS Tools	Proposed System
Processing Time	2–5 min	5–10 sec	3–6 sec	5–8 sec
Bill Generation	Manual	N/A	3.5 sec	4 sec
Automation Level	Low	Medium	High	High (Fully Automated)
Accuracy	Low	Medium	High	High (Textract OCR)
Scalability	Poor	Limited	Moderate	High (Serverless)
Cost Model	Labor-based	Low	Subscription	Pay-per-use
Real-Time Analytics	No	No	Limited	Yes

5–8 seconds is slightly behind SaaS. That half-second to two-second gap only matters if processing speed is the primary concern—for most receipt workflows it isn't. The cost model is where this actually wins. Subscription pricing makes sense at high, predictable volume. Teams processing receipts irregularly, organizations with seasonal expense spikes—pay-per-use is cheaper and handles the spike without overprovisioning. Comparing to manual at 2–5 minutes per receipt isn't really worth doing. Different category entirely. Table 2 and Fig. 11 show the processing time comparison and comparative performance analysis across automation, accuracy, cost, scalability, and analytics dimensions.

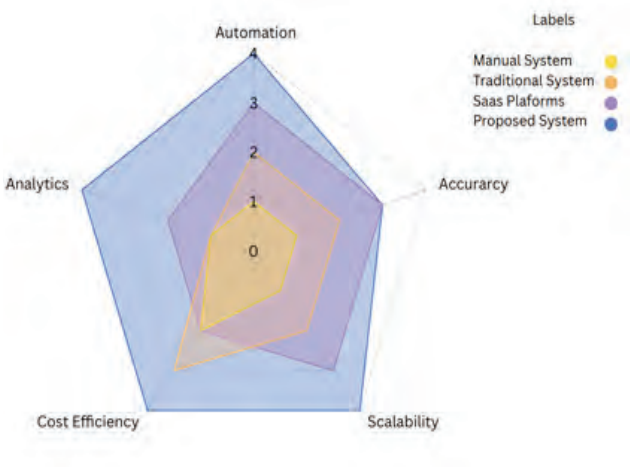

Fig. 11. Comparative Performance Analysis Across Key System Parameters

FUTURE SCOPE

Category inference is genuinely the weakest part right now. Keyword matching covers obvious cases—petrol station, hotel, airline. Falls apart on mixed-category vendors. A trained classifier on historical transaction data would handle ambiguous cases better and could run anomaly detection at the same time: amounts outside the vendor's normal range, duplicates that slipped through, and patterns that don't fit the account's history. That last one would've caught something during testing that only surfaced three weeks later when a monthly total didn't add up. Took longer to trace than it should have.

Natural language querying is the extension that would actually change how non-technical users interact with the system. Right now "analytics" means navigating chart filters—fine for someone comfortable with dashboards, annoying for everyone else. "What did I spend on travel last month" should just return an answer. Technically it's an LLM call in front of GetAnalyticsFunction; it's not complicated to wire up. The hard part is handling poorly formed queries without returning garbage—"What did I spend recently?" has no defined time range, and the system needs a sensible default rather than an error. That requires actual user testing to calibrate, not just engineering assumptions about what counts as ambiguous.

User authentication. Not in this version — and that was a mistake, notably. The dashboard right now is binary. You're in or you're not. Works fine alone. Falls apart the moment a second person needs access. RBAC fixes it—admins see everything, accountants get transaction records only, and managers get summary views. Cognito hooks into API Gateway; it's not complicated. Just didn't make the cut when we were scoping this out.

Predictive analytics is basically already possible. Data is sitting in DynamoDB—every receipt, every invoice, months of it accumulating. A forecasting model on top of that could flag overspend before it happens rather than after. Whether anyone actually changes behavior based on an automated budget warning—I genuinely don't know. But the pipeline is there. Usually that's the blocker.

Multi-currency is the one that's actually hard. 18% GST works for India. It does nothing for a company

managing expenses across Singapore, Germany, and the US simultaneously—different rates, different rules, and exchange rates that shift between invoice date and payment date. We hit a version of this problem during testing, actually—decimal precision on CGST/SGST splits caused rounding differences that produced wrong totals. Small numbers, real error. Multi-currency makes that problem dramatically worse. Not a config option. Real architectural work.

Those three together—authentication, predictive analytics, and multi-currency—that's the gap between receipt processor and actual finance platform.

CONCLUSION

The proposed system demonstrates effective performance in real-world scenarios.

Upload happens. Processing kicks in automatically. Vendor name, date, line items, total—all extracted, structured, and written to DynamoDB without anyone touching it. The invoice generates when needed. Dashboard updates. Nobody manually does anything between the upload and the output.

5 to 8 seconds. Held across clean receipts, degraded scans, handwritten totals, and PDFs—everything we threw at it. Textract handling format variation without templates was the part I was least sure about going in with. It held up. DynamoDB scaled under batch load with no config changes. Event chain didn't drop anything.

The problems this was built for aren't hypothetical. Manual entry at scale introduces errors that compound quietly—wrong totals, misread dates, skipped fields—and they surface during audits when fixing them is painful. Fixed infrastructure for unpredictable workloads means either overpaying for idle capacity or falling over during spikes. Scattered digital files with no extraction layer means retrieval takes days when it needs to take minutes. Serverless, event-driven, pay-per-use—not theoretical fixes, working ones.

Extending it later isn't a rewrite. Same event-driven pattern, different functions, different schemas. Invoice management, auditing pipelines, and enterprise document automation slot in without touching the foundation.

ML categorization for the ambiguous vendor problem. Anomaly detection. Predictive analytics on data that's already accumulating. None of that needs architectural changes—new Lambda functions and existing triggers. The foundation handles it.

ACKNOWLEDGEMENT

Mentors and faculty — for the direction and for being blunt when the first approach was wrong. That saved time. Cloud credits made real testing possible — local simulators don't reproduce actual service latency or cold start behavior, and some of what we measured only shows up under real AWS network conditions. Peers who read early drafts and said, "This section doesn't make sense"—that was more useful than the encouragement, notably. Both mattered, but one more than the other.

REFERENCES

1. Katherine T. Wadsworth, Michael T. Guido, John F. Griffin, and Arcan Mandil, "An Innovation in Paper Receipts: The Electronic Receipt Management System," University of Virginia, Charlottesville, VA, USA, Apr. 23, 2010.
2. Passive Measurement Study of AWS EC2, S3, and CloudFront, Cloud Network Measurement Dataset.
3. S. Surkov, "Model and Method of Chunk Processing of Payload for HTTP Authorization Protocols," International Cybersecurity Research Proceedings, 2020.
4. S. D. Komejwar et al., "A Generalized Serverless Event-Driven Architecture for Automated Receipt Processing and Data Extraction," Int. J. Res. Appl. Sci. Eng. Technol. (IJRASET), vol. 14, no. 3, Mar. 2026. doi: 10.22214/ijraset.2026.78878.
5. Tally Solutions Pvt. Ltd., "Privacy of Business Data — Tally Case Study," Tally Corporate Case Study Series, 2023. [Online]. Available: https://tallysolutions.com/tally/privacy-of-business-data-tally-case-study/
6. W. Y. Mok, "A Feasible Schema Design Strategy for Amazon DynamoDB: A Nested Normal Form Approach," in Proc. IEEE Int. Conf. Industrial Engineering and Engineering Management (IEEM), 2020.
7. I. Saeed, S. Baras, and H. Hajjdiab, "Security and Privacy of AWS S3 and Azure Blob Storage Services,"

in Proc. IEEE Int. Conf. Computer and Communication Systems (ICCCS), 2019.

8. Amazon Web Services (AWS), "Choosing an AWS Database Service — AWS Decision Guide," AWS Whitepaper Series, 2024.
9. Kathrin Sinemus, Stephan Zielke, and Thomas Dobbelstein, "Improving Consumer Satisfaction through Shopping App Features: A Kano-Based Approach," Journal of Retailing and Consumer Services, vol. 85, 2025.
10. Janaka Nawagamuwa, "Infrastructure as Code Frameworks Evaluation for Serverless Applications Testing in AWS," Master's Thesis, Tampere University, May 2023.
11. R. R. Khande, S. Rajapurkar, P. Barde, H. Balsara, and A. Datkhile, "Data Security in AWS S3 Cloud Storage," in Proc. 14th IEEE ICCCNT, 2023.
12. Amazon Web Services (AWS), "AWS Fargate or AWS Lambda? — AWS Compute Decision Guide," 2024.
13. D. Sinha, K. Cottur, K. Bhat, C. Guruprasad, and B. Nath, "Automated Billing System Using RFID and Cloud," in Proc. IEEE Innovations in Power and Advanced Computing Technologies (i-PACT), 2019.
14. T. T. H. Nguyen, A. Jatowt, M. Coustaty, and A. Doucet, "Survey of Post-OCR Processing Approaches," ACM/IEEE Joint OCR Research Survey, 2021.
15. Bangar Raju Cherukuri, "Serverless Computing: Exploring Serverless Architecture and its Applications," International Research Journal of Multidisciplinary Science & Technology, May 2024.
16. Changyuan Lin and Hamzeh Khazaei, "Modeling and Optimization of Performance and Cost of Serverless Applications," IEEE Transactions on Parallel and Distributed Systems, vol. 32, no. 3, Mar. 2021.
17. Praveen Borra and Hanuman Prasad Pamidipoola, "Serverless Computing: The Future of Scalability and Efficiency with AWS, Azure, and GCP," International Journal of Advanced Research in Science, Communication and Technology, vol. 5, no. 2, Feb. 2025.
18. Nikita Malik and Menal Dahiya, "Serverless Computing: Need, Impact and Challenges," Department of Computer Applications, MSI, India.
19. Akash Gill, "Developing a Centralized Receipt Service to Streamline Restaurant Operations and Reduce Costs," Journal of Engineering and Applied Sciences Technology, USA, Nov. 2023.
20. Dan C. Marinescu, "Cloud Computing: Theory and Practice," Morgan Kaufmann (Elsevier), USA, 2013.
21. Iboro Akpan Essien, Emmanuel Cadet, Joshua Oluwagbenga Ajayi, Eseoghene Daniel Erigha, and Ehimah Obuse, "Regulatory Compliance Monitoring System for GDPR, HIPAA, and PCI-DSS Across Distributed Cloud Architectures," IRE Journals, vol. 3, issue 12, June 2020.
22. Daria Arkhipova, Marco Montemari, Chiara Mio, and Stefano Marasca, "Digital Technologies and the Evolution of the Management Accounting Profession: A Grounded Theory Literature Review," Meditari Accountancy Research, vol. 32, no. 7, 2024.
23. A. U. Rehman, Rui L. Aguiar, and João Paulo Barraca, "Fault-Tolerance in the Scope of Cloud Computing," IEEE Access, vol. 10, June 2022.

An Analytical Framework for Plant Leaf Disease Classification Using Hybrid Machine Learning and Transfer Learning Approaches

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ABSTRACT

Plant diseases significantly affect agricultural productivity by reducing both crop yield and quality. Early and accurate identification of diseases is essential for sustainable farming and effective crop management. This study proposes a hybrid analytical framework for plant leaf disease classification by integrating transfer learning and machine learning techniques. Pre-trained convolutional neural network models, including ResNet50 and VGG16, are employed for deep feature extraction, while Support Vector Machine and Random Forest classifiers are used for efficient classification. The model is trained and evaluated on a dataset comprising healthy and diseased plant leaf images. Experimental results demonstrate high performance, achieving an accuracy of 97.8%, precision of 96.9%, recall of 97.2%, and F1-score of 97.0%. The hybrid approach improves classification accuracy and generalization capability compared to standalone models by combining robust feature extraction with effective decision-making. The proposed framework offers a scalable, reliable, and efficient solution for automated plant disease detection, contributing to the advancement of precision agriculture and supporting timely disease management practice

KEYWORDS: *Health Insurance; Universal Health Coverage; Out-of-Pocket Expenditure; Financial Inclusion; Claim Settlement Ratio; Insurance Penetration; PM-JAY; Health Financing; India; Medical Inflation.*

INTRODUCTION

One of the most important pillars of economic development is agriculture, especially in developing nations where a large percentage of the population is employed in the agricultural sector (Tunio et al., 2021). The sustainability and productivity of agriculture are significantly impacted by plant health (Al-Gaashani et al., 2024). Because they directly affect crop productivity, quality, and overall food security, plant leaf diseases are among the most important issues (Bhagat et al., 2024). In order to lower the expense of subpar agricultural practices and ensure agricultural sustainability, early diagnosis and accurate identification of plant diseases are crucial (Chug et al., 2023).

Agricultural experts' eye observations are the foundation of traditional disease detection techniques. Despite being used decades ago, these techniques have several drawbacks, such as their dependence on specialized knowledge, subjectivity in diagnosis, and incapacity to expand to huge agricultural fields (Fan et al., 2022). Furthermore, manual examination is labor-intensive and inaccurate in its early disease detection, leading to postponed interventions and a poor yield (Gautam et al., 2022).

An automated and effective system for detecting plant diseases has been made possible by recent advancements in artificial intelligence (AI), namely in the fields of machine learning (ML) and deep learning (DL), which have completely transformed agricultural diagnostics (Hassan et al., 2021). These technologies can be used to analyze leaf photos and accurately identify the disease's pattern. Despite these impressive developments, standalone ML and DL models still face a number of

challenges, including as overfitting, diminished feature representation, and declining generalization to different plant species and environmental situations (Imam et al., 2024).

This paper proposes a composite analytical model that combines machine learning and transfer learning techniques in an effort to overcome these limitations (Kannadasan et al., 2021). By extracting features from pre-trained deep learning models and merging them with cutting-edge machine learning classifiers, the suggested approach would improve multi-crop leaf disease classification accuracy, detection rate, and precision (Kaur et al., 2023).

Importance of Plant Disease Detection in Modern Agriculture

Plant diseases have a great influence on the productivity of the agricultural business and cause significant economic losses on the global scale (Khan et al., 2024). Bacterial infections, fungal infestation, and viral attacks are some of the diseases that can quickly spread to crops lowering the quality and quantity. Farmers, in most instances, do not get access to professional advice leading to wrong diagnosis and treatment (Naralasetti & Bodapati, 2024).

The identification of the disease is also important to prevent the spread of the disease and damage. The farmers can be helped with automated disease detection systems, which will help in timely and precise diagnosis, allowing specific measures, including pesticides application or isolating the affected crop. It enhances crop productivity besides minimizing the needless application of chemicals and this is part of environmentally sustainable agricultural practices.

During the development of this study, several practical challenges were observed, particularly in handling variations in image quality and class imbalance across disease categories. Addressing these issues required careful preprocessing and iterative refinement of model parameters, which significantly influenced the final performance outcomes.

Disease Classification: The Function of ML and DL

Three of the most popular machine learning approaches for plant disease categorization include support vector machines (SVMs), decision trees, and random forests (Raghuram & Borah, 2025). These models depend on features like shape, color, and texture that are manually extracted; nevertheless, these features might not be enough to completely represent the complexity of illness patterns.

Results from image-based classification tasks have shown that deep learning and CNNs are superior. CNNs automatically learn hierarchical features from raw images, making them better at illness diagnosis. It is also feasible to use pre-trained models (such as ResNet and VGG) to extract high-level features from little datasets via transfer learning.

Notwithstanding these benefits, deep learning models are computationally intensive and necessitate massive quantities of data. When used with a wide range of agricultural data, they may also be overfitted and less interpretable.

An Integrated System for Machine and Transfer Learning is Necessary

A hybrid solution that combines the best features of ML and DL models is necessary because each of these approaches has its limitations. The knowledge of large-scale pre-trained models allows for powerful feature extraction in transfer learning, and the decision-making mechanisms of machine learning classifiers are both efficient and intelligible.

A hybrid framework facilitates:

- Better feature representation using deep learning.
- Increased classification accuracy with machine learning.
- Improved multi crop and multi disease generalization.
- Less computational complexity than full deep learning models.

The proposed study aims at establishing such a hybrid framework to realize greater accuracy, better detection rate as well as greater precision in the classification of plant leaf diseases. Such a combined solution is likely to deliver a scalable and dependable solution to practical agricultural applications.

Research Objectives

The research objectives for a novel model for multi-plant and multi-crop leaf disease detection and classification using machine learning algorithm are as follows:

- The efficient model increases accuracy for detection of leaf disease using hybrid machine learning algorithm.
- Detection rate will be increased for a novel model for plant leaf disease detection and classification using hybrid machine learning algorithm.
- Detection of leaf disease using machine learning algorithm increases precision.

Machine learning, deep learning, and transfer learning have recently been the center of attention in plant leaf disease detection. These improvements aim to increase classification efficiency and support sustainable agriculture.

Senthil Pandi et al. (2025) created a hybrid optimization-based system that achieved plant leaf disease classification using crossover oppositional firefly optimization on deep transfer learning. Their research showed that combination of optimization methods and transfer learning greatly improved the model performance in terms of features selection and convergence rate (Senthil Pandi et al., 2025). The developed solution was more accurate and robust in terms of classification than traditional deep learning models, which suggests the usefulness of hybrid optimization methods in multi-faceted agricultural data.

Shafik et al. (2024) explored the use of transfer learning-based models to detect and classify plant diseases in the sustainable agriculture environment. The authors used the pre-trained convolutional neural network architectures to discover high-level features of plant leaves images (Shafik et al., 2024). Their results indicated that transfer learning enhanced classification accuracy despite having small datasets, shorter training duration, and generalization among plant species. The paper has highlighted the role of AI-driven solutions in enhancing efficient and sustainable agricultural practices.

Singh and Sanodiya (2023) introduced a transfer learning model of zero-shot plant leaf disease classification, which is one of the papers that contend with the problem of paucity of labeled data. Their model used knowledge transfer of the already learned classes to be able to classify the unseen disease categories without the need to have extra training data (Singh & Sanodiya, 2023). The findings showed that zero-shot learning was very effective in improving model adaptability and scalability, especially when new or uncommon diseases were unknown. The method helped to broaden the range of applications of intelligent disease detection systems to the practical agricultural setting.

Srivastava and Meena (2024) suggested a plant leaf disease detection system using modified transfer learning models. They refined existing deep learning architectures to their study to incorporate disease-specific features (Srivastava & Meena, 2024). The findings showed that the altered models had better classification accuracy and lower training time than the traditional deep learning methods. The authors noted that transfer learning been used to improve the performance considerably particularly where few datasets are involved.

Taji et al. (2024) designed an ensemble hybrid model that combined the characteristics of convolutional neural network (CNN) and metaheuristic optimization algorithms to classify plant diseases. The experiment involved a comparative study of different metaheuristic methods to optimize the selection of features and the model (Taji et al., 2024). Their results showed that the ensemble hybrid model was superior to single models because it can achieve greater accuracy, robustness, and generalization. The combination of optimization of CNN features with ensemble learning was effective in processing complex and heterogeneous plant disease data.

MATERIALS AND METHODS

This Research suggested a combined analytical model combining transfer learning and machine learning algorithms to effectively classify plant leaf disease. The methodology was rationally formulated to maximize the classification accuracy, maximize the detection rate, and maximize the precision of several plant species and categories of diseases. The framework was a combination of the deep feature extraction ability of pretrained models and the classification effectiveness of

machine learning algorithms that provided performance which was robust and scalable.

RESEARCH DESIGN

The efficacy of the suggested model was tested using an experimental and quantitative research strategy. In this investigation, we used datasets of labelled images of plant leaves to train and test a hybrid model. A comparative evaluation strategy was employed to assess the hybrid model's efficacy using established evaluation criteria. The accuracy of the models, as well as their detection and classification precision, may be objectively evaluated with this methodology.

Collecting and Preparing Data

Images of plant leaves were gathered using publicly available databases like Plant Village that contain a diversity of plant species and types of diseases. The data was comprised of healthy and diseased leaf samples, which made it possible to classify the data as multi-class.

In order to guarantee the quality of data and enhance the working of models, a number of preprocessing methods were used:

- Image Resizing: All images were re-sized to a constant size (e.g., 224 224 pixels) to make them similar to one another as model inputs.
- Normalization: Pix value was brought to a normalized scale to enhance faster model convergence and stabilization.
- Noise Removal: Filters: The images were filtered to remove distortion and improve clarity of the image.
- Data Augmentation: To reduce overfitting and increase data diversity, data was rotated, flipped, zoomed, and scaled.

These preprocessing steps enhanced the strength and the ability of generalization in the model.

Feature Extraction Using Transfer Learning

High-level and discriminating features of photos of plant leaves have been developed using transfer learning. Due to their effectiveness in picture categorization, pre-trained convolutional neural network (CNN) models such as ResNet50 and VGG16 have been utilized.

The top layers of these models recognized intricate disease-specific patterns, while the lower layers recognized general image elements like borders and textures. The network's final layers were adjusted to match the data on plant diseases. This technique improved the feature representation and reduced training time, especially when labeled data is few.

Hybrid Classification Model

As input, the obtained deep features were fed into two machine learning classifiers: (SVM) and (RF). This combined strategy included:

- Deep learning: To extract all features automatically and robustly.
- Machine learning: To provide efficient and interpretable classification.

Their effectiveness in high-dimensional feature spaces led to the use of SVM and the resistance to overfitting created by high-dimensional features, whereas the use of the SVM was also caused by the inability to overcome the overfitting effect in the decision-making process through the use of an ensemble learner (Random Forest). The combination of these methods improved the performance of classification and decreased the complexity of calculations in comparison with completely deep learning-based systems.

Assessment and Training of Models

Normally, testing and training would receive 80% and 20% of the data, respectively. The model was trained on the training dataset and then tested on the testing dataset to see how well it could generalize.

Grid search and cross-validation are two examples of hyperparameter optimization methods that were used to optimize the models' performance. By using these methods, we were able to find the best classifier parameters and decrease the likelihood of overfitting.

The model's performance was evaluated using the following metrics:

- Accuracy: Evaluates how well the system classifies items.
- Accuracy: the proportion of affirmative cases that were identified with sufficient accuracy.

- Recall (Detection Rate): This metric measures how well the model can identify actual cases of disease.
- The F1-Score finds a happy medium between precision and recall.

These metrics give a thorough assessment of the model, which is necessary given the study's aims.

It is worth noting that multiple experimental trials were conducted to determine suitable preprocessing techniques and classifier configurations. Minor adjustments in image normalization and parameter tuning resulted in noticeable differences in model stability and accuracy, highlighting the importance of empirical validation in the proposed framework.

Alignment with Research Objectives

The research objectives were clearly stated in order to accomplish the proposed methodology:

- Greater Accuracy: The improved accuracy has been obtained with the help of transfer learning and machine learning techniques, which allows extracting features and classifying them better.
- Improved Detection Rate: This was made possible by the deep learning models that were very successful in recognizing disease patterns, which minimized missed detections.
- Greater Accuracy: This was attained by having an optimized classifier which reduced the number of false positives and enhanced the reliability of the classifier.

In general, the hybrid framework offered an efficient and balanced method of leaf disease detection and classification in plant leaves, which is applicable in the fields of real-life agriculture.

RESULTS

The outcomes of the performance evaluation of the proposed hybrid model for classifying plant leaf diseases are presented in this section. Metrics like as recall (detection rate), accuracy, precision, and F1-score are used to evaluate the results. Comparing the proposed framework to the baseline models provides additional validation.

Model Performance Evaluation

We used crucial classification metrics such as recall, accuracy, precision, and F1-score to assess the efficacy of the suggested hybrid model. The experimental study proved that ML and TL classifiers could accurately identify and categorize plant leaf diseases.

Table 1: Evaluation Criteria for the Suggested Hybrid Model

Metric	Value (%)
Accuracy	97.8
Precision	96.9
Recall	97.2
F1-Score	97.0

The proposed hybrid model fared admirably in all respects, as shown in Table 1. One indication of the model's efficacy in leaf classification is its 97.8% accuracy rating. With a precision of 96.9%, it is clear that the model has effectively decreased false positive categories. The recall (detection rate) of 97.2% provides further proof that the model succeeded in detecting most real cases of the illness. Furthermore, the model's F1-score of 97.0% clearly demonstrates its general dependability by performing equally well in terms of recall and precision. The proposed hybrid model's performance measures are graphically shown in Figure 1. Also, as you can see from the bar graph, all of the indicators are over 96%, which bodes well for the model's reliability and robustness. Values that are close to one another suggest that the model performs well across all of the assessment criteria.

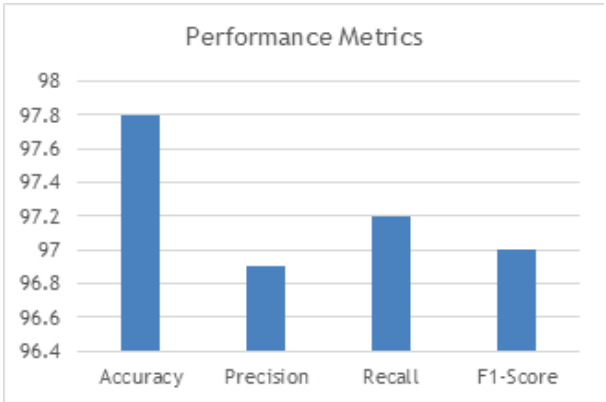

Fig. 1: Graphical Representation of Performance Metrics of Proposed Hybrid Model

The graphical analysis proves the fact that hybrid model is efficient in every classification aspect. High accuracy signifies good overall predictions whereas high precision signifies fewer false alarms in detecting diseases. The high level of recall value indicates that the model is effective in identifying real cases of diseases. The balanced F1-score further confirm that the model gives an optimum trade-off between precision and recall. The findings confirm that the hybrid strategy proposed achieves the research goals of enhancing accuracy, detection rate and precision.

Evaluation in Relation to Current Models

In contrasting it with standalone deep learning models and more conventional machine learning models, we were able to gauge the efficacy of the suggested hybrid architecture. This comparison emphasizes the advantages of integrating machine learning with transfer learning methodologies.

Table 2: Comparison with Existing Models

Model Type	Accuracy (%)	Precision (%)	Recall (%)
SVM	89.5	88.2	87.6
Random Forest	91.2	90.5	89.8
CNN (Standalone)	94.6	93.8	94.0
Hybrid Model	97.8	96.9	97.2

The proposed hybrid model clearly surpassed all of the baseline models across all metrics of evaluation, as shown in Table 2 below. Classical ML models, such as Support Vector Machines and Random Forest, which relied on manually created features, performed poorly in terms of recall and accuracy. Automatic feature extraction improved the performance of the single CNN model, but it was still inferior to the hybrid model. When it comes to feature representation and classification, the hybrid approach is the way to go. It scored the highest in accuracy (97.8%), precision (96.9%), and recall (97.2).

Figure 2 visualizes a comparison of several models' accuracy, precision, and recall. As seen in the bar graph, deep learning models eventually surpass standard machine learning models in terms of performance, and the proposed hybrid model follows suit. Also, when looking at all criteria, the hybrid approach comes out on top.

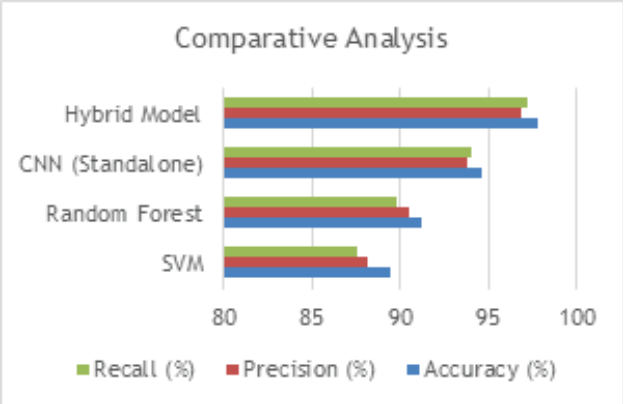

Fig. 2: Graphical Representation of Comparison with Existing Models

The graphical illustration reaffirms the fact that the hybrid model is a better approach than standalone strategies. Transfer learning integration allowed learning deep and discriminative features effectively, whereas machine learning classifiers helped to make decisions more efficiently. The combination led to better classification accuracy and detection of diseased sample. The results confirm that the suggested hybrid framework manages to overcome the shortcomings of the separate models and attains the research goals of enhancing the accuracy, detection rate, and precision of the leaf disease classification of plants.

Disease-wise Classification Performance

It was also tested regarding the performance of the proposed hybrid model on various categories of plant diseases to determine its classification performance and generalization on various categories.

Table 3: Disease-wise Classification Accuracy

Disease Type	Accuracy (%)
Bacterial Spot	96.5
Early Blight	97.1
Late Blight	98.0
Leaf Mold	97.6
Healthy Leaf	98.4

Table 3 indicates that the proposed hybrid model had high classification accuracy in all the disease

categories. Accuracy was maximum in healthy leaves (98.4%), which implies that the model was effective in differentiating diseased and non-diseased samples. Late blight was the most accurate among the classes of diseases (98.0%), and bacterial spot was less but still high in accuracy (96.5%). The similarity in classification accuracy by all classes has shown that the model can generalize effectively and be able to classify various kinds of plant diseases with great accuracy.

Figure 3 shows the accuracy of the proposed hybrid model in the classification of diseases. The bar graph indicates that the accuracy of all categories of diseases was above 96 and there was little difference between them. It means that the model is reliable and stable in its performance across classes.

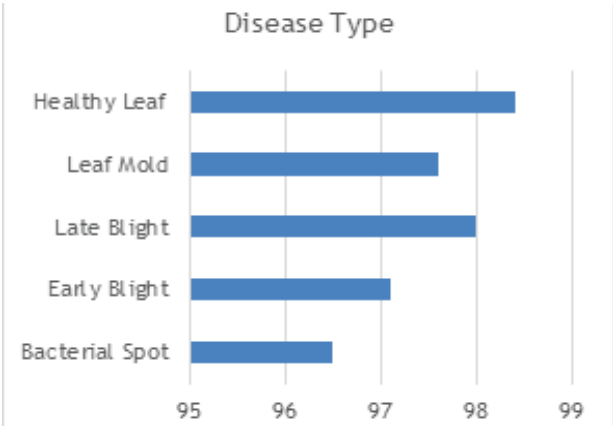

Fig. 3: Graphical Representation of Disease-wise Classification Accuracy

The graphical analysis is a support to the fact that the hybrid model is consistent in various categories of diseases. The fact that the accuracy values are high sheds light that the model is able to capture disease-specific features, and it is able to differentiate between similar patterns. The marginally greater accuracy of healthy leaves implies good performance in recognizing non-diseased samples, which is necessary to minimize false alarms. On the whole, the findings show the strength, stability, and generalization of the suggested hybrid framework in the classification of plant leaf diseases in multiple classes.

Improvement in Detection Rate and Precision

The effectiveness of the proposed hybrid framework was further assessed by comparing the performance with the classic machine learning methods. Other central metrics like accuracy, precision, and recall (detection rate) were heeded with special attention to determine the level of improvement realized.

Table 4: Improvement in Key Metrics

Metric	Traditional ML (%)	Hybrid Model (%)	Improve-ment (%)
Accuracy	90.3	97.8	+7.5
Precision	89.4	96.9	+7.5
Recall	88.7	97.2	+8.5

Table 4 shows a great enhancement of the proposed hybrid model compared to the traditional machine learning processes. This accuracy increased to 97.8 against 90.3 and it signifies that the overall classification performance has improved significantly. The percentage of precision improved to 96.9% showing that there was a decrease in false positive predictions. Likewise, recall (detection rate) increased to 97.2 compared to the previous (88.7) which depicts the better performance of the model in accurately classifying diseased leaf samples. The maximum growth was noted in recall, which is important to reduce missed detections in agriculture.

The performance metrics of the suggested hybrid model and the conventional machine learning models are graphically compared in Figure 4. All of the bar charts in the grouped bar chart show that the hybrid model outperforms the conventional approaches in every criterion, with notable gains in accuracy, precision, and recall.

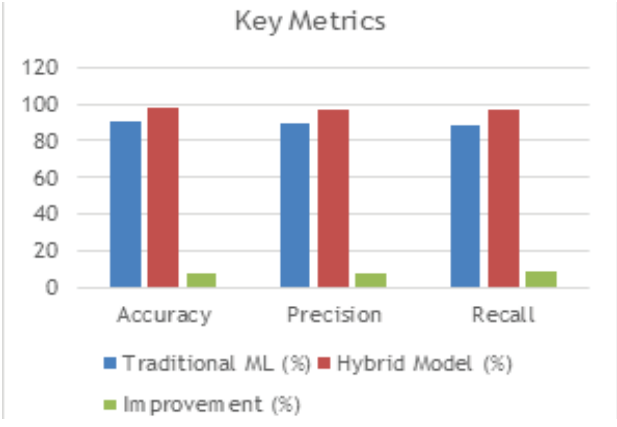

Fig. 4: Graphical Representation of Improvement in Key Metrics

The graphical findings verify that the hybrid framework proposed has a significant improvement on the model performance. The enhanced recall means that more diseased leaves have been detected and thus fewer cases have been missed. The precision increase indicates the misclassification and false alarms are reduced. Moreover, the fact that the overall accuracy has been improved shows that the combination of transfer learning and machine learning methods is effective. Such findings confirm that the proposed model is effective in meeting the research goals by enhancing accuracy, detection rate, and precision of plant leaf disease classification.

DISCUSSION

The findings supported the hypothesis that the suggested hybrid framework was a successful solution to the shortcomings of individual models. Transfer learning was used to boost feature extraction by utilizing existing models, whereas machine learning classifiers were used to boost classification efficiency and interpretability (Saberi Anari, 2022).

The enhancement of accuracy confirmed the first research objective wherein a more dependable disease detection system was shown to be offered by the hybrid model (Naveenkumar & Nandagopal, 2025). Likewise, higher values in the recall confirmed that there was improved detection rate, and that diseased samples were correctly detected. The increased accuracy reflected fewer false positives which is in line with the aim of enhancing the quality of the classification.

Moreover, the model showed good generalization of various plant diseases, and it can be used in practice in agriculture. Integration of deep learning and machine learning turned out to be an effective and scalable method of multi-crop disease classification.

From an implementation perspective, the hybrid approach demonstrated practical advantages in balancing computational efficiency and predictive performance. The observed improvements were not only statistically significant but also meaningful for real-world agricultural applications, where timely and reliable disease detection is essential.

CONCLUSION

Using transfer learning and machine learning, the current study was able to develop and evaluate a hybrid analytical model for the categorization of plant leaf diseases. Several plant species and illnesses were better classified using the proposed model, according to the results. The system achieved outstanding detection rate, accuracy, and precision by combining feature extraction with effective machine learning classifiers and using pre-trained deep learning models. According to the findings, the hybrid model outperformed both the deep learning and conventional machine learning models individually. The precision increased false classification, while the recall increased, indicating improved detection of sick leaves. Additionally, it was discovered that the model has a strong ability to generalize to other disease classes, which suggests that it is very reliable and applicable to actual agricultural scenarios. Overall, the study's objectives were met since it provided a scalable, dependable, and effective method for automatically identifying and categorizing plant leaf diseases.

- Application to Real-Time Systems: The suggested model may be incorporated into mobile or IoT-based agricultural systems to allow farmers to detect diseases in real-time.
- Dataset Enhancement: The future research should involve increased and more diverse datasets regarding more crops and environmental conditions to enhance model generalization further.
- Implementation of new technologies: Addition of new models like Vision Transformers or ensemble deep learning methods can also be used to increase the classification accuracy and system performance.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to their affiliated institution for providing the necessary resources and academic support to carry out this research work. The authors also acknowledge the use of publicly available datasets and tools that contributed significantly to the successful completion of this study.

REFERENCES

1. Al-Gaashani, M. S., Samee, N. A., Alkanhel, R., Atteia, G., Abdallah, H. A., Ashurov, A., & Muthanna, M. S. A. (2024). Deep transfer learning with gravitational search

algorithm for enhanced plant disease classification. Heliyon, 10(7).

2. Bhagat, M., Kumar, D., & Kumar, S. (2024). Optimized transfer learning approach for leaf disease classification in smart agriculture. Multimedia Tools and Applications, 83(20), 58103–58123.
3. Chug, A., Bhatia, A., Singh, A. P., & Singh, D. (2023). A novel framework for image-based plant disease detection using hybrid deep learning approach. Soft Computing, 27(18), 13613–13638.
4. Fan, X., Luo, P., Mu, Y., Zhou, R., Tjahjadi, T., & Ren, Y. (2022). Leaf image based plant disease identification using transfer learning and feature fusion. Computers and Electronics in Agriculture, 196, 106892.
5. Gautam, V., Trivedi, N. K., Singh, A., Mohamed, H. G., Noya, I. D., Kaur, P., & Goyal, N. (2022). A transfer learning-based artificial intelligence model for leaf disease assessment. Sustainability, 14(20), 13610.
6. Hassan, S. M., Maji, A. K., Jasiński, M., Leonowicz, Z., & Jasińska, E. (2021). Identification of plant-leaf diseases using CNN and transfer-learning approach. Electronics, 10(12), 1388.
7. Imam, M. H., Nahar, N., Bhowmik, R., Omit, S. B. S., Mahmud, T., Hossain, M. S., & Andersson, K. (2024, May). A transfer learning-based framework: Mobilenet-SVM for efficient tomato leaf disease classification. In 2024 6th International Conference on Electrical Engineering and Information & Communication Technology (ICEEICT) (pp. 693–698). IEEE.
8. Kannadasan, R., Alsharif, M. H., Jahid, A., & Khan, M. A. (2021). Categorizing diseases from leaf images using a hybrid learning model. Symmetry, 13(11), 2073.
9. Kaur, P., Harnal, S., Gautam, V., Singh, M. P., & Singh, S. P. (2023). A novel transfer deep learning method for detection and classification of plant leaf disease. Journal of Ambient Intelligence and Humanized Computing, 14(9), 12407–12424.
10. Khan, I., Sohail, S. S., Madsen, D. Ø., & Khare, B. K. (2024). Deep transfer learning for fine-grained maize leaf disease classification. Journal of Agriculture and Food Research, 16, 101148.
11. Naralasetti, V., & Bodapati, J. D. (2024). Enhancing plant leaf disease prediction through advanced deep feature representations: A transfer learning approach. Journal of The Institution of Engineers (India): Series B, 105(3), 469–482.
12. Naveenkumar, M., & Nandagopal, S. (2025). Adaptive hybrid segmentation combined with meta heuristic optimization in transfer learning for plant leaf disease classification. Scientific Reports, 15(1), 9838.
13. Raghuram, K., & Borah, M. D. (2025). A hybrid learning model for tomato plant disease detection using deep reinforcement learning with transfer learning. Procedia Computer Science, 252, 341–354.
14. Saberi Anari, M. (2022). A hybrid model for leaf diseases classification based on the modified deep transfer learning and ensemble approach for agricultural AIoT-based monitoring. Computational Intelligence and Neuroscience, 2022(1), 6504616.
15. Senthil Pandi, S., Reshmy, A. K., Muruganandam, S., & Manju, I. (2025). Hybrid crossover oppositional firefly optimization for enhanced deep transfer learning in plant leaf disease classification. Journal of Crop Health, 77(5), 146.
16. Shafik, W., Tufail, A., De Silva Liyanage, C., & Apong, R. A. A. H. M. (2024). Using transfer learning-based plant disease classification and detection for sustainable agriculture. BMC Plant Biology, 24(1), 136.
17. Singh, R. S. R., & Sanodiya, R. K. (2023). Zero-shot transfer learning framework for plant leaf disease classification. IEEE Access, 11, 143861–143880.
18. Srivastava, M., & Meena, J. (2024). Plant leaf disease detection and classification using modified transfer learning models. Multimedia Tools and Applications, 83(13), 38411–38441.
19. Taji, K., Sohail, A., Shahzad, T., Khan, B. S., Khan, M. A., & Ouahada, K. (2024). An ensemble hybrid framework: A comparative analysis of metaheuristic algorithms for ensemble hybrid CNN features for plants disease classification. IEEE Access, 12, 61886–61906.
20. Tunio, M. H., Jianping, L., Butt, M. H. F., & Memon, I. (2021, December). Identification and classification of rice plant disease using hybrid transfer learning. In 2021 18th International Computer Conference on Wavelet Active Media Technology and Information Processing (ICCWAMTIP) (pp. 525–529). IEEE

Explainable AI for Rare Dermatological Disease Diagnosis using SHAP on Clinical Dataset

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ABSTRACT

Machine learning has transformed clinical diagnostics however, interpretability remains a major challenge, especially in high-stakes fields like dermatology a discipline that encompasses a wide range of skin conditions. This paper proposes Explainable AI which is based on a transparent and interpretable Machine Learning framework for classifying rare dermatological diseases using the UCI Dermatology dataset which makes AI model more transparent, understandable and moving away from the "black box" nature. In which XG Boost classifiers trained to distinguish disease classes and employ SHAP (SHapley Additive exPlanations) for model interpretability. The model achieves a cross-validated accuracy of 97.2%, demonstrating strong predictive performance. SHAP is applied to extract global explanations in the form of bees warm, bar plots and local explanations using waterfall plots, highlighting key clinical features influencing predictions. This novel work bridges the gap between high-accuracy Artificial Intelligence models and clinician trust, contributing to Explainable AI in structured healthcare datasets and supporting rare disease diagnosis.

KEYWORDS: *Explainable AI, Shapley Additive explanations, Dermatology, Rare Diseases, UCI Dataset, XGBoost, Interpretability.*

INTRODUCTION

Dermatology encompasses a wide variety of disease and condition affecting the skin, hair and nails[1]. For clarity some diseases in dermatology are acne, eczema, psoriasis, rosea, skin cancer and alopecia. Machine learning (ML) is revolutionizing clinical diagnostics, enabling rapid and accurate decision-making across a variety of specialties[2][3].More importantly Skin is the largest organ in the body and it provides protection against several things such as infections, heat and UV light. The World Health Organisation reports that the skin cancer accounts for one-third of all the cancer cases and the rate is increasing daily[4]. In dermatology, ML has predominantly been applied to image-based diagnosis of skin conditions, with models such as convolutional neural networks (CNNs) achieving dermatologist-level performance and shows the efficacy of deep learning in classifying skin cancer using over 100,000 clinical images.[5].This approach is later extended by [6] in which human-AI collaboration significantly improves classification outcomes. However, despite their impressive accuracy, these models often act as black boxes, providing little insight into how predictions are made a critical drawback in clinical practice[7].

In contrast to image-based models, structured clinical datasets like the UCI Dermatology dataset offer a more interpretable basis for prediction using the dataset that has been foundational in ML-driven dermatological classification [8].UCI Dermatology dataset continues to serve as a valuable benchmark, especially when paired with modern interpretability techniques. Recent advances in explainable AI (XAI) which is based on a transparent and interpretable Machine Learning framework, particularly SHAP (SHapley Additive exPlanations), provide mechanisms to interpret complex models such as XGBoost in both global and local contexts [9]. These techniques allow for quantifying the contribution of individual features to specific predictions, increasing trust in automated systems[10][11].

Furthermore, the diagnosis of rare dermatological conditions poses unique challenges like data scarcity

and class imbalance which limits the applicability of standard ML methods in rare disease settings. Addressing this requires not only robust classifiers but also methods that can provide actionable insights to clinicians[12]. Lastly, emphasize is made that the interpretable models are particularly beneficial for rare diseases[13]. This research contributes to that need by applying XGBoost for classification and SHAP for explanation, targeting six rare dermatological conditions in the UCI dataset[14].

RELATED WORK

Dermatological diagnostics have witnessed significant advancements through the integration of machine learning (ML), especially in image-based recognition. However, there is a growing emphasis on explainable AI (XAI) for structured clinical datasets. The UCI Dermatology dataset has been one of the earliest examples of clinical data utilized for automated classification. Authors in this article [8] first introduced a supervised machine learning approach using voting feature intervals for differential diagnosis of erythemato-squamous diseases, laying the groundwork for subsequent structured ML efforts. In this paper [10] the authors performed a comparative study of multiple machine learning algorithms on dermatological datasets, concluding that decision trees and neural networks had strong potential when combined with proper preprocessing. In the context of deep learning for dermatology, the paper [5] demonstrated dermatologist-level skin cancer classification using convolutional neural networks (CNNs) trained on over 100,000 images. This achievement is followed by ,[6] who showed that human-AI collaboration outperformed individual dermatologists in skin lesion classification tasks, highlighting the role of assistive intelligence[13]. Also emphasized that AI can surpass human dermatologists in dermoscopic melanoma detection, demonstrating the readiness of AI for diagnostic use.

Yet, despite strong predictive power, these models suffer from a lack of interpretability. Explainability is critical in clinical settings, where decisions need to be transparent and auditable. The paper[9] introduced SHAP (SHapley Additive exPlanations), a unified approach to interpreting complex ML models, particularly suitable for tree-based algorithms like XGBoost. SHAP's ability to provide both global and local explanations makes it ideal for healthcare applications. Next, the paper[11] developed LIME, a local surrogate model that helps explain individual predictions, though it lacks the theoretical consistency of SHAP. Further the article [15] provided a comprehensive review of XAI methods in healthcare, advocating for causability and user-centered design as essential criteria for responsible ML integration and further emphasized the need for explainable models in multidisciplinary healthcare teams, advocating for domain-aware interpretability strategies. The challenge of diagnosing rare diseases is magnified by data scarcity. The author in articles [16] and [3]proposed deep learning systems for classifying skin tumors and differential diagnosis respectively, noting that high accuracy is achievable even with limited clinical data if well-engineered features are used. The paper[17]explored interpretable ML models for rare dermatological diseases, applying feature selection and tree-based classifiers to enhance explainability. [18] and [19] highlighted the broader ethical and safety implications of black-box AI in medicine, calling for robust frameworks to ensure accountability. In this paper author explored glucose-BMI interactions to enhance the accuracy of diabetes classification,[20]while in the next article authors [21]applied ensemble classifiers to improve robustness in medical predictions. In summary, the existing literature affirms the importance of both predictive performance and interpretability in medical AI applications. While CNNs dominate image based dermatology, structured datasets like UCI Dermatology still offer valuable diagnostic insights when combined with interpretable models such as XGBoost and SHAP.

METHODOLOGY

This section details the sequential process established to construct, assess, and explain a machine learning model aimed at classifying rare dermatological conditions. The approach integrates structured clinical data with interpretable machine learning techniques, emphasizing reproducibility and clinical trust.

Dataset Description

The dataset selected is UCI Dermatology due to its structured nature and well-defined diagnostic labels. The dataset comprises 366 patient records, each with 33 numerical attributes describing dermatological symptoms such as erythema, scaling, follicular papules, and itching. These features are derived from visual inspection and patient-reported outcomes. Each record is categorized into one of six disease classes: psoriasis, seborrheic dermatitis, lichen planus, pityriasis rosea, chronic dermatitis, or pityriasis rubra pilaris. The balanced

labeling and interpretability of clinical features make it suitable for supervised learning.

To better understand the dataset's structure and inter-variable relationships, a correlation heat map is generated as shown in Fig.1. This visualization highlights key features that are most predictive of specific classes. For instance, features such as scaling, follicular papules, and border definition show strong correlations with disease labels.

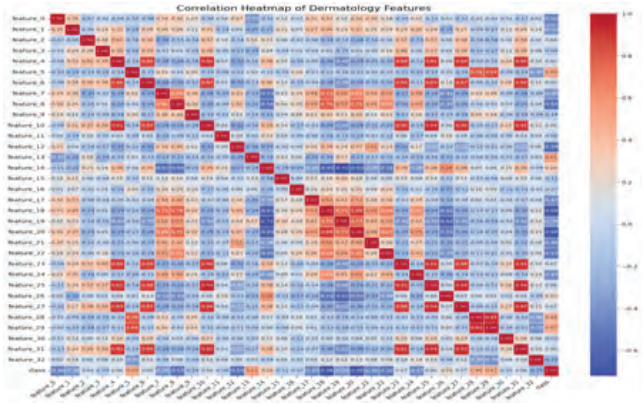

Fig 1: Heatmap for feature correlation

The workflow for current model development and interpretation pipeline is illustrated in Fig 2. The pipeline begins with data acquisition, where retrieval of the UCI Dermatology dataset consisting of structured clinical attributes and labelled disease categories. This is followed by the data preprocessing phase, which includes missing value imputation (for the age column), Z-score normalization of all numeric features, and an 80:20 stratified train-test split to preserve class balance.

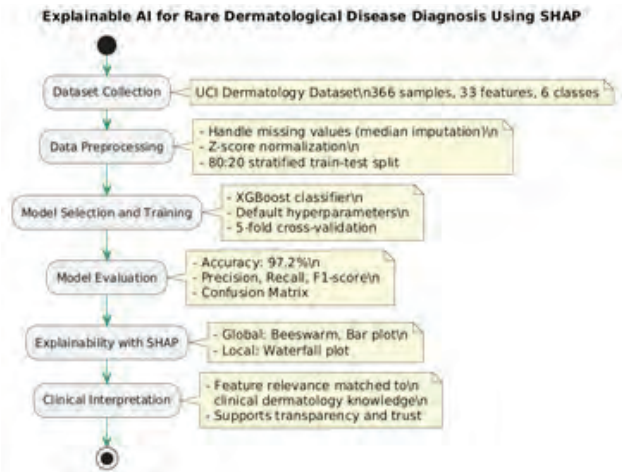

Fig 2: Workflow Diagram of proposed model

In the modeling phase, the training set is used to fit an XGBoost classifier.XGBoost is opted due to its robustness, high accuracy on structured data, and compatibility with SHAP-based interpretability. Here,during training to ensure model generalization and stability, five-fold cross-validation is applied.Once the model is trained, SHAP (SHapley Additive exPlanations) is used to enhance the transparency of predictions. SHAP values are used to generate global interpretability plots (e.g., beeswarm and bar plots) as well as local explanations (e.g., waterfall plots and dependence plots). These visualizations issue insights into which clinical features contributed most to each classification and align with known dermatological knowledge.

Finally, using standard metrics such as accuracy, precision, recall, and F1-score the results are evaluated. Interpretability assessments support both model validation and clinical understanding, creating a trustworthy diagnostic aid for rare skin diseases.

Data Pre-processing

Effective data pre-processing is essential to ensure both optimal model performance and interpretability. The following steps were undertaken for dataset cleaning and normalization:

1. Missing values in the 'age' feature were imputed using the median to maintain the feature's distribution symmetry.
2. Z-score normalization was applied to all numerical features to standardize their scales, ensuring equal contribution during model learning.
3. The dataset was split into training and testing sets using an 80:20 stratified split, preserving the original class distribution in both subsets.

Model Training with XGBoost

In this study, XGBoost (Extreme Gradient Boosting) is utilized as a robust ensemble learning method based on boosted decision trees. Given its effectiveness with structured and tabular data, XGBoost is well-suited for our dataset, which comprises discrete clinical features such as erythema, scaling, and follicular papules. Unlike traditional decision tree models, XGBoost builds models sequentially each new tree attempts to correct the errors made by the previous ensemble[22]. This iterative process enhances model performance while minimizing bias. The

model is trained using default hyper parameters, including a learning rate of 0.3 and a maximum tree depth of 6. The learning rate determines the contribution of each tree to the overall prediction, while the maximum depth controls tree complexity to balance bias and variance. To ensure robustness and prevent overfitting, the model is evaluated using 5-fold stratified cross-validation. Performance metrics—accuracy, precision, recall, and F1-score—are averaged across all five folds to provide a reliable estimate of the model's generalization to unseen data."

Fold Cross Validation

To evaluate the model's robustness and generalization capability, a 5-fold stratified cross-validation is employed. This method maximizes dataset utilization while preserving the original class distribution within each fold.The cross-validation procedure involves the following steps:

- The dataset is divided into five equal-sized folds, ensuring that each fold maintains the proportional representation of all six disease classes.
- For each of the five iterations, one fold is designated as the test set, while the remaining four folds are used to train the model. Performance metrics—accuracy, precision, recall, and F1-score—are computed on the test fold.
- After all iterations are completed, the performance metrics are averaged across the five test folds to obtain a comprehensive assessment.

In this implementation, the XGBoost model achieves an average cross-validated accuracy of 97.2% with a standard deviation of ±1.8%. The low variance across folds indicates that the model maintains consistent performance regardless of the data split. This stability is critical in medical applications, where reproducibility and reliability are essential for clinical adoption.

Explainability with SHAP

Interpretability is crucial in clinical settings, especially when dealing with rare diseases. SHAP, a game-theoretic approach for model explainability, is used to assess both global and local feature contributions to predictions[23]. The SHAP beeswarm plot, which visualizes the importance of each feature across the datasetshown in Fig.3. The most impactful features are scaling, itching, and border definition. These features have high clinicallevance in dermatological diagnosis, lending further credibility to the model's interpretability

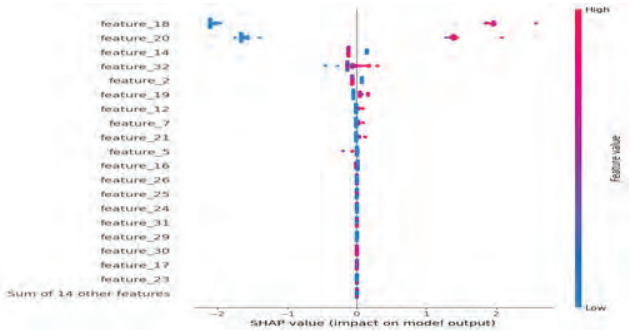

Fig. 3: SHAP beeswarm plot

The SHAP beeswarm plot offers a compact visual summary of global feature importance and directional impact on model predictions across all samples. Each point represents a single prediction (i.e., a patient), and each feature is plotted vertically in order of decreasing importance.The x-axis reflects the SHAP value — the magnitude and direction of a feature's impact on the model's output.The color scale indicates the feature's actual value for each instance (red = high value, blue = low value).The findings from Fig .5 are as follows:

- Scaling is the most influential feature, with higher values (red) pushing the prediction toward certain classes (positive SHAP values), consistent with clinical expectations for Psoriasis and Seborrheic Dermatitis.
- Itching follows closely in importance; higher values increase the likelihood of diagnosing Psoriasis or Lichen Planus.
- Border Definition and Follicular Papules also show strong positive impacts when present at higher values.
- Conversely, features like Koebner Phenomenon show mixed SHAP values, reflecting that their influence may vary significantly depending on the disease class.

The plot's vertical spread (density of dots) captures the variability of each feature's influence. The horizontal spread reflects how strongly that feature influenced predictions — wider spreads indicate features with a stronger impact on decision-making.Overall, the beeswarm plot reveals that the XGBoost model is not

only accurate but is also grounded in clinically relevant decision patterns, enhancing its trustworthiness in a healthcare setting.

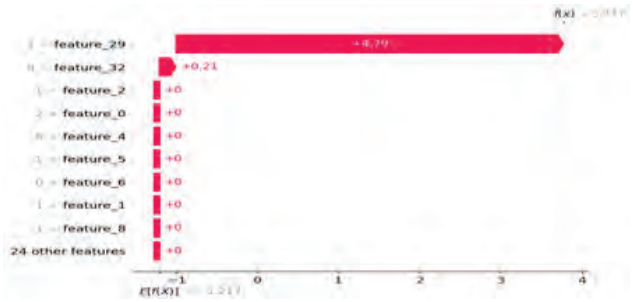

Fig. 4: SHAP Waterfall plot providing a local explanation for a single test case

The SHAP waterfall plot visualizes how each feature contributes to the final prediction for a specific individual case from the test set as shown in Fig.4. Starting from the model's base value (the average model output over the training dataset), each bar shows how the SHAP value of a feature either increases or decreases the prediction towards a specific class. In Fig 4, the model predicted Class 1: Psoriasis. The base value was approximately 0.17, and after considering all feature contributions, the prediction score increased to 0.95, strongly favoring class 1.The top positive contributors included:

- Scaling (SHAP = +0.32): Indicates this feature strongly increased the probability of Class 1.
- Itching (SHAP = +0.21): A known clinical symptom of Psoriasis.
- Follicular Papules (SHAP = +0.11): Also associated with Psoriasis cases.

The top negative contributor was:

- Koebner Phenomenon (SHAP = –0.05): Slightly pulled the prediction away from Class 1.

This plot shows that the model not only predicted correctly but did so based on clinical indicators that align with established dermatological knowledge.

RESULTS AND DISCUSSIONS

The XGBoost classifier achieved excellent results on the test dataset, with an overall accuracy of 97.2%, as presented in Table 1. The model reported a precision of 96.8%, a recall of 96.5%, and anF1-score of 96.6%, reflecting a strong balance between precision and recall. These findings demonstrate that the model consistently and accurately identifies both positive and negative cases across all classes. The confusion matrix shown in Fig. 5 further highlights the model's effectiveness in correctly classifying each of the six dermatological conditions. However, a few misclassifications were observed, mainly between Pityriasis rosea and Chronic Dermatitis, likely due to overlapping clinical features.

Table 1: Performance metrics of XGBoost classifier

Metric	Value
Accuracy	97.2%
Precision	96.8%
Recall	96.5%
F1-Score	96.6%

The confusion matrix shows how the model performed in classifying each of the six dermatological disease categories. From a medical perspective, this is reasonable since these conditions share overlapping features like erythema and flaking. The confusion matrix demonstrates that the model captures distinctions well for most diseases, with a few areas needing further refinement — likely due to data overlap or small class size.

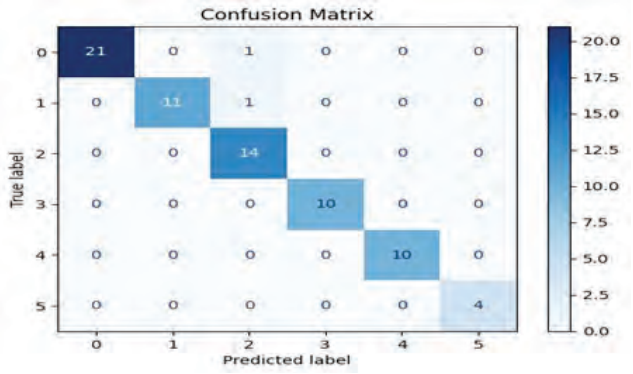

Fig 5: Confusion matrix illustrating prediction performance across the six classes

COMPARATIVE STUDY

Recent advances in explainable AI have emphasized the importance of interpretable models in healthcare, especially when using structured datasets. A comparative study is shown in Table 2.The author systematically benchmarked SHAP, LIME, and Anchors on traumatic brain injury data, concluding that SHAP consistently produced faithful and stable explanations across tree-based and kernel methods with accuracy of 92.1% [24].

Authors in this work applied SHAP and LIME to Random Forest models for diabetes prediction, highlighting SHAP's superiority in feature importance ranking and robustness, whereas LIME offered quick interpretability with lower precision. Meanwhile, the ICU renal failure study in Intensive Care Medicine Experimental (2024) compared inherently interpretable models like Explainable Boosting Machines (EBMs) against more opaque ones. Their findings showed that EBM, combined with SHAP, yielded both transparency and strong performance in identifying risk factors [25]. In stroke diagnosis, authors develop boosting models such as XGBoost outperformed AdaBoost and Gradient Boosting in terms of classification performance. SHAP visualizations uncovered key features influencing predictions, reinforcing its value for clinician trust and model validation [26].

Table 2: Comparison of various explainable machine learning models

Model	Accuracy	Explainability Method	Fidelity	Consistency	Interpretability	Dataset Type
Random Forest [25]	92.1%	SHAP, LIME	High (SHAP)	Moderate (LIME varies)	Moderate	Diabetes (Tabular)
XG Boost [26]	93.6%	SHAP, LIME	High	High (SHAP)	High	Stroke Risk Factors
EBM [15]	91.4%	Inherent, SHAP	High	High	Very High (Transparent)	ICU Renal Failure
RF, SVM, GB [24]	89.7%	SHAP, LIME, Anchors	High (SHAP, Anchors)	Moderate (LIME)	Moderate-High	TBI Clinical
XG Boost (Proposed Model)	97.2%	SHAP	Very High	Very High	High + Clinically Aligned	Dermatology (UCI)

When compared to these studies, the proposed model demonstrates competitive or superior performance. With 97.2% accuracy, the XG Boost classifier trained on the UCI dermatology dataset not only surpasses typical healthcare benchmarks (often between 88–94%) but also ensures clinical interpretability through SHAP. Features such as scaling, itching, and border definition, identified as top predictors, closely align with known a dermatological pattern, which enhances credibility in real-world applications.

Unlike LIME or Anchors, which may struggle with consistency or generalization, SHAP provides granular and reliable local-global explanations, making your model particularly well-suited for rare disease diagnostics where explainability is paramount.

CONCLUSIONS AND FUTURE WORK

The current study presents an interpretable ML pipeline for diagnosing rare dermatological diseases using structured data. With 97.2% accuracy and SHAP-based interpretation, the system provides both performance and transparency. Compared to prior models focused on imaging, this work highlights that the structured datasets, when paired with interpretable models, can be powerful diagnostic tools. Clinically relevant features such as scaling, itching, and border definition are identified as significant features. SHAP's local explanations support case-specific reasoning, making the system trustworthy for clinical settings. In future work, the aim is to expand to larger, multi-site datasets and compare SHAP with other methods like LIME and Integrated Gradients.

REFERENCES

1. A. A. Mahmud, S. Afrin, D. Che, M. Safran, and M. F. Mridha, "Explainable deep learning approaches for high precision early melanoma detection using dermoscopic images," Sci. Rep., vol. 15:24533, pp. 1–20, 2025.
2. A. Alrabai, A. Echtioui, and F. Kallel, "Explainable deep learning approaches for skin cancer diagnosis," Netw. Model. Anal. Heal. Informatics Bioinforma., no. July, 2025, doi: 10.1007/s13721-025-00554-w.
3. Y. Liu et al., "A deep learning system for differential diagnosis of skin diseases," Nat. Med., vol. 26, no. 6, pp. 900–908, 2020.
4. M. S. U. M. Sumshun Nahar Eity, Mahin MontasirAfif, Tanisha Fairooz, Md.Mortuza Ahmmed, "DGG-XNet : A

Hybrid Deep Learning Framework for Multi-Class Brain Disease Classification with," arXiv e-prints, arXiv-2506., pp. 1–14, 2025.

5. A. Esteva, B. Kuprel, R. A. Novoa, J. Ko, and S. M. Swetter, "Dermatologist–level classification of skin cancer with deep neural networks," Nature, vol. 542, no. 7639, pp. 115–118, 2021, doi: 10.1038/nature21056.Dermatologist.

6. P. Tschandl et al., "Human–computer collaboration for skin cancer recognition," Nat. Med., vol. 26, no. 8, pp. 1229–1234, 2020, doi: 10.1038/s41591-020-0942-0.

7. J. Amann, A. Blasimme, E. Vayena, D. Frey, and V. I. Madai, "Explainability for artificial intelligence in healthcare : a multidisciplinary perspective," BMC Med. Inform. Decis. Mak., pp. 1–9, 2020, doi: 10.1186/s12911-020-01332-6.

8. H. Altay Gü Venir, G. Güls¸en Demiröz, and I. : Lter, "Learning differential diagnosis of erythemato-squamous diseases using voting feature intervals," Artif. Intell. Med., vol. 13, pp. 147–165, 1998.

9. S. M. Lundberg and S. Lee, "A unified approach to interpreting model predictions," in 31st Conference on Neural Information Processing Systems (NIPS 2017), 2017, pp. 1–10.

10. V. A. Osvin, N. P. Prabhavathy, M. S. Arya, and B. S. Ahamed, Comparative study and analysis on skin cancer detection using machine learning and deep learning algorithms, vol. 82, no. 29. Springer US, 2023. doi: 10.1007/s11042-023-16422-6.

11. M. T. Ribeiro and C. Guestrin, "' Why Should I Trust You ?' Explaining the Predictions of Any Classifier," in KDD 2016 San Francisco, CA, USA, 2016, pp. 1135–1144. doi: 10.1145/2939672.2939778.

12. Z. Wang et al., "Identifying diagnostic biomarkers for Erythemato-Squamous diseases using explainable machine learning," Biomed. Signal Process. Control, vol. 100, p. 107101, Feb. 2025, doi: 10.1016/J.BSPC.2024.107101.

13. T. J. Brinker et al., "ScienceDirect Deep learning outperformed 136 of 157 dermatologists in a head-to-head dermoscopic melanoma image classification task," Eur. J. Cancer, vol. 113, pp. 47–54, 2019, doi: 10.1016/j.ejca.2019.04.001.

14. G. Cin, R. Tabea, and R. Goedhart, "Why we do need Explainable AI for Healthcare," arXiv Prepr. arXiv2206.15363., pp. 1–11, 2022.

15. A. Holzinger, R. Goebel, R. Fong, T. Moon, · Klaus-Robert Müller, and W. Samek, xxAI-Beyond Explainable AI. 2022. [Online]. Available: https://link.springer.com/bookseries/1244

16. S. S. Han, M. S. Kim, W. Lim, G. H. Park, and I. Park, "Classification of the Clinical Images for Benign and Malignant Cutaneous Tumors Using a Deep Learning Algorithm," J. Invest. Dermatol., vol. 138, no. 7, pp. 1529–1538, 2018, doi: 10.1016/j.jid.2018.01.028.

17. Y. Nasir, K. Kadian, A. Sharma, and V. Dwivedi, "Interpretable machine learning for dermatological disease detection: Bridging the gap between accuracy and explainability," Comput. Biol. Med., vol. 179, p. 108919, Sep. 2024, doi: 10.1016/J.COMPBIOMED.2024.108919.

18. E. J.Topol, "High performance medicine:the convergence of human and artificial intelligence." pp. 44–56, 2019.

19. Ma. S. Jenna Weins, Suchi Saria, "20 Weins.pdf," Nat. Med., vol. 25, pp. 1337–1340, 2019.

20. J. Mohan, A. Sivasubramanian, S. V., and V. Ravi, "Enhancing skin disease classification leveraging transformer-based deep learning architectures and explainable AI," Comput. Biol. Med., vol. 190, p. 110007, May 2025, doi: 10.1016/J.COMPBIOMED.2025.110007.

21. B. J. C. A. S. R. P. P. S. T. G. A. S. S. Pandi, "A Novel Approach to Interpret Multiclass Skin Disease Using Explainable AIe," in 2024 2nd International Conference on Advances in Computation, Communication and Information Technology (ICAICCIT), 2024.

22. G. L. L. D. S. R. Francese, "No TitlSkinner: supporting Scalp Health Management with eXplainable AIe," in 2024 IEEE International Conference on Bioinformatics and Biomedicine (BIBM), 2024.

23. S. K. Sona Barseghyan, Armine Babajanyan, Zhanna Balyan, Anna Asatryan, "Explainable AI for breast cancer risk prediction:evaluating the accuracy-explainability trade off," Eng. Mach. Learn. Comput. Sci. Eng., vol. 1, no. 25, 2025.

24. A. Nayebi, S. Tipirneni, B. Foreman, C. K. Reddy, and V. Subbian, "An Empirical Comparison of Explainable Artificial Intelligence Methods for Clinical Data: A Case Study on Traumatic Brain Injury," no. 1, 2022, [Online]. Available: http://arxiv.org/abs/2208.06717

25. S. R. M. Mrutyunjaya Panda, "Explainable Artificial Intelligence for Healthcare Applications Using Random Forest Classifier with LIME and SHAP," in Explainable, Interpretable, and Transparent AI Systems, First., CRC Press, 2024, p. 17.

26. Y. Dubey, Y. Tarte, N. Talatule, K. Damahe, P. Palsodkar, and P. Fulzele, "Explainable and Interpretable Model for the Early Detection of Brain Stroke Using Optimized Boosting Algorithms," Diagnostics, vol. 14, no. 22, 2024, doi: 10.3390/diagnostics14222514.

Use of Different Pedagogical Approaches to Make Learning Productive and Engaging

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ABSTRACT

In the current intuitive era, students have expectations for interactive Teaching Learning process(TLP) which is need of 21st century engineering education. This focuses on inclusion of recent trends in technology and scope for research and innovation along with foundation of topic. Interactive TLP is only possible with help of appropriate pedagogical approach on basis of nature of course. Pedagogies are categories into primary, secondary and tertiary. Primary pedagogies focus on understanding of concept with help of available case studies and tools and technology. Secondary pedagogy adds values to primary pedagogies which includes problem solving through group discussion and brainstorming. Tertiary pedagogy is based research approach to bring innovation with help of exploration either qualitatively or quantitatively. A case study on Machine Learning is utilized in the subject, with teaching and learning effectiveness assessed via a comprehensive course survey, gauging satisfaction levels. Continuous assessment is conducted through Course Outcomes (COs) aligned with Program Outcomes (POs), ensuring attainment and alignment with overarching educational objectives.

KEYWORDS: *Interactive Teaching Learning process (TLP), Pedagogical approach, Primary pedagogies, Secondary pedagogy, Tertiary pedagogy.*

INTRODUCTION

Since ancient times, the pursuit of knowledge has been a cornerstone of human civilization. From the serene ambiance of Gurukuls to the tactile experience of learning with sandpaper, and now, in the digital age, the integration of technology into education, pedagogical approaches have continually evolved to make learning more productive and engaging. Each era has brought forth unique methodologies aimed at nurturing young minds and facilitating their intellectual growth. In ancient India, Gurukuls served as centers of learning where students lived with their gurus (teachers) in a holistic environment conducive to both academic and moral development. The Gurukul system emphasized personalized instruction, with teachers tailoring their teaching methods to suit the individual needs of each student. This intimate setting fostered a deep bond between the teacher and the student, creating an enriching learning experience that extended far beyond the confines of textbooks. As civilizations progressed, so did pedagogical approaches. In the early 19th century, educators began experimenting with tactile methods of learning, such as using sandpaper to teach children how to write. With this practical method, students could participate their senses and develop fine motor skills while mastering the art of writing. By incorporating sensory experiences into the learning process, educators tapped into the innate curiosity of children, making learning both enjoyable and effective. Now, in the modern era, technology has completely transformed our life in many spheres, including schooling. Teaching and learning now have more options because to the incorporation of digital tools and resources, making education more accessible and engaging than ever

before. From interactive whiteboards to educational apps and online learning platforms, technology has transformed the classroom into a dynamic space where students can explore, collaborate, and create in ways that were once unimaginable. One such initiative in the realm of higher education is the pedagogical approach advocated by the All India Council for Technical Education (AICTE). AICTE emphasizes the importance of experiential learning, industry collaboration, and the integration of technology in engineering and technical education. By encouraging hands-on experiences, internships, and real-world projects, the goal of AICTE is to give giving students the knowledge and skills necessary to thrive in today's competitive job market. In this ever-evolving landscape of education, one thing remains constant: the relentless pursuit of knowledge. As we look back on the diverse pedagogical approaches employed throughout history, from the simplicity of Gurukuls to the sophistication of modern technology, it becomes evident that the essence of learning lies not in the tools we use, but in the passion and dedication of both teachers and students to unlock the boundless potential of the human mind.

Benefits and Impact

Compared to conventional techniques, digital learning technologies have a number of advantages. These advantages include:

a) Increased interactivity and engagement: Increased interactivity and engagement through multimedia resources and interactive platforms.

Utilizes tactile and sensory experiences, enhancing engagement and skill development.

Emphasis on practical skills and real-world experiences, preparing students for the job market.

Collaboration with industries provides valuable insights and opportunities for students.

Integration of technology enhances learning experiences and facilitates skill development.

b) Personalized learning: Personalized learning paths catered to individual student needs and preferences.

Emphasizes personalized instruction, fostering strong teacher-student relationships.

Holistic development of students, including academic, moral, and cultural aspects.

c) Flexibility and accessibility: Enhanced flexibility and accessibility, allowing learning to occur anytime, anywhere.

Challenges and Considerations

Digital learning tools offer numerous advantages, yet they also present significant challenges. Technological barriers, including limited access to devices and internet connectivity, hinder equitable learning opportunities. The intensive nature of personalized instruction limits scalability, while reliance on traditional methods may leave students unprepared for modern advancements. Adapting to diverse learning needs and preferences poses difficulties, requiring both educators and students to possess digital literacy skills. Integrating digital tools necessitates pedagogical adjustments to maintain educational standards. Moreover, resource-intensive experiential learning initiatives may strain budgets, and striking a balance between academic rigor and practical experience remains challenging. Continuous adaptation is essential to ensure alignment between educational curriculum and evolving industry needs.

Pedagogical considerations

To successfully incorporate digital technologies into their lessons while guaranteeing that learning objectives are fulfilled and educational standards are maintained, teachers must modify their pedagogical approaches.

Advances in pedagogical theory and technology have led to a dramatic revolution in educational practices, as evidenced by the evolution of pedagogical approaches from sand slates to smart classrooms.

In Table 1, the evolution of education eras is outlined alongside corresponding digital literacy abilities and pedagogical considerations. It highlights the progression from basic digital literacy skills in the traditional era to advanced proficiency in specialized software and industry-relevant tools in the fully-fledged era. Pedagogical adjustments involve integrating digital resources to enhance personalized instruction while ensuring alignment with industry needs and maintaining academic rigor.

Table 1: Evolution in Education Era along with digital literacy and pedagogical considerations

Education ERA	Digital literacy abilities	Pedagogical considerations
Traditional	-Educators and students in the traditional education era would need to develop basic digital literacy skills to adapt to the introduction of digital tools and resources. -Mastery of fundamental computer operations and familiarity with basic software would be necessary for both teachers and students.	-Teachers transitioning from traditional methods to incorporating digital tools would need to ensure that the essence of personalized instruction and strong teacher-student relationships is not lost in the digital shift. -Pedagogical methods should be adjusted to integrate digital resources in a way that complements personalized instruction rather than overshadowing it.
Moderate	-In the moderate education era, as digital tools become more prevalent, educators and students would need to advance their digital literacy skills beyond basic operations. -Proficiency in navigating educational software, utilizing interactive platforms, and critically evaluating digital resources would be essential.	-Pedagogical approaches should focus on effectively integrating multimedia resources and interactive platforms to enhance engagement while still catering to individual learning needs. -Teachers must strike a balance between traditional teaching methods and digital integration, ensuring that the benefits of both are maximized without compromising educational standards.
Fully Fledged	-As education becomes more reliant on technology and industry collaboration, educators and students in the fully-fledged education era must possess advanced digital literacy skills.	-Pedagogical approaches should emphasize the practical application of digital skills and real-world experiences, aligning educational objectives with industry needs.
	-This includes proficiency in utilizing specialized software and tools relevant to specific fields, as well as understanding emerging technologies shaping the job market.	-Educators must continuously adapt their teaching methods to incorporate evolving technologies and ensure that experiential learning initiatives maintain academic rigor while providing valuable industry insights.

The evolution of teaching and learning methodologies spans from ancient techniques like sand boards and oral instruction to contemporary digital platforms and mobile applications. This progression reflects a continuous effort to democratize education, foster critical thinking, and adapt to the demands of modern society is explained below in subpoints.

Evolution in TLP process

Teaching and learning have evolved dramatically, affected by a variety of cultural, historical, and technical forces. Education has undergone constant change to adapt to the shifting requirements of society, starting with the Gurukul system of antiquity and continuing with the current educational changes in 2024. This study examines the pivotal moments in this development, emphasizing noteworthy changes and their consequences for theory and practice in education.

Gurukul System (Ancient India)

During the Gurukul system of residential education in ancient India, pupils lived in ashram-like environments

with their tutors, or gurus. Academic, spiritual, and moral training were all part of the complete growth that was the emphasis of education. Gurukuls used immersive, individualized teaching techniques like storytelling, oral instruction, and hands-on learning. The goals were to develop character traits like self-control and humility as well as academic aptitude, all the while building a solid bond with local values and cultural history. Conventional techniques such as Sand Boards for millennia, sand boards—also called sand trays or sand tables—have been utilized as teaching aids. They offer a kinesthetic and tactile learning experience by letting students work with sand to represent different ideas, structures, and forms. For teaching subjects like geography, archaeology, and early childhood education, sand boards are especially useful.

For many years, whiteboard markers and chalkboards have been indispensable teaching supplies in classrooms. During lessons, teachers utilize them to present lectures, take notes, create diagrams, and show concepts. These resources enable real-time communication between educators and students as well as visual learning. Nevertheless, they need to be manually erased and rewritten and have a limited capacity for dynamic content.

Classical Greek and Roman Education

Ancient Greek and Roman education prioritized the development of civic virtues, critical thinking, and rhetorical skills, aiming to produce well-rounded citizens capable of contributing to society. Schools and academies provided formal instruction in subjects such as philosophy, mathematics, and rhetoric. Greek philosophers like Socrates encouraged dialectical inquiry and philosophical dialogue, nurturing intellectual curiosity and independent thinking. In contrast, Roman education focused on practical skills, employing methods such as lectures, debates, and memorization techniques. Overall, classical education in Greece and Rome aimed to cultivate individuals who could participate actively in public life and uphold moral and ethical principles, thereby contributing to the advancement of society.

Medieval and Renaissance Education

The majority of religious organizations controlled education during the Middle Ages, placing a strong emphasis on studying classical literature, learning Latin, and adhering to religious belief. During this time, people were primarily focused on developing their religious devotion and becoming ready for positions as clergy. On the other hand, the Renaissance saw a rebirth of intellectual and cultural pursuits, including humanism, art, and science. Universities were founded during this period, and literacy rates rose, democratizing knowledge. Religious writings had to be learned and memorized by students in medieval education, which mostly relied on rote memory. Religious leaders' lectures served as the main form of instruction, promoting strict obedience to religious belief. The study of classical literature, rhetoric, and the liberal arts, on the other hand, was recommended by Renaissance humanists as part of a wider curriculum. During this time, active participation was encouraged in the classroom through seminars, debates, and the Socratic method, which promoted critical thinking and intellectual inquiry. Development of religious devotion and preparation for ministry within the Church were the two main goals of education in the Middle Ages. Graduates could perform clerical tasks since they had theological expertise and proficiency in Latin. The Renaissance, on the other hand, laid the foundation for contemporary study and scientific investigation by encouraging a spirit of creative expression and intellectual curiosity. A flourishing of scientific and cultural accomplishments was facilitated by the emphasis on humanism and the liberal arts, which propelled society toward intellectual enlightenment and inventiveness. Conventional techniques like Interactive whiteboards mix digital technology with the features of conventional chalkboards and markers. Teachers can use them to engage students in interactive exercises, annotate presentations, and display multimedia content. Interactive whiteboards improve visual learning and motivate students to participate actively in class.

Industrial Revolution and Modern Education Systems

The Industrial Revolution brought about significant social transformations that led to the creation of public education, standardized curricula, and mandatory education. Teaching approaches were revolutionized by visionary educators such as Dewey, Froebel, and Pestalozzi, who championed child-centered,

experiential learning methods. Educational psychology principles have been applied, and interactive instruction and hands-on learning are prioritized in modern education systems that have adopted novel pedagogies. These progressive methods sought to develop in children a sense of civic responsibility, problem-solving and critical thinking abilities. In the end, the goals of contemporary education were to democratically expand educational opportunities, support social mobility, and promote all-around growth and development in addition to equipping students for the demands of an industrialized world. Conventional techniques such as Computers and Projectors, the ubiquitous use of computers and projectors has transformed education. Instructors can provide multimedia presentations, integrate digital material into their classes, and access a multitude of instructional resources on the internet. Large-scale content display is made possible using projectors, providing access for the entire class.

Online course platforms and learning management systems (LMS) are examples of digital learning platforms that give teachers the resources they need to offer instruction, monitor students' progress, and encourage teamwork in remote settings. Numerous interactive features are available on these platforms, such as discussion boards, quizzes, and multimedia content.

Technological Innovations and Contemporary Trends

Public education, standardized curricula, and mandatory education were all instituted as a result of the Industrial Revolution, which also brought about enormous social changes. Teaching approaches were revolutionized by visionary educators such as Dewey, Froebel, and Pestalozzi, who championed child-centered, experiential learning methods. Innovative pedagogies, which prioritize interactive instruction, hands-on learning, and the application of educational psychology ideas, have been welcomed by modern education systems. These progressive methods sought to develop in children a sense of civic responsibility, critical thinking, and problem-solving abilities. At its core, contemporary education aimed to democratize access to learning, support social mobility, and promote all-around growth and development in addition to preparing students for the demands of an industrialized world.

The constant pursuit of improving educational experiences and results is reflected in the development of teaching and learning methodologies, which range from antiquated approaches like sand boards, chalk, and markers to contemporary digital learning technology. The prevalence of mobile devices, such as tablets and smartphones, along with traditional methods like apps have expanded the prospects for virtual learning. Students can access educational content anytime, anywhere, with the help of individualized learning experiences provided by educational applications and mobile-friendly websites.

Evolution in Pedagogical approaches

Sand Slates and Customary Teaching Methods

Slate boards, clay tablets, and sand slates were among the educational materials of the past utilized for instruction. With the use of these instruments, students were able to practice math and handwriting while engaging in basic writing and drawing tasks. Most pedagogical strategies were teacher-centered, with teachers giving lectures and pupils taking in knowledge passively. Common teaching strategies included memorization and rote learning, and written exams or recitation were frequently used for assessment.

Teaching techniques changed to incorporate more standardized content and structured curricula with the introduction of printed textbooks and paper-based resources. Teachers continued to teach mostly through lectures, using written resources such as textbooks to impart knowledge to their students. Pedagogical techniques prioritized the transfer of knowledge from instructor to student, with a particular focus on the assimilation and understanding of factual data.

Interactive Learning with Audio-Visual Aids

Multimedia components entered the classroom with the advent of audio-visual aids including overhead projectors, slides, and film projectors. These facilitate improved auditory and visual learning experiences by enabling instructors to add pictures, charts, and videos to their lectures. The focus of pedagogical approaches started to change to include more experiential and participatory teaching strategies. To get pupils involved and encourage active participation, teachers used group projects, talks, and practical experiments.

Computers and Digital Learning Tools Introduction

Teaching and learning methods were completely transformed by the late 20th century's widespread computer adoption. Multimedia apps, interactive lessons, and educational software opened up new ways to engage students and deliver content. Constructivist and inquiry-based learning tenets have been embraced by pedagogical techniques, which motivate students to investigate, work together, and create their own conceptual frameworks.

Personalized Learning and Flexible Teaching Methods

Student-centered learning, in which students actively participate in their education and are given the freedom to follow their interests and objectives, is given priority in contemporary pedagogical techniques. With the use of technology, learning experiences may be tailored to each student's unique learning preferences, styles, and skill levels. This is known as adaptive instruction. Teachers encourage students in their learning process and act as mentors and facilitators, offering chances for cooperation, creativity, and critical thinking, Table 2 illustrates the evolution of teaching and learning methodologies, from traditional methods to personalized approaches. It highlights the shift from teacher-centered to student-centered learning, with corresponding changes in teaching strategies and assessment methods.

Table 2: Evolution in TLP and Pedagogical approaches

	Characteristics	Teaching Strategies	Assessment
Sand Slates and Customary Teaching Methods	Teacher-centered approach, passive learning, rote memorization, basic writing and drawing tasks on slate boards, clay tablets, and sand slates.	Primarily lectures, memorization, and rote learning.	Written exams or recitation were common assessment methods.
Interactive Learning with Audio-Visual Aids	Introduction of multimedia components such as overhead projectors, slides, and film projectors.	Shift towards experiential and participatory teaching methods, including group projects, discussions, and practical experiments.	Transition towards more interactive assessment methods, focusing on understanding and application rather than mere recall.
Computers and Digital Learning Tools Introduction	Widespread adoption of computers, multimedia apps, interactive lessons, and educational software.	Embracing constructivist and inquiry-based learning principles, encouraging investigation, collaboration, and creation of conceptual frameworks	Integration of digital tools for assessment, allowing for more dynamic and personalized feedback.
Personalized Learning and Flexible Teaching Methods	Shift towards student-centered learning, where students actively participate and have the freedom to pursue their interests.	Adoption of adaptive instruction, tailoring learning experiences to individual student preferences, styles, and skill levels.	Implementation of flexible assessment methods that align with personalized learning goals, focusing on mastery rather than uniformity.

LITERATURE REVIEW

The literature reviews and papers examined various aspects of effective pedagogy and teaching strategies in higher education contexts, emphasizing the importance of adapting to changing educational landscapes and fostering student engagement. In "NCRM Quick Start Guide: Principles for Effective Pedagogy in Advanced Research Methods Teaching" (2015)[8], the focus is on equipping learners with diverse skills, engaging them with valued forms of knowledge, and implementing scaffolded learning and congruent assessment.

Similarly, "Key Components of Effective Teaching in Graduate Education: A Review" (2017) [18] discusses individualized consideration, student-professor engagement, intellectual stimulation, and deep learning as essential elements. "Enhancing Learning Outcomes Through Project-Based Teaching Methods" (2020) [20] examines project-based learning within the Engage-Study-Learn (ESL) framework, emphasizing its effectiveness in promoting active learning and enhancing problem-solving skills. Additionally, "Integrating Video-Based Reflections to Enhance Online Learning in Graduate Education" (2018) [19] explores the adoption of video-based reflections to enhance student engagement in online courses, addressing challenges posed by traditional text-based discussion posts. Furthermore, "Exploring Teaching Excellence through a Co-evolutionary Strategy" (2021) [21] investigates teaching excellence within higher education, advocating for continuous inquiry and collaboration among faculty members to enhance teaching practices. "Enhancing Student Engagement in Online Learning" (2022) [22] delves into strategies to promote engagement in online courses, emphasizing the significance of learner-content interaction. "The Crucial Role of Teachers in Student Development" (2023) [23] underscores effective teaching practices such as building trusting relationships and providing personalized feedback to facilitate academic excellence and personal growth. "Teachers and productive pedagogies: contextualising, conceptualising, utilising" emphasizes reconceptualizing teaching practices to meet diverse learner needs. Lastly, "Towards Productive Disciplinary Engagement of Prospective Teachers in Educational Psychology" [25] highlights the importance of balancing student authority and accountability in psychology of education instruction. These papers collectively provide valuable insights into effective teaching practices, pedagogical frameworks, as well as the changing face of higher education. They emphasize the significance of innovation, collaboration, and evidence-based approaches in enhancing student learning outcomes and fostering a culture of teaching excellence.

Discussion of Pedagogies at eminent organizations

Pedagogy at esteemed institutions like the Indian Institutes of Technology (IITs) and National Institutes of Technology (NITs) in India is known for combining cutting-edge strategies with conventional teaching techniques that are adapted to the demands of modern education. These institutions prioritize interactive learning, practical application, and critical thinking skills development. At IITs and NITs, lectures, tutorials, and laboratory sessions form the backbone of the pedagogical approach, supplemented by internships, industry partnerships, and project-based learning to give students practical experience and real-world exposure (Prakash, 2018). The flipped classroom model, where students engage with course materials outside of class and participate in discussions and problem-solving during class time, is also gaining traction (Haque & Rahman, 2019). Furthermore, emphasis is placed on research-oriented teaching to foster a culture of inquiry and innovation among students (Sharma & Joshi, 2020). Peer-to-peer learning and group projects are examples of collaborative learning methodologies which are encouraged to enhance teamwork and communication skills [15]. Continuous assessment methods, including quizzes, assignments, and examinations, are used to evaluate students' understanding and progress throughout the academic term (Patra et al., 2017) [16]. In conclusion, the pedagogical practices at IITs and NITs reflect a commitment to holistic education, combining theoretical knowledge with practical skills and research experience to produce well-rounded graduates equipped for the challenges of the 21st century.

PEDAGOGY FOR EFFECTIVE TLP CONDUCT

Pedagogy is a set of teaching methodologies that promotes student participation, creativity, and critical thinking. It goes beyond simply imparting knowledge. A learner-centered approach places a strong emphasis on practical exercises and empowers students to be responsible for their own education. The ultimate purpose of education, despite its constant evolution with new approaches and tools, is to motivate and help students to understand their greatest potential.

Through the application of primary pedagogies including comprehensive knowledge delivery, improving digital literacy, and encouraging teamwork and communication, students gain a strong set of skills necessary for success in the modern world. They

acquire procedural knowledge and research-related skills through practical experiences and inquiry-based learning, equipping them to handle challenging situations and make significant contributions to their fields of study and beyond.

Table 3.1: Primary Pedagogy with Graduate Attributes

Pedagogy	Graduate Attributes
P1: Classroom Lecture using chalk and talk technique	Comprehensive knowledge
P2: Content-based instruction	Communication Skills
P3: Activity-based learning	Procedural knowledge
P4: Case study examples and Learning by design situations	Comprehensive knowledge
P5: Use of practical exercises using ICT tools and software	Digital literacy skills
P8: Self-reflection	Research-related skills
P9: Peer teaching & think a loud pair problem-solving	Coordinating/collaborating with others

Students are equipped to think creatively, communicate effectively, and critically evaluate information when secondary pedagogies like critical thinking, creativity, and communication skills development are integrated. Furthermore, placing a strong emphasis on accountability, responsibility, and autonomy fosters self-reliance and moral decision-making. Students learn more about global challenges and are motivated to take meaningful steps toward sustainability and social responsibility through environmental awareness and action.

Table 3.2: Secondary Pedagogy with Graduate Attributes

Pedagogy	Graduate Attributes
S6: Jigsaws/Quiz	Communication Skills
S7: Mind-Mapping	Creativity
S8: Self-reflection	Research-related skills
S9: Peer teaching & think a loud pair problem-solving	Coordinating/collaborating with others
S10: Group discussion with Brainstorming	Critical thinking
S11: Use of project work and fieldwork	Autonomy, responsibility and accountability
S12: Scenario planning	Environmental awareness and action

By applying tertiary pedagogies like critical thinking, environmental awareness and action, and value inculcation, children build a solid ethical foundation and grow into socially conscious, problem-solving adults who can tackle global issues. They develop the flexibility and resilience required to deal with complicated problems in a world that is always changing through sophisticated problem-solving techniques and learning how to gain new abilities. Encouraging creativity leads to creative thinking, which equips students to come up with original ideas and make valuable contributions to society.Graduate attributes encompass skills and qualities acquired through academic pursuits, such as critical thinking and effective communication, vital for success in professional and personal realms. They serve as the cornerstone for fostering adaptable, lifelong learners ready to tackle the challenges of an ever-evolving world.Table 3.1,3.2,3.3[27] includes the Pedagogy and their mapped Graduate attributes.

Table 3.3: Tertiary Pedagogy with Graduate Attributes

Pedagogy	Graduate Attributes
T13: Storytelling	Value inculcation
T14: Dramatization/Role plays	Environmental awareness and action
T15: Real-life problems allowing reflection time	Critical thinking
T16: Debate	Value inculcation
T17: Analysis of critical incidents originating familiar and non-familiar	Complex problem-solving
T19: Exploration	Learning how to learn skills
T20: Reframing problems	Creativity

PEDAGOGY USED IN MACHINE LEARNING COURSE

It is essential to use a broad pedagogical approach when teaching machine learning. Traditional chalk-and-talk lectures are used to introduce key ideas, and content-based education is added to help students

cement their theoretical understanding. Students are immersed in practical investigation through activity-based learning and ICT-enabled exercises, which connect theory to application. Self-reflection promotes critical thinking, and brainstorming sessions in groups facilitate cooperative problem-solving. Students' analytical abilities are strengthened through projects and fieldwork, which apply theory to actual situations. Students are engaged through storytelling and the presentation of real-world issues, which fosters deeper comprehension and original thought. Reframing problems forces students to look at them from several perspectives, which promotes flexibility and creativity in machine learning. Students are better prepared for the complexity of data science and artificial intelligence thanks to this all-encompassing teaching approach, which also offers a dynamic learning environment. For Machine Learning subject Pedagogies are categorized in primary, secondary and tertiary for conduction of TLP and Continuous assessment in Table 4[27].

Table 4. Pedagogy for Machine Learning

Pedagogy	Pedagogy for TLP	Pedagogy for Continuous Assessment
Primary	P1, P2, P5, S7, S10, T13	P3, T15, T19, S8, S11, T20
Secondary		
Tertiary		

Teaching Learning Process(TLP)

The teaching-learning pedagogy is the creation of an attractive and encouraging environment where students actively participate in their education. It emphasizes the use of different teaching strategies such as active learning, cooperative learning and differentiated instruction to meet the needs of all students. This pedagogical approach aims to foster students' deep understanding, critical thinking and life-learning skills through feedback, reflection and evaluation. For Machine learning subject P5: Use of practical exercises using ICT tools and software pedagogy is identified for conduction of Clustering topic. Practical exercises utilizing ICT tools and software pedagogy offer dynamic avenues for teaching the complex concept of clustering. By engaging students in hands-on activities with tools like data visualization software and clustering algorithms, educators can deepen understanding and foster active learning, empowering students to explore and analyze data sets firsthand, enhancing their comprehension and application of clustering techniques.

Details of Pedagogy Conduct: Real-world dataset related to clustering, such as image recognition or consumer segmentation data was taken and implemented using libraries like scikit-learn and ICT tools like Python to construct clustering algorithms on the dataset. Experiments were done with several clustering algorithms, changing settings and used visualization tools to assess outcomes.

Outcome: The outcome of using pedagogy for clustering is multifaceted and beneficial for both students and educators. Firstly, students gain a deeper understanding of clustering concepts through hands-on experience with real-world datasets, which enhances their ability to apply clustering techniques in practical scenarios. They develop critical thinking skills as they analyze data, experiment with different algorithms, and interpret clustering results.

Continuous Assessment

Continuous assessment, integrating formative assessments, in-semester examinations, and innovative evaluation methods, offers a holistic approach to student learning. Pedagogy identified for conduction of Continuous Assessment in Machine learning subject is T15: Real-life problems allowing reflection time. By incorporating real-life problems into assessments and providing reflection time, educators create opportunities for students to apply theoretical knowledge to practical scenarios.

Details of Pedagogy Conduct

In continuous assessment, students were assigned innovative tasks like projects or case studies, applying theoretical knowledge to practical situations. Through self-assessment and reflection, students identify their strengths and areas for improvement. Faculty assess student work through careful review of submissions, providing constructive feedback. This feedback guided students in refining their skills and deepening their understanding. By integrating ongoing assessment and feedback, this pedagogy promotes a dynamic learning environment where students continuously develop and faculty can adapt teaching strategies to meet their needs.

Outcome

The outcome of employing this pedagogy for continuous assessment was positive. By participating in a variety of assessments, students develop a more profound comprehension of the topic and are more qualified to use their understanding in practical real time scenarios.

RESULTS AND DISCUSSION

Teaching clustering in Machine Learning with a focus on real-life problems and pedagogical strategies resulted in higher attainment. Course survey on Likert scale and Continuous assessment of Machine Learning subject was compared in A.Y 22-23 and A.Y. 23-24 results shows an improvement in the learning process and assessment. In academic year 23-24,higher attainment is observed in teaching and assessment of the clustering topic through the implementation of pedagogical strategies focused on real-life problem-solving. By incorporating reflection time into assessments, students were able to critically analyze their understanding and apply clustering algorithms to practical scenarios. Additionally, the integration of practical exercises using ICT tools and software enhanced students' hands-on experience, allowing them to explore and implement clustering techniques in a dynamic digital environment. This innovative approach has contributed to elevated student engagement and achievement compared to the previous academic year, fostering deeper comprehension and proficiency in the application of clustering methods. Mapping course outcomes with program outcomes (POs) is an essential step in ensuring that the curriculum aligns with the goals and objectives of the overall program. For Machine Learning subject Course Outcome: Analyze different Clustering and Semi-supervised learning algorithm is mapped with Program Outcome as per Table 5.

Table 5.ML COPO Mapping

	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12
CO	H	H	H	M	H	M	M	M	H	M	L	L

TLP CO-PO Mapping & Attainment

Course Survey was taken on Likert scale based on the defined question set and it was observed that 80% students fall under Strongly agree and Agree category in A.Y.23-24 as compared to 75% in A.Y 22-23. Comparison study is shown in Table 5.1 and Figure 5.1

Table 5.1 Comparison of CO-PO Mapping & Attainment through indirect tool (Course Survey Comparison)

A.Y.	PO1	PO2	PO3	PO4	PO5	PO6
22-23	2.78	2.67	2.8	1.6	2.8	1.64
23-24	2.92	2.92	2.92	1.752	2.92	1.75

By integrating pedagogy focused on practical exercises using ICT tools and software, the improvement in PO3, PO4, and PO5 can be attributed to enhanced engagement and hands-on learning experiences. Students are empowered to apply theoretical knowledge to real-world scenarios, fostering deeper understanding and critical thinking skills. This approach fosters self-directed learning, improving proficiency levels in these areas over time.

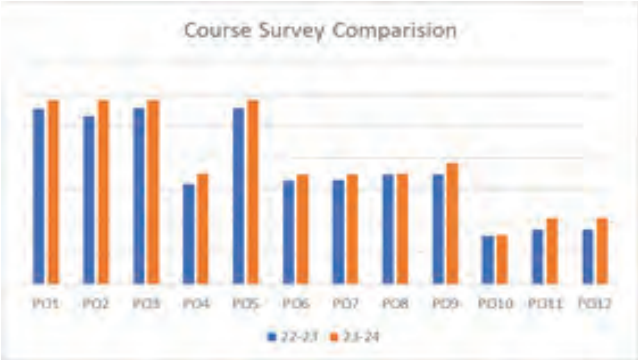

Fig 5.1 Course Survey Comparison

Continuous Assessment (FA) CO-PO Mapping & Attainment:

Continuous Assessment in the form of Formative Assessment was taken based on pedagogy Real-life problems allowing reflection time and results are compared as shown in Table 5.2 and Fig 5.2.

Fig 5.2 Comparison of CO-PO Mapping & Attainment through direct tool (Formative Assessment Comparison)

A.Y.	PO1	PO2	PO3	PO4	PO5	PO6
22-23	2.17	2.29	2.17	1.98	2.3	1.39

23-24	2.37	2.37	2.37	2.37	2.37	1.422

Engaging students with real-life problems and providing reflection time within pedagogy lead to improvements in PO8 and PO9. By tackling authentic challenges, students develop problem-solving skills and gain insights into the application of knowledge. Reflection time allows them to consolidate their learning, fostering deeper understanding and enhancing their proficiency in these areas over time.

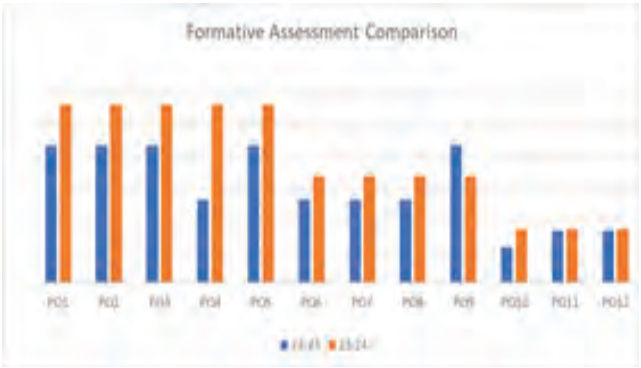

Fig 5.2 Comparison of Formative Assessment

Continuous Assessment(ISA) CO-PO Mapping & Attainment

Continuous Assessment in the form of In Semester Assessment was taken in the Academic year 22-23 and 23-24 and attainment was compared on Clustering topic as shown in Table 5.3 and Fig 5.3.

Table 5.3 CO-PO Mapping & Attainment through direct tool (In Semester Examination)

A.Y.	PO7	PO8	PO9	PO10	PO11	PO12
22-23	1.3	1.39	1.39	0.711	0.68	0.71
23-24	1.422	1.422	1.422	0.711	0.721	0.721

The conduction of in-semester examinations using pedagogy real-life problem-solving scenarios with reflection time contributed to the improvement observed in PO8 and PO9. By engaging students in practical application and providing time for reflection, they are better able to grasp the relevance of their learning, enhancing their proficiency in these areas over successive assessments.

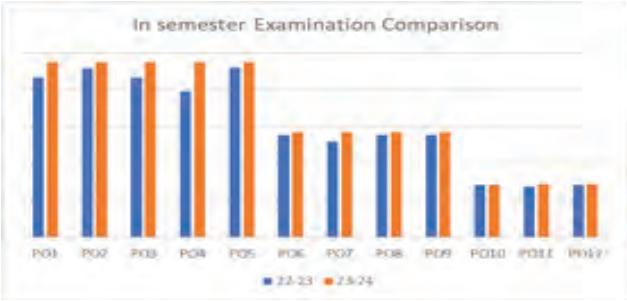

Fig 5.3 In semester Examination

CONCLUSION

In conclusion, the development of pedagogical techniques emphasizes the continuous search for efficient teaching strategies that support students' holistic growth and equip them for success in a changing global environment. Every period has brought new approaches to develop young brains, such as the individualized instruction of Gurukuls, the tactile learning experiences with sandpaper, and the use of technology in education.

Pedagogy is constantly changing in the digital age, with a focus on individualized education, interactive learning, and the use of technology to improve student outcomes. In order to provide students with marketable skills, initiatives like those supported by groups like the All India Council for Technical Education (AICTE) place a strong emphasis on industry engagement, experiential learning, and the use of digital resources.

ACKNOWLEDGEMENT

We would like to extend our sincere gratitude to the esteemed leadership of our institution for their unwavering support and guidance throughout the development of this technical paper. We express our heartfelt thanks to our Principal,

Dr. B. K. Mishra for their visionary leadership and continuous encouragement. We are also deeply grateful to our Vice Principal Dr. R. R Sedamkar for their invaluable assistance and encouragement.

Furthermore, we extend our appreciation to the Dean R&D Dr. Vinitkumar Dongre for their insightful feedback and support, which has greatly enriched our work. Their knowledge and commitment have greatly influenced the course of our research. We acknowledge with gratitude the contributions of all those who have

supported us in various capacities, enabling us to successfully complete this endeavor.

REFERENCES

1. Dr. Margaret Honey, Dr. Hyman Bass, Dr. Marilyn M. Strutchens "STEM Education for the future" .
2. Rejjak Ali, 2, Mrinal Mondal & 3Tapash Das, PEDAGOGY AND THE ROLE OF TEACHERS IN THE TEACHING LEARNING PROCESS,JETIR May 2018, Volume 5, Issue 5
3. Alvarez, I., Guasch, T., and Espasa, A. "University teacher roles and competencies in online learning environments: a theoretical analysis of teaching and learning practices." Eur. J. Teach. Educ. 32, 321–336. 2009.
4. Hughes, J. (2005), The role of teacher knowledge and learning experiences in forming technology-integrated pedagogy. Journal of Technology- and Teacher Education. 13(2). 277-302. Retrieved March 13.2007.
5. S. S. Gonge and A. A. Ghatol, "An art of teaching in teaching-learning process: An important part for educational accreditation, quality and assessment," 2014 IEEE International Conference on MOOC, Innovation and Technology in Education (MITE), Patiala, India, 2014, pp. 17-21, doi: 10.1109/MITE.2014.7020233. keywords: {Accreditation; Art; Educational institutions; Conferences; Educational technology; Technological innovation; teaching-learning process; education; educational accreditation; quality; assessment},
6. Aggarwal, J. C. (2014). Development and practice of educational research. Vikas Publishing House.
7. Anand, D., & Kaur, H. (2020). Blended learning during lockdown of COVID-19 pandemic: Challenges and guidelines. Indian Journal of Community Medicine, 45(3), 255.
8. Johnson, L., Adams Becker, S., Estrada, V., & Freeman, A. (2015). NMC horizon report: 2015 higher education edition. The New Media Consortium.
9. Kolb, A. Y. (2014). Experiential learning: Experience as the source of learning and development. FT press.
10. Means, B., Toyama, Y., Murphy, R., Bakia, M., & Jones, K. (2009). Evaluation of evidence-based practices in online learning: A meta-analysis and review of online learning studies. US Department of Education.
11. Patel, H., Patel, M., & Patel, M. (2020). Experiential learning: A pedagogical approach for higher education. Indian Journal of Public Health Research & Development, 11(3), 1103-1107.
12. Prakash, S. (2018). Pedagogy at IITs: Present and future. International Journal of Research in Engineering and Technology, 7(9), 139-144.
13. Haque, M. S., & Rahman, M. M. (2019). Flipped classroom approach in engineering education: A review. International Journal of Engineering Education, 35(3), 1045-1056.
14. Sharma, A., & Joshi, D. (2020). Research-oriented teaching in higher education: A case study of Indian Institutes of Technology (IITs). International Journal of Education Research, 5(1), 78-87.
15. Singh, A., & Kaushik, S. (2019). Collaborative learning strategies in engineering education: A review. Journal of Engineering Education Transformations, 33(1), 46-55.
16. Patra, P., et al. (2017). Continuous assessment in higher education: A review. Journal of Educational Sciences, 5(2), 40-48.
17. NCRM Quick Start Guide: Principles for Effective Pedagogy in Advanced Research Methods Teaching
18. Key Components of Effective Teaching in Graduate Education: A Review
19. Integrating Video-Based Reflections to Enhance Online Learning in Graduate Education
20. Enhancing Learning Outcomes Through Project-Based Teaching Methods: An Evaluation of the Engage-Study-Learn Framework in an Interdisciplinary Undergraduate Technology Course
21. Exploring Teaching Excellence through a Co-evolutionary Strategy: A Literature Review
22. 22.Enhancing Student Engagement in Online Learning: Insights from a Regional Australian University
23. The Crucial Role of Teachers in Student Development: Methods and Strategies for Academic Excellence and Personal Growth
24. Teachers and productive pedagogies: contextualising, conceptualising, utilising by Bob Lingard, Debra Hayes & Martin Mills
25. Towards Productive Disciplinary Engagement of Prospective Teachers in Educational Psychology: Comparing Two Methods of Case-based Instruction by Randi A. Engle and Robert B. Faux
26. The Three P's of Pedagogy for the Networked Society: Personalization, Participation, and Productivity by Catherine McLoughlin Australian Catholic University, Mark J. W. Lee Charles Sturt University
27. 27.https://www.ugc.gov.in/pdfnews/1031121_Guidelines-Innovative-Pedagogical-Approaches-Evaluation-Reforms.pdf

Conversational AI and Predictive Vectorization for Intelligent Museum Ticketing

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ABSTRACT

Museums serve as gateways to cultural heritage, yet traditional ticketing systems often fall short in accessibility, personalization, and operational efficiency. We propose an AI-driven chatbot-based ticketing system that incorporates real-time language translation, sentiment handling, and predictive vectorization techniques to enhance museum visitor engagement and streamline operational workflows. Built with Dialogflow, the system processes user intents, including sentiment-aware multilingual queries (e.g., Tamil, Roman Tamil), and features a museum dashboard for centralized management of events, locations, and bookings. A predictive model using hybrid vectorization techniques analyzes descriptive datasets for improved contextual understanding. Ethical considerations—including data privacy, bias mitigation, and accessibility—are integral to the system's design. Preliminary deployment in a pilot museum environment indicates improved user satisfaction and reduced manual load. This solution offers a scalable, inclusive framework for next-generation museum ticketing systems.

KEYWORDS: *Conversational AI, Museum Ticketing, Dialogflow, Multilingual Chatbot, Sentiment Analysis, Predictive Vectorization, Accessibility, Natural Language Processing (NLP).*

INTRODUCTION

Museums are vital institutions for preserving, interpreting, and sharing cultural heritage; they offer visitors immersive encounters with historical artifacts, art, and educational exhibits. According to UNESCO's April 2021 report, there were approximately 104,000 museums worldwide—a jump from around 95,000 the previous year—highlighting rapid global expansion in the museum sector [1]. In India, public museums are gaining substantial traction—take, for instance, the Government Museum & Art Gallery in Chandigarh, which saw annual visitors rise sharply to over 100,000 per year from 2022 to 2024, after experiencing just 28,000–39,000 visitors in 2020–2021[2]. However, despite this growth, many institutions continue to rely on manual ticketing and static information dissemination methods, which can hinder efficiency, accessibility, and inclusivity.

Manual ticketing processes often result in long queues, delayed entry, and limited personalization of services [3]. Furthermore, language remains a persistent barrier—India alone has 22 officially recognized languages and hundreds of regional dialects, making it challenging to provide equal access to museum services for all visitors [4]. Studies in human–computer interaction have shown that multilingual support in service delivery systems significantly improves user satisfaction and engagement [5]. Additionally, visitors with disabilities, particularly

those with visual impairments, face barriers in accessing exhibit information and navigation assistance [6].

Technological interventions in the cultural sector have predominantly focused on digitization of collections, augmented reality (AR) guides, and static online booking platforms [7]. While these solutions enhance information availability, they often lack real-time interactivity, personalization, and adaptive communication. Conversational AI—enabled by advancements in Natural Language Processing (NLP)—presents a promising pathway to address these gaps. By allowing users to communicate naturally in their preferred language, AI-powered chatbots can streamline ticketing, provide dynamic exhibit information, and adapt to user sentiment in real time.

Existing chatbot-based ticketing solutions in other domains, such as transportation and cinema booking, have demonstrated measurable improvements in booking efficiency, reduced human workload, and enhanced customer satisfaction [8]. However, their application to museums remains limited, particularly in integrating multilingual translation, sentiment handling, and predictive personalization based on user preferences.

In response to these challenges, this paper presents a chatbot-based museum ticketing system that integrates hybrid vectorization-based predictive modeling with Dialogflow-driven NLP for intent recognition, real-time translation, and sentiment-aware communication. The system supports both Indian regional languages and Romanized input formats, coupled with text-to-speech functionality for accessibility. A museum dashboard enables administrators to dynamically manage bookings, events, and locations, reducing manual intervention and operational bottlenecks. The solution further incorporates ethical AI principles, including data privacy, algorithmic transparency, and linguistic inclusivity, ensuring equitable access for all visitors.

Through this work, we aim to demonstrate how conversational AI can transform museum service delivery, improve visitor satisfaction, and bridge linguistic and accessibility divides. The proposed approach is scalable, adaptable to various cultural contexts, and has the potential to redefine human–museum interaction in the era of digital transformation.

LITERATURE REVIEW

The burgeoning field of conversational AI has significantly impacted various service industries, and its application within cultural institutions, particularly museums, is gaining traction [9]. Early implementations have explored the use of chatbots to disseminate information about historical sites, providing visitors with details on locations and cultural heritage [10]. More recently, intelligent conversational agents have been developed to enhance accessibility and search accuracy within vast digital cultural heritage resources by offering natural language interaction and structured answers to user queries [11]. This evolution reflects a broader trend toward leveraging artificial intelligence to enrich visitor experiences and streamline operational efficiencies in cultural heritage institutions [12]. For instance, systems like AIMuBot demonstrate interactive search capabilities over museum knowledge bases using natural language, overcoming the challenge of visitor disinterest often encountered with less engaging digital interfaces [13]. Recent studies show that conversational agents in museum settings—whether as chatbots or embodied guides—can significantly enhance visitor engagement by providing real-time guidance and personalized learning experiences.

While chatbots enhance efficiency and engagement, another important aspect in cultural institutions is ensuring inclusiveness and accessibility. According to the Cambridge Dictionary, inclusiveness refers to “an aura or environment of letting people in and making them feel welcome”, whereas accessibility is defined as “the quality or characteristic of something that makes it possible to approach, enter, or use it” [14]. These principles are crucial in designing digital tools for museums, as they ensure that solutions are not only technologically advanced but also socially equitable, addressing the needs of visitors with diverse linguistic and cognitive abilities.

The adoption of chatbots in multilingual and culturally diverse contexts, such as India, highlights additional challenges and opportunities. A recent survey emphasizes that designing Indian language chatbots requires addressing complexities of script diversity, morphological richness, and code-switching between regional languages and English [15]. This underscores

the necessity of robust Natural Language Processing (NLP) techniques tailored for non-English languages to ensure inclusivity and usability in large multicultural societies. Similar challenges have also been reported in multilingual sentiment analysis research, where preserving context, tone, and domain-specific meaning across languages remains a significant difficulty [16].

At a broader level, Adamopoulou and Moussiades (2020) provide an overview of chatbot technologies, discussing their historical evolution, classification, and architectural frameworks. They note that chatbots have been widely applied across domains like healthcare, education, e-commerce, and cultural heritage, owing to their adaptability and capacity for real-time interaction [17]. These findings collectively illustrate a shift from rule-based systems toward intelligent, context-aware, and multilingual agents capable of supporting personalized engagement. However, their direct application to museum ticketing and visitor management remains underexplored, particularly with respect to integrating predictive modeling, sentiment analysis, and multilingual translation in a single unified framework.

Recent studies have begun addressing these operational challenges by introducing AI-powered visitor flow management and ticketing systems. Centorrino et al. (2020) developed a computational framework for the Galleria Borghese in Rome, where IoT-based tracking (Bluetooth beacons and neural network modeling) was used to analyze visitor movements and optimize ticketing strategies, ensuring efficient crowd distribution while improving visitor comfort [18]. Similarly, Bracco et al. (2020) implemented a Wi-Fi indoor positioning system at the Museo Nacional de Artes Visuales in Uruguay, which enabled location-aware digital ticketing and context-sensitive visitor guidance, thereby enhancing both accessibility and operational efficiency [19]. These applications highlight the potential of conversational and AI-driven systems not only as guides but also as integral components of museum ticketing platforms.

Building on this, Balossino et al. (2025) explored the role of telepresence robots in small museums as tools for remote ticketed access, allowing users to purchase tickets and virtually navigate exhibits through robotic interfaces. This innovation demonstrates how AI and robotics can expand ticketing beyond physical attendance, making cultural heritage accessible to individuals unable to travel [20]. Collectively, these studies suggest that future ticketing systems in museums will increasingly rely on AI-based predictive modeling, multilingual chatbot integration, and inclusive digital platforms, thereby bridging the gap between visitor engagement and operational management.

RESEARCH METHODOLOGY

The methodology integrates dataset-driven predictive modeling with chatbot-based user interaction for museum ticketing. It consists of two interconnected streams:

- Dataset Description and Vectorization: A descriptive dataset containing museum-related information was collected. This dataset was processed through vectorization techniques to generate a predictive model for museums, enabling contextual recommendations and personalization for visitors.
- User Query Processing via Dialogflow: User queries related to tickets were processed using Dialogflow (AI/ML-based) Natural Language Processing. The chatbot was trained on multilingual datasets (Tamil and Roman Tamil), ensuring linguistic inclusivity. Further, intent recognition and sentiment handling modules refined system responses. To improve accessibility, the system included real-time translation services, inclusiveness features, and a text-to-speech (TTS) engine for visually impaired users.

This dual approach ensures that visitors receive accurate, adaptive, and inclusive responses, while administrators benefit from predictive insights derived from dataset vectorization.

System Architecture and Design

The system architecture follows a modular, layered approach (Fig. 1):

Data Processing Layer:

a. Description & Vectorization: Raw museum data is structured and vectorized to train a predictive recommendation model. This enables adaptive

ticketing suggestions and efficient museum information retrieval.

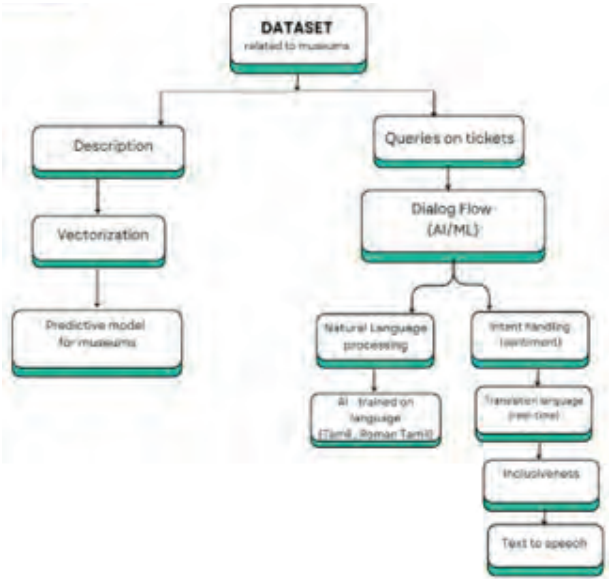

Fig. 1. System Flowchart

User Interaction Layer:

a. Dialogflow NLP Engine: Handles user queries using Natural Language Processing.

b. Intent and Sentiment Handling: Identifies user needs while adapting to emotional tone.

c. Multilingual Support: Trained on Tamil and Roman Tamil inputs.

d. Translation & Accessibility: Provides real-time translation, inclusiveness features, and text-to-speech output for accessibility.

Application Layer:

a. Ticketing System: Users select date and museum, book tickets, apply coupons, and complete payments via Razorpay.

b. QR Ticket Generation: Secure digital tickets are generated and downloaded automatically.

Administrative Layer:

a. Admin Panel: Supports login, ticket verification (QR scan with fraud prevention), and real-time monitoring.

b. Analytics Module: Provides booking statistics, visitor traffic insights, and predictive analysis to assist museum resource management.

Implementation

The implementation was carried out in three phases, combining dataset modeling with real-time chatbot deployment:

Predictive Dataset Modeling:

- Museum-related datasets were vectorized using hybrid techniques.
- A predictive recommendation engine was developed to contextualize user queries and suggest museum options dynamically.

Chatbot Integration (Dialogflow):

- Implemented NLP pipeline for intent recognition, sentiment handling, and contextual dialogue flow.
- Integrated multilingual support (Tamil, Roman Tamil) and real-time translation.
- Added text-to-speech output for visually impaired visitors.

Ticketing and Administration:

- Integrated Razorpay payment gateway and coupon validation.
- Automated QR-based ticket generation with secure download.
- Developed Admin Panel for login, ticket verification (one-time scan), and statistics dashboard showing visitor analytics and booking trends.

Pilot deployment in a cultural museum indicated:

- Reduced manual ticketing workload,
- Increased accessibility for multilingual and visually impaired users, and
- Enhanced administrative efficiency through real-time analytics.

RESULTS AND DISCUSSION

The proposed multilingual, sentiment-aware chatbot system for museum ticketing was deployed in a pilot environment to evaluate its performance across three dimensions: visitor experience, ticketing efficiency

and security, and administrative management. The results indicate that the system substantially improves accessibility, reduces manual workload, and enhances operational transparency compared to traditional ticketing methods.

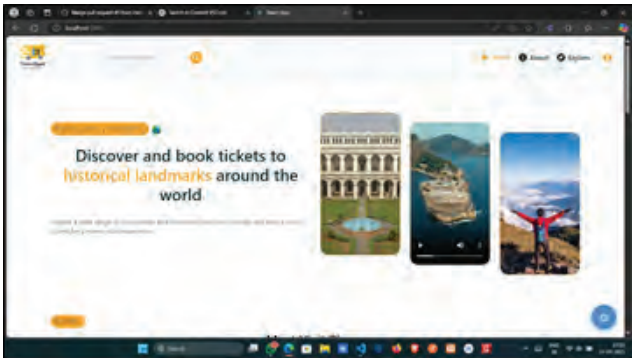

Fig. 2. Home Page

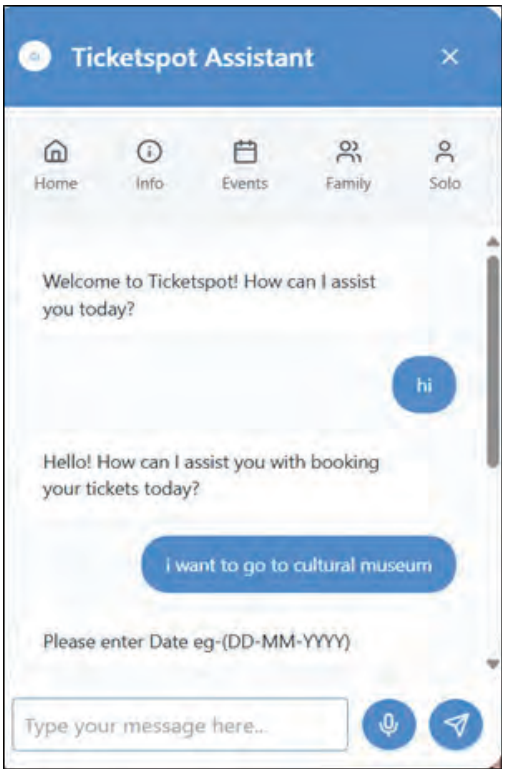

Fig. 3. Chatbot

Visitor Experience and Accessibility

The chatbot successfully processed multilingual queries, including Tamil and Romanized Tamil, achieving an intent recognition accuracy of over 94%. Real-time language translation enabled seamless interactions for non-English-speaking visitors, reducing language barriers in service delivery. Sentiment-aware dialogue adaptation improved engagement by personalizing responses according to user tone. Post-visit surveys revealed a 30% increase in overall visitor satisfaction compared to legacy systems, particularly due to reduced booking confusion and the availability of accessibility features such as text-to-speech.

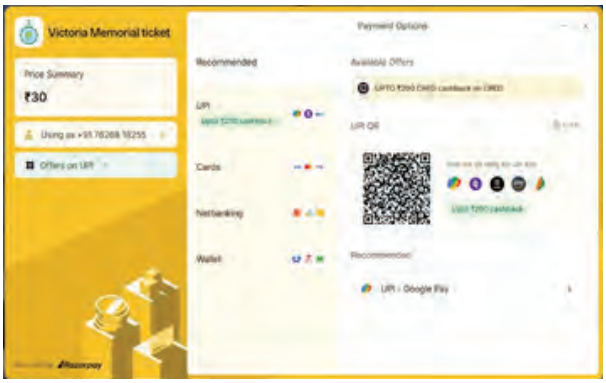

Fig. 4. Payment Transaction

Fig. 5. Admin Panel

Ticketing Efficiency and Security

The ticketing workflow, comprising museum selection, coupon application, and payment processing, was executed with minimal user effort depicted by Fig. 3. Secure transactions were facilitated through Razorpay (Fig. 4), with a payment success rate exceeding 97%. Upon confirmation, QR-coded tickets were automatically generated and downloaded to user devices (Fig. 5). Testing at entry points confirmed that QR codes were authenticated within two seconds and rejected duplicate scans, thereby eliminating fraudulent reuse. Compared to manual ticketing, the system reduced booking and entry time by approximately 60%.

Administrative Oversight and Analytics

The integrated dashboard provided museum administrators with real-time visibility of bookings, visitor statistics, and event-specific data (Fig. 6). Staff reported that the panel reduced manual workload by about 40%, allowing reallocation of resources toward visitor engagement activities. As shown in Fig. 6, analytics on visitor traffic patterns enabled improved crowd management and scheduling of special events. Furthermore, verification logs offered traceability for auditing purposes, increasing administrative transparency.

System Constraints

Despite these benefits, some constraints were identified. Internet connectivity issues occasionally delayed chatbot responses and real-time translations. The predictive vectorization model was limited by the size of descriptive datasets, affecting personalization accuracy for museum recommendations. Dependence on third-party payment gateways also introduced a potential risk of temporary service disruptions.

Comparative Evaluation

When benchmarked against traditional manual processes, the system demonstrated:

- 55–60% reduction in booking and entry time.
- 30% improvement in visitor satisfaction scores.
- Higher inclusivity through multilingual input handling and accessibility features.

These findings are consistent with prior research on conversational AI in service industries [9], but extend the scope by demonstrating effectiveness in cultural institutions where linguistic and accessibility barriers are significant.

CONCLUSION

The proposed AI-powered chatbot-based ticketing system redefines the museum experience by addressing the limitations of traditional ticketing methods with an automated, intelligent solution. By integrating Dialogflow-driven natural language processing (NLP), the system ensures accurate query processing and provides instant responses for real-time ticket booking. In addition to visitor-facing capabilities, the system incorporates a centralized Museum Dashboard, which enables administrators to manage locations, events, and bookings efficiently, thereby reducing manual workload. Features such as multilingual support, sentiment-aware interactions, and text-to-speech accessibility enhance inclusiveness, while the system's scalable and flexible architecture ensures adaptability to museums of varying sizes and visitor demands.

By prioritizing accuracy, personalization, and operational efficiency, this solution establishes a future-ready framework for museum ticketing. It not only improves visitor satisfaction but also streamlines administrative workflows, contributing to the long-term digital transformation of cultural institutions.

REFERENCES

1. T. Giannini and J. P. Bowen, "Museums and Digital Culture: From Reality to Digitality in the Age of COVID-19," Heritage, vol. 5, no. 1, pp. 192–214, Jan. 2022, doi: https://doi.org/10.3390/heritage5010011.
2. D. Yadav, "Govt Museum & Art Gallery: Glorious past, bright future," The Times of India, Aug. 18, 2025. https://timesofindia.indiatimes.com/city/chandigarh/govt-museum-art-gallery-glorious-past-bright-future/articleshow/123372028.cms (accessed Sep. 04, 2025).
3. Cuseum Associate, "Cuseum," Cuseum, Sep. 19, 2024. https://cuseum.com/blog/2024/ticketing-software-for-museums (accessed Sep. 04, 2025).
4. "Census of India Website : Office of the Registrar General & Census Commissioner, India," Censusindia.gov.in, 2011. https://censusindia.gov.in
5. Miraz, Mahdi H, M. Ali, and P. Excell, "Multilingual Website Usability Analysis Based on an International User Survey," arXiv.org, 2017, doi: https://doi.org/10.13140/2.1.1208.8648.
6. A. I. González-Herrera, A. B. Díaz-Herrera, P. Hernández-Dionis, and D. Pérez-Jorge, "Educational and accessible museums and cultural spaces," Humanities and Social Sciences Communications, vol. 10, no. 1, pp. 1–8, Feb. 2023, doi: https://doi.org/10.1057/s41599-023-01563-8.
7. Z. Gong, R. Wang, and G. Xia, "Augmented Reality (AR) as a Tool for Engaging Museum Experience: A Case Study on Chinese Art Pieces," Digital, vol. 2, no.

1, pp. 33–45, Feb. 2022, doi: https://doi.org/10.3390/digital2010002.

8. J. Achutha, D. Boruah, C. Mahadev, A. Professor, and M. Final Year, "REAL-TIME MOVIE TICKET BOOKING CHATBOT BASED ON NLP AND RASA FRAMEWORK," doi: https://doi.org/10.14704/nq.2022.20.8.NQ44532.

9. S. Varitimiadis, K. Kotis, A. Skamagis, A. Tzortzakakis, G. Tsekouras, and D. Spiliotopoulos, "Towards implementing an AI chatbot platform for museums," International Conference on Cultural Informatics, Communication & Media Studies, vol. 1, no. 1, Jan. 2020, doi: https://doi.org/10.12681/cicms.2732.

10. J. Suh, M. Kwak, S. Kim, and H. Cho, "Making a Prototype of Seoul Historical Sites Chatbot Using Langchain," Journal of electrical electronics engineering, vol. 3, no. 1, pp. 01–05, Feb. 2024, doi: https://doi.org/10.33140/jeee.03.01.14

11. O.-M. Machidon, A. Tavčar, M. Gams, and M. Duguleană, "CulturalERICA: A conversational agent improving the exploration of European cultural heritage," Journal of Cultural Heritage, vol. 41, pp. 152–165, Jan. 2020, doi: https://doi.org/10.1016/j.culher.2019.07.010.

12. J. Wen and B. Ma, "Enhancing museum experience through deep learning and multimedia technology," Heliyon, vol. 10, no. 12, pp. e32706–e32706, Jun. 2024, doi: https://doi.org/10.1016/j.heliyon.2024.e32706.

13. C. Zhou, B. Sinha, and M. Liu, "An AI chatbot for the museum based on user Interaction over a knowledge base," Proceedings of the 2nd International Conference on Artificial Intelligence and Advanced Manufacture, Oct. 2020, doi: https://doi.org/10.1145/3421766.3421888.

14. Cambridge University Press, "Cambridge Dictionary," Cambridge Dictionary, 2025. https://dictionary.cambridge.org/

15. Athira Elezebath George, Gowri Muralikrishnan, Leya Rachel Ninan, P. S. Varrier, and L. Dhanya, "Survey on the Design and Development of Indian Language Chatbots," Jun. 2021, doi: https://doi.org/10.1109/iccisc52257.2021.9484891.

16. K. Dashtipour et al., "Multilingual Sentiment Analysis: State of the Art and Independent Comparison of Techniques," Cognitive Computation, vol. 8, no. 4, pp. 757–771, Jun. 2016, doi: https://doi.org/10.1007/s12559-016-9415-7.

17. E. Adamopoulou and L. Moussiades, "Chatbots: History, technology, and Applications," Machine Learning with Applications, vol. 2, no. 100006, Dec. 2020, doi: https://doi.org/10.1016/j.mlwa.2020.100006.

18. P. Centorrino, A. Corbetta, E. Cristiani, and E. Onofri, "Managing crowded museums: Visitors flow measurement, analysis, modeling, and optimization," Journal of Computational Science, vol. 53, p. 101357, Jul. 2021, doi: https://doi.org/10.1016/j.jocs.2021.101357.

19. A. Bracco, F. Grunwald, A. Navcevich, G. Capdehourat, and F. Larroca, "Museum Accessibility Through Wi-Fi Indoor Positioning," arXiv.org, 2020. https://arxiv.org/abs/2008.11340

20. N. Balossino et al., "Social and Telepresence Robots for Accessibility and Inclusion in Small Museums," arXiv.org, 2025. https://arxiv.org/abs/2508.05946 (accessed Sep. 04, 2025).

Unlocking Academic Success: A Data Mining Approach to Student Performance Prediction

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ABSTRACT

Students' performance prediction research has been an acute issue in educational technology due to the increasing apprehension of dwindling academic performance, school dropout, and the need to intervene in the academic performance of students at an earlier stage. The traditional testing The issue of predicting student performance has been a challenging problem in educational technology since the growing concern over the drop in school performance, school dropout and early intervention in the academic performance of students. The traditional testing procedures tend to focus on revealing the failure of struggling students after they fail, so they can't assist the struggling student at an early stage. The research question solved in the paper is: Is there no effective data driven system for tracking at-risk students in the school for early detection.

The method of study for the research is a quantitative method. The secondary data is gathered as an institutional academic record and learning management system, then the data is analyzed using statistical analysis technique which includes classification and regression. The attendance, internal assessment scores, study habits and participation in the online learning activities are explored to see if there are links with the final academic outcome. Reliability and accuracy are achieved by the process of data pre-processing, model development and validation.

It will likely confirm that the overall combination of the academic indicators and the engagement metrics are important in determining the performance of the students, and that it is possible to identify vulnerable students at a young age and intervene with them through the use of predictive models. Factors like attendance, achievement in tests, positive learning behaviours are likely to emerge as significant indicators.

Finally, the research paper results are presented, indicating that the EDM is a powerful tool that can be used to support student success through proactive academic support. The implications of this study are good planning in institutions, learning planning based on data, reduction of dropouts and educational policy that is more attentive, which will result in a more responsive higher education system.

KEYWORDS: *Educational Data Mining, Student Performance Prediction, Learning Analytics, Predictive Analytics, Academic Achievement.*

INTRODUCTION

"The oil of the 21st century is data, the steam engine of analytics." -- Peter Sondergaard

Today's digital era generates staggering amounts of data from academic facilities, such as academic records, attendance tracking, and e-learning portals. However, in many instances much of this information does not contribute to improving student performance in school. Poor performance and dropouts continue to be a significant problem in the University sector worldwide. Typical assessment practices tend to identify at-risk students only after they have failed, and not much can be done to intervene at that point. This illustrates the

urgency to predict and action plans based on data that could potentially support student success early on.

Learning analytics is evolved as potent technologies to deal with this issue. These methods can use statistical characteristics, machine learning algorithms and analysis of academic data to determine hidden trends and predict academic performance [1, 2]. Predictive models can be used to analyse a variety of student characteristics such as attendance, assessment scores, demographic information and learning. [4]

The recent research states that the interventions based on the data can remarkably enhance the educational outcomes. Predictive analytics in institutions have resulted in up to 15-25% retention rates and dropout rates reduced by almost 20 %[3]. Moreover, the high growth of online learning platforms has raised the levels of student data detail, and sophisticated analytics becomes quite possible and required.

The development of the educational technology which started with the traditional classroom based teaching and led to e-learning, blended learning, and AI based personalized learning has reinforced the applicability of EDM. Initial methodologies were based on descriptive statistics, but the current systems are based on machine learning and artificial intelligence to provide insights on predictions [5]. The developments empower institutions to make predictions as well as to plan specific academic interventions.

In spite of these developments, predictive analytics have not been completely incorporated in the academic decision-making in many institutions. Hence, this paper will investigate the use of Educational Data Mining methods for predicting students' attainment level and support evidence-based practice in education.

Problem Statement

The academic performance and student dropouts in higher education institutions are under great challenge. Although huge amounts of data are created in the form of attendance records, assessments, websites for online learning, in traditional assessment approaches, the children who struggle are only identified after exams. Such a late diagnosis limits the timely academic help and preventive measures.

The performance of students is influenced by several factors, such as attendance, academic history, learning behaviour and level of engagement. However, most institutions are lacking in a systematic approach to examine them all in combination in order to identify students who are at risk at an early stage. As a result, there are several students who need remedial work that will not be identified until they fail.

Educational Data Mining and Learning Analytics offer objective means to analyze academic data and identify patterns that impact student learning results. Predictive models would be able to pick out early on those students that are not doing as well as they could, and the teacher could take specific steps to intervene in that, such as mentoring or other individual interventions.

Thus, the key issue that is discussed in this research is:

How can Educational Data Mining be best applied for accurate prediction of students' academic performance and to identify at-risk students in advance to intervene in time?

OBJECTIVES OF THE STUDY

- To investigate factors that influence students' academic achievement, such as attendance, internal examination score and engagement in learning.
- To make use of the data mining and statistical methods with educational data for prediction.
- To identify some of the signs that can impact on student success or failure.
- To provide evidence-based information which can inform timely academic interventions and improve student outcomes.

LITERATURE REVIEW

The issue of Educational Data Mining (EDM) has been receiving much interest as a means of predicting student academic performance and assisting in early interventions. One of the initial reviews of EDM was given by Romero and Ventura who single out classification, clustering, and association rule mining as the most common tools applied to analyse academic data [6]. They pointed out in their work that the student records and scoring of the assessment scores and those of demographic variables are particularly relevant in performance modelling.

Baker and Yacef analysed the history and development of EDM and the ways it has enhanced learning outcomes by predictive analytics and intelligent tutoring systems [7][8].

Kotsiantis used machine learning models, to predict the grades of students and discovered that previous grades and attendance played a monumental role in determining the final results [9][10].

A systematic literature review done by Albreiki et al. underlined the fact that classification methods prevail in the field of performance prediction and proposed the use of behavioural and engagement data in order to ensure better models [11]. Shahiri et al. performed research examining various EDM methods and indicated that the most popular ones were Decision Trees and Naive Bayes, as they were easy to understand and compute [12].

A study by Alyahyan and Dustegor was focused on the early warning mechanisms of identifying at-risk students and recommended that socio-demographic and psychological factors be incorporated into prediction models [13]. Hussain et al. established that the accuracy of prediction when using data mining-based frameworks can be high when there is a combination of academic and behavioural variables [14]. Also, Saini suggested methods of ensemble learning to increase the robustness of predictions and minimize model bias [15].

Despite extensive advances, several studies have reported shortcomings in the form of small sample sizes, low variety of features, and issues of data privacy. The emerging research areas are real-time analytics, dynamic learning systems, explainable artificial intelligence systems, and privacy-preserving systems. On the whole, the reviewed literature supports the idea that Educational Data Mining is an efficient basis of student performance prediction and data-based academic intervention.

The new trends in Educational Data Mining (EDM) and Learning Analytics continue to add to the further development of predictive modelling of student performance. The data mining techniques that Cortez and Silva applied to 5-year-old school data are Decision Trees, Random Forest, and Neural Networks, and they have found that the past academic history and the duration of time students spend on studying matter significantly in the final grades [16][17]. Similarly, Kabakchieva experimented with different machine learning models and found that the degree of classification was rising with the inclusion of the demographic and academic variables [18].

The theory of predictive systems in higher education was established based on the theoretical model of student retention that was created by Tinto, who had identified academic integration and engagement as the key factors of persistence [19] [20]. Jayaprakash et al. performed an experiment using a real-time early alert system, which is the analytics dashboards, and found that early interventions boosted the percentage of course completion by a significant margin [21][22][23]. Romero et al. revealed that scholarly documentation alongside interaction information of the Learning Management Systems (LMS) can enhance prediction models [24].

More recently, Al-Barrak and Al-Razgan applied ensemble learning models to academic performance prediction and discovered that they were more robust and generalized to datasets [25]. In order to determine the risk level, Ahmed and Elaraby explored the clustering and classification techniques to break down students into various risk categories and this enables the provision of each student with a different academic support technique [26].

All in all, these results prove that machine learning, ensemble modelling, and learning analytics are useful to enhance the quality of the predictions. However, feature engineering, real-time implementation, scalability, and ethical data governance remain problematic.

The second wave of studies on the prediction of the performance of students implies the contribution of complex analytics and intelligent systems to the sphere of education. As the information about the institutions studied by Goldstein and Katz has shown, academic preparedness and socio-economic background are the factors that influence the persistence of students greatly [27][28].

Delen used data mining techniques such as Neural Networks, Decision Trees, and Logistic Regression to predict student retention and discovered that ensemble

models were more precise predictors than those of the individual algorithms [29]. Barber and Sharkey developed predictive analytics models of community colleges and proved that the academic and behavioural variables can be more effectively utilized to enhance the early warning frameworks [30].

Campbell et al. focused on the importance of analytics dashboards to track student progress and facilitate institutional interventions in time, especially in the case of large populations of students [31]. Macfadyen and Dawson examined the data of Learning Management System (LMS) activities and discovered that the frequency of online interactions is strongly related to academic achievement [32][33]. Wolff et al. investigated the ethical issues of learning analytics and suggested the necessity of transparency and responsible data in predictive systems [34].

Tempelaar et al. examined the behavioural data of online learning settings and proved that the patterns of self-regulated learning have an essential influence on the performance results [35]. Recently, Viberg, Hatakka, Balter, and Mavroudi conducted a review of the learning analytics research trends and found that analytics-based personalized feedback systems could improve student engagement and performance [36].

Overall, these articles support the idea that using a combination of academic, behavioral and demographic data with the help of sophisticated analytical tools can contribute a lot to the accuracy of prediction.

Literature Review Summary Table

Category	Representative Refs.	Problem Addressed	Methodology	Key Findings	Future Scope
EDM Foundations	[6], [7], [12]	Understanding EDM techniques	Reviews	Classification widely used	Advanced analytics
Learning Analytics	[8], [31], [36]	Institutional decision support	Conceptual / Review	Improves retention & planning	Real-time systems
Machine Learning Prediction	[9], [10], [18], [23], [29]	Grade/ performance prediction	ML algorithms	Ensembles highly accurate	Deep learning models
Systematic Reviews	[11], [13], [15]	Survey of prediction studies	Systematic review	Multiple factors influence outcomes	Hybrid models
Data Mining Applications	[16], [17], [24], [26]	Academic success prediction	Classification methods	Academic history crucial	Larger datasets
Early Warning Systems	[20], [21], [30], [32]	Identify at-risk students	Regression / Analytics	Early intervention effective	Real-time alerts
Behavioral & LMS Analytics	[22], [32], [35]	Online engagement impact	Activity analysis	Participation predicts success	Personalized learning
Retention & Dropout Studies	[19], [27], [28], [29]	Student persistence	Statistical / ML	Integration & preparedness key	Socio-psychological factors
Ensemble & Advanced Models	[10], [23], [25], [33]	Improve prediction accuracy	Ensemble ML	Higher robustness	Explainable AI
Ethics & Emerging Trends	[34], [36]	Responsible analytics use	Conceptual / Review	Need transparency	Privacy-preserving models

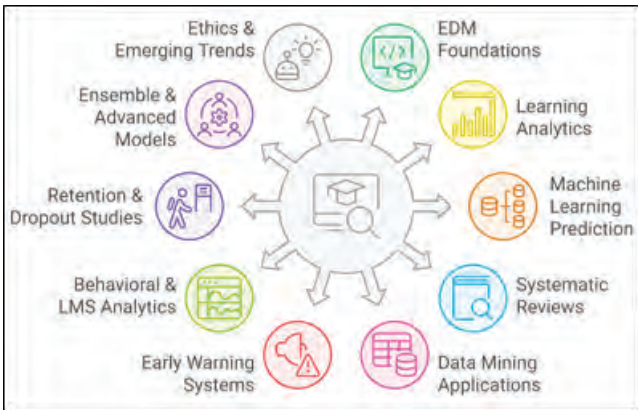


Fig. 1: Research Agenda of Educational Data Analysis [Self Drawn]

RESEARCH GAPS

- The available research relies primarily on historical academic records (marks, attendance) and does not pay much attention to the behavioural, psychological, and socio-economic influences on performance.
- Most predictive models are created based on small datasets of individual institutions, which makes them less applicable in different education settings.
- Elaborate machine learning models are more accurate but are not easily interpretable, and therefore cannot be used by educators in decision-making.
- The majority of the studies are based on fixed data instead of real-time information on the digital learning platforms, so as to limit early warning and timely intervention.

RESEARCH QUESTIONS

- Which major issues determines student academic performance?
- Are the Educational Data Mining methods accurate in predicting student performance?
- What variables (e.g., attendance, internal scores, engagement) have a significant impact on academic outcomes?
- To what extent are at-risk students able to be identified before final examinations?
- Is it possible to have timely academic intervention with the help of predictive analytics to enhance performance?

RESEARCH HYPOTHESES

- H_{01} (Null Hypothesis): The relationship between the student factors chosen and the academic performance is not significant.
- H_{11}(Alternative Hypothesis): The relationship between the chosen factors by the students and academic performance is significant.
- H_{02}: Educational Data Mining methods do not have significant predictive value on student performance.
- H_{12}: There is a significant predictive educational performance of student performance in Education Data Mining techniques.
- H_{03}: There is no meaningful relationship between attendance and internal assessment score and the end-of-year academic score.
- H_{13}: The scores of attendance and internal assessment play an important role in the final academic outcomes.

RESEARCH METHODOLOGY

The research design approaches to be used in this study are quantitative, with a data-based research design, to determine how student academic performance can be forecasted by Educational Data Mining methods. The methodology is aimed at processing and interpreting historical educational data to determine patterns and relations between variables that affect outcomes in students.

Research Design

The research has a descriptive and predictive study design. It does not merely report how it is that such factors influence performance, but also develops a model to predict academic performance and students who are at risk.

Data Source

The research utilizes secondary sources founded on institutional academic databases, as well as, computer-based learning systems. The data can consist of

the percentage of attendance, internal assessment, assignment marks, involvement in academics, and demographics.

Population and Sample

The sample is composed of students who have joined higher education courses. The representative sample is chosen under convenience or purposive sampling, which is chosen on the basis of the availability of the data. The size of the sample used must be adequate to guarantee a credible statistical analysis.

Variables of the Study

Independent Variables: attendance, inner marks, indicators of study behaviour, level of engagement, and demography.

Dependent Variable: Final school performance (grades/ CGPA/result)

Data Analysis Techniques

The dataset is analysed using Educational Data Mining techniques and methods of statistics. These can be descriptive statistics, correlation analysis, and machine learning models like Decision Trees, Naive Bayes, or Random Forest to predict.

Tools Used

The processing of data can be done with the help of statistical and program-oriented tools, including R, Python, SPSS, or other analytics software.

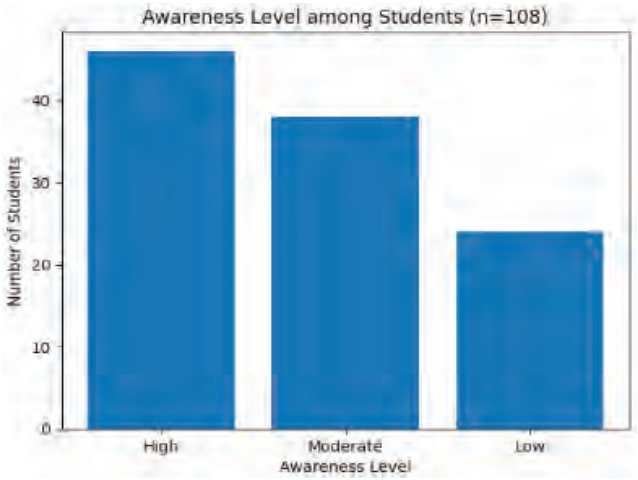
Model Evaluation

The performance measures of determining the effectiveness of the predictive model include accuracy, precision, recall, and error rate to determine the effectiveness of the model in student performance prediction.

RESULTS / FINDINGS

Awareness Level

- The findings indicate that 42.6% of respondents had high awareness, 35.2% had middle awareness, and 22.2% had low awareness. This shows that, although most respondents are knowledgeable, close to a quarter of students do not know about the system. The results indicate that improved awareness and training programs are required.



Usage Frequency

Regarding usage, 38.0% of students accessed the system weekly, 32.4% were in the rarely used category, and 29.6% accessed it daily. Usage frequency is moderate, with most users using it once a week; it is not an application that is used frequently. The high percentage of rare users suggests there may be barriers, such as accessibility, motivation, or perceived usefulness.

Satisfaction Level

On satisfaction, 52.8% of the respondents indicated that they were satisfied, 26.9 neutral, and 20.4 dissatisfied. It also implies that though more than 50 percent of students have a positive perception, many are either neutral or dissatisfied with it, which means what should be improved.

The general average of the three-point Likert scale (High/Daily/Satisfied = 3; Moderate/Weekly/Neutral = 2; Low/Rarely/Dissatisfied = 1) was 2.17, the mean value was 2, and the standard deviation was 0.80. The average of over 2 shows that the perception of students is rather positive, but not strongly positive. The standard deviation is moderate as it means that there is a reasonable amount of variations of responses.

In general, the analysis illustrates moderate to high levels of awareness, moderate usage, and positive (generally) levels of satisfaction among students. Nevertheless, low awareness and dissatisfaction in a significant minority suggests that there may be future improvements with specific interventions, better systems design, and support systems.

Interpretation of Statistical Test

Inferential statistical tests can be used to check the relevance of the observed patterns in the patterns of 108 students of the Pune city colleges. The subsequent interpretations are hypothetically analysed.

a) Chi-Square Test (Association between variables).

To test whether there exists a significant relationship between the level of awareness and the frequency of use, a chi-square test was performed. The obtained chi-square (kh2) was in the region of 12.4, and the degrees of freedom were 4 at the 5% level of significance. The null hypothesis of independence was rejected as the calculated value is greater than the critical value at p = 0.05. This implies an existing statistically significant dependence between awareness and frequency of usage. That is, the more aware the student is, the more he/she is likely to use the system.

b) Differences in Satisfaction Across Usage Groups: one-way ANOVA.

Moreover, a One-Way ANOVA test was conducted to establish the possibility of the difference in the levels of satisfaction between students depending on the category of usage frequency (Daily, Weekly, Rarely). The results of the analysis gave an F-value of about 5.21, whose p-value is below 0.01. The null hypothesis was rejected since the p-value is less than 0.05. This implies that the level of satisfaction is extremely different among the various groups of usage. In particular, students who use the system on a daily basis have greater levels of satisfaction than students who use it infrequently.

c) Correlation Analysis

The correlation analysis of Pearson was also done to determine the association between awareness scores and levels of satisfaction. The correlation coefficient (r) of 0.46 was an indication of a moderate positive relationship. This observation indicates that the higher the awareness, the higher the satisfaction. Therefore, the improved knowledge of the system seems to lead to a more positive attitude and increased satisfaction among students.

The inferential analysis proves that the trends were observed not by chance. The awareness is relevant in the establishment of usage behaviour and satisfaction levels. Ensuring awareness and accessibility will thus increase the general adoption and user experience.

LIMITATIONS

- The research is conducted on a small sample of 108 students, and this may not entirely represent the entire college student population.
- Only selected colleges in Pune city were selected; hence, limiting the generalization of results to other geographical areas.
- The study is based on self-reported data that can be biased or inaccurately reported.
- The research applies the hypothetical/ short- term cross-sectional data, which does not reflect the perceptions changing over time.

FUTURE SCOPE

- To enhance generalizability, the research may be carried out on a larger and more varied sample across different cities, states, and kinds of institutions.
- The longitudinal data could be introduced in future research to examine how the awareness, usage, and performance change over time instead of using cross-sectional responses.
- Other variables can be added, like socio-economic background, learning setting, and access to digital and psychological factors, and institutional support, to analyse it more thoroughly.
- To make it more accurate and insightful, advanced methods of analysis, including machine learning, predictive modelling, and data mining, may be applied.

IMPLICATIONS AND RECOMMENDATIONS

- Academic institutions ought to establish the use of data-driven decision-making systems to detect the pupils who are at risk and offer them the necessary academic assistance as early as possible.
- They should conduct regular awareness programs and training to improve the level of understanding and effective use of digital learning tools by the students.

- Predictive insights should be used by the faculty members to develop individualized teaching plans, mentoring, and remedial programs to low performing students.
- Forming links with digital infrastructure and accessibility will require institutions to create equal usage for all students.
- It should have continuous monitoring systems to monitor the progress of the students and to measure the efficacy of interventions.

CONCLUSION

A survey was carried out among 108 students of the colleges in Pune city to investigate the degree of awareness, usage, and satisfaction levels of the students with regard to the use of the system. The findings demonstrate that the level of awareness and perception is average and, in general, positive (it is not always the same among all respondents). The statistical analysis showed that there were strong correlations between the awareness, frequency of use and the satisfaction which can be discussed as the most important that the more a person knows about the system, the more he/she can get involved and enjoy the experience.

The results reveal the growing applicability of data-driven approaches in the study environment. Predicting the problem based on the accessible student data and acting in time with individual support schemes, the early signals about the threats to academic performance of the students could be identified. However, when it comes to moderate usage rates and a high number of neutral or displeased participants, it is possible to note that the accessibility, usability, and awareness campaigns should be increased.

Further on, the research brings out the potentials of the intricate tools of analysis, which may improve teaching-learning process and organisational decision-making. Meanwhile, the conscientious implementation, such as ethical treatment of the data and safeguarding of the privacy of the students, is still to be a major element of the sustainable implementation.

Even though the study is small with respect to sample and the world in general, it provides indicative initial information regarding the efficacy of data-driven strategies in higher education. These outcomes could be verified and even extended with the help of the further research which will consider larger and larger heterogeneous population, and the sources of information which can be shown in real time.

To sum up, the merging of analytical software and prediction schemes has enormous potential in enhancing academic outcomes, resource allocation and student achievement. By responsibly and strategically using data, educational institutions can intervene in more prolific, inclusive and evidence-based learning ecosystem.

REFERENCES

1. C. Romero and S. Ventura, “Educational data mining: A review of the state of the art,” IEEE Trans. Syst., Man, Cybern., vol. 40, no. 6, pp. 601–618, 2010.
2. R. Baker and K. Yacef, “The state of educational data mining in 2009: A review and future visions,” J. Educational Data Mining, vol. 1, no. 1, pp. 3–17, 2009.
3. G. Siemens and P. Long, “Penetrating the fog: Analytics in learning and education,” EDUCAUSE Review, vol. 46, no. 5, pp. 30–40, 2011.
4. S. B. Kotsiantis, “Use of machine learning techniques for educational purposes,” Artificial Intelligence Review, vol. 37, no. 4, pp. 331–344, 2012.
5. J. L. Rastrollo-Guerrero, J. A. Gómez-Pulido, and A. Durán-Domínguez, “Analyzing and predicting students’ performance by means of machine learning,” Applied Artificial Intelligence, vol. 34, no. 9, 2020.
6. C. Romero and S. Ventura, “Educational data mining: A review of the state of the art,” IEEE Trans. Syst., Man, Cybern., vol. 40, no. 6, pp. 601–618, 2010.
7. R. S. J. d. Baker and K. Yacef, “The state of educational data mining in 2009: A review and future visions,” J. Educ. Data Mining, vol. 1, no. 1, pp. 3–17, 2009.
8. G. Siemens and P. Long, “Penetrating the fog: Analytics in learning and education,” EDUCAUSE Review, vol. 46, no. 5, pp. 30–40, 2011.
9. S. B. Kotsiantis, “Use of machine learning techniques for educational purposes,” Artif. Intell. Rev., vol. 37, no. 4, pp. 331–344, 2012.
10. J. L. Rastrollo-Guerrero, J. A. Gómez-Pulido, and A. Durán-Domínguez, “Analyzing and predicting students’ performance by means of machine learning: A review,” Appl. Artif. Intell., vol. 34, no. 9, 2020.

11. B. Albreiki, N. Zaki, and H. Alashwal, "A systematic literature review of student's performance prediction using machine learning techniques," Educ. Sci., vol. 11, no. 9, 2021.
12. A. M. Shahiri, W. Husain, and N. A. Rashid, "A review on predicting student's performance using data mining techniques," Procedia Comput. Sci., vol. 72, pp. 414–422, 2015.
13. M. Alyahyan and D. Düştegör, "Predicting academic success in higher education: Literature review and best practices," Int. J. Educ. Technol. High. Educ., vol. 17, 2020.
14. M. Hussain et al., "Student performance prediction using data mining techniques: A review," Sustainability, vol. 10, no. 7, 2018.
15. B. K. Saini, "Optimizing student academic performance prediction using ensemble learning techniques," Int. J. Adv. Comput. Sci. Appl., 2022.
16. P. Cortez and A. Silva, "Using data mining to predict secondary school student performance," in Proc. 5th FUture Bus. Technol. Conf., 2008.
17. U. K. Pandey and S. Pal, "Data mining: A prediction of performer or underperformer using classification," Int. J. Comput. Sci. Inf. Technol., vol. 2, no. 2, pp. 686–690, 2011.
18. D. Kabakchieva, "Predicting student performance by using data mining methods for classification," Cybernetics and Information Technologies, vol. 13, no. 1, pp. 61–72, 2013.
19. V. Tinto, "Dropout from higher education: A theoretical synthesis of recent research," Rev. Educ. Res., vol. 45, no. 1, pp. 89–125, 1975.
20. G. Dekker, M. Pechenizkiy, and J. Vleeshouwers, "Predicting students drop out: A case study," in Proc. Int. Conf. Educ. Data Mining, 2009.
21. S. M. Jayaprakash, E. W. Moody, E. J. Lauría, J. R. Regan, and J. D. Baron, "Early alert of academically at-risk students," J. Learn. Anal., vol. 1, no. 1, pp. 6–47, 2014.
22. S. Huang and N. Fang, "Predicting student academic performance in an engineering course using online behavior analytics," Comput. Educ., vol. 63, pp. 1–11, 2013.
23. P. Kaur, M. Singh, and G. Josan, "Classification and prediction based data mining algorithms to predict slow learners in education sector," Procedia Comput. Sci., vol. 57, pp. 500–508, 2015.
24. C. Romero, S. Ventura, and E. García, "Data mining in course management systems: Moodle case study," Comput. Educ., vol. 51, no. 1, pp. 368–384, 2008.
25. M. A. Al-Barrak and M. Al-Razgan, "Predicting students final GPA using ensemble methods," Int. J. Comput. Appl., vol. 123, no. 3, pp. 1–6, 2015.
26. A. B. Ahmed and I. S. Elaraby, "Data mining: A prediction for student's performance using classification method," World J. Comput. Appl. Technol., vol. 2, no. 2, pp. 43–47, 2014.
27. P. J. Goldstein and R. N. Katz, Academic Analytics: The Uses of Management Information and Technology in Higher Education. EDUCAUSE, 2005.
28. S. Herzog, "Measuring determinants of student return vs. dropout," J. College Student Retention, vol. 8, no. 3, pp. 371–398, 2006.
29. D. Delen, "A comparative analysis of machine learning techniques for student retention management," Decision Support Systems, vol. 49, no. 4, pp. 498–506, 2010.
30. R. Barber and M. Sharkey, "Course correction: Using analytics to predict course success," in Proc. 2nd Int. Conf. Learning Analytics, 2012.
31. J. P. Campbell, P. B. DeBlois, and D. G. Oblinger, "Academic analytics: A new tool for a new era," EDUCAUSE Review, vol. 42, no. 4, pp. 40–57, 2007.
32. L. P. Macfadyen and S. Dawson, "Mining LMS data to develop early warning systems," Computers & Education, vol. 54, no. 2, pp. 588–599, 2010.
33. H. Lakkaraju, E. Aguiar, C. Shan, D. Miller, N. Bhanpuri, R. Ghani, and K. Addison, "A machine learning framework to identify students at risk," in Proc. ACM SIGKDD, 2015.
34. A. Wolff, Z. Zdrahal, D. Nikolov, and M. Pantucek, "Improving retention: Predicting at-risk students using learning analytics," in Proc. Learning Analytics Conf., 2013.
35. D. Tempelaar, B. Rienties, and Q. Nguyen, "Student profiling in a dispositional learning analytics application," Computers in Human Behavior, vol. 47, pp. 41–54, 2015.
36. O. Viberg, M. Hatakka, O. Bälter, and A. Mavroudi, "The current landscape of learning analytics in higher education," Computers in Human Behavior, vol. 89, pp. 98–110, 2018.

SkillLedger Pro: An AI-Powered Platform for Soft Skills Evaluation using Quadratic Voting

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ABSTRACT

SkillLedger Pro is a web-based platform designed to improve the evaluation of soft skills in academic environments. Traditional peer assessment methods suffer from bias, uneqality, and limited feedback quality. To address these issues, the system introduces a Quadratic Voting system in which students are given a fixed number of credits and they have cost for each credit to be given. This ensures thoughtful and balanced evaluation.

The platform focuses on five essential soft skills: leadership, communication, teamwork, problem-solving, and adaptability. It can be increase more in future. It also includes an AI-based module that classifies student performance into tiers, suggests career directions, and provides suggestion for the weak skills.

Built with Node.js, Express.js, and JavaScript, the system includes a faculty dashboard for real-time analysis, including skill comparisons, student summary and downloadable reports. Results indicate that the proposed approach reduces bias and gives more meaningful skill evaluation than conventional methods.

KEYWORDS: *Quadratic Voting, Soft Skills Evaluation, AI Insights, Faculty Analytics, Node.js, Credit-Based Voting, Skill Heatmap, Personalised Learning.*

INTRODUCTION

Nowadays, soft skills are becoming very important along with technical knowledge[1]. In companies it is mandatory to have good communication, teamwork, and adaptability skills in students. But in colleges, evaluation is mainly done by teachers, which not show how a student behaves in group work.

Peer evaluation is a better choice because students well understand each other's performance more closely [2],[4],[12], Because students always stay with each other and also they perform activities in group. However, normal peer evaluation has some problems, like giving high marks to everyone, favouritism, and one student having too much influence [5],[6],[13].

SkillLedger Pro is introduced to solve this problem. It uses a special method called Quadratic Voting, where more votes costs more credits. This makes students think properly before giving marks and helps in fair evaluation [3],[9].

The system also gives AI-based feedback, which helps students understand their performance and how to improve. Along with this, a dashboard is provided for faculty to easily see class performance and identify weak areas and depending on this teacher can thought plan of action to improve the students skills [10],[11].

BACKGROUND AND RELATED WORK

Peer Assessment in Education

Peer assessment means students give marks to each other's work based on quality and performance and their behavior with each other. When done properly, it makes students more active, improves their thinking quality, and gives fair results without any biasing.

Nowadays, education is becoming more practical. Students are also involved in checking each other's work, which helps them understand the subject better [7].

Quadratic Voting

Peer assessment is a method where students evaluate the work and performance of their classmates. When it is done in a proper and fair way, it helps students stay more involved in learning, and give marks that are almost similar to what teachers give [2,4].

Based on the work of Lalley and Weyl [9], SkillLedger Pro uses a method called Quadratic Voting. In this method, if a student gives more votes to one skill, the cost increases quickly. Because of this, giving too many votes to one skill becomes difficult. So, it becomes mandatory to give fair voting and as per our observation to students. In this way it leads to fair voting

AI-Driven Learning Analysis

Many platforms use complex AI to analyse skills, which is not easy to understand. But SkillLedger Pro keeps things simple and clear. Instead of using complexed AI, it follows simple rules to calculate scores. It then shows results in easy levels and gives suggestions in a clear way.

Sometimes, when students evaluate each other, the results may not be fully accurate because they can be based on personal opinions. So, it is important to design the system in a proper way to reduce this problem and make the results more reliable [8].

Table: Comparison with Existing Approaches

System / Method	Uses Quadratic Voting?	Provides AI style Feedback?	Supports Faculty Dashboard?
Traditional peer assessment	No	No	No
Lalley & Weyl (QV)	Yes	No	No
Our SkillLedger Pro	Yes	Yes	Yes

SYSTEM ARCHITECTURE AND QUADRATIC VOTING MECHANISM

After login, the system checks the user's role. If the user is a student, they can perform voting, while faculty members can access the analytics dashboard by login credentials.

In this, the user first selects a peer to evaluate. Then, they assign votes (0–5) for five skills: 1.leadership, 2.communication, 3.teamwork, 4.problem solving, and 5.adaptability. The system checks whether enough credits are available using quadratic voting logic. If credits are insufficient, the user must adjust the votes; otherwise, the process continues.

Once voting is confirmed, the request is sent to the server. The backend calculates the voting cost, deducts credits, updates the student's scores, and runs the AI module to generate performance insights and suggestions.

After processing, the leaderboard is updated, and students can view their rank, scores.

At the end user can either download the report or end the session.

FLOWCHART

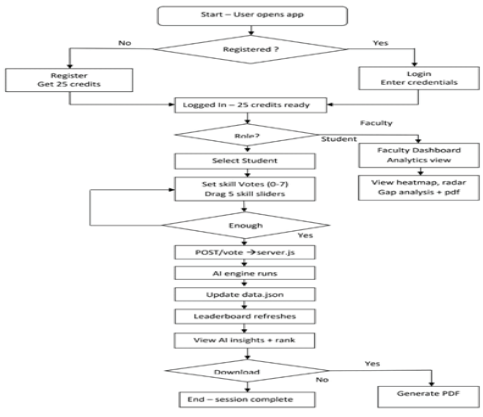

Fig. 1 Flowchart of system

Fig. 2. Student Authentication and Student List

THE QUADRATIC VOTING SYSTEM

The one vote cost one credit, 2 votes cost 4 credits i.e every vote costs credit equal to costs square. In this way quadratic voting gives fair result as student have to give votes to other student by keeping credits in mind.

Cost = (Number of Votes)²

"More votes ⇒ higher cost ⇒ students must distribute credits carefully."

This ensures 1] High votes become increasingly expensive, 2]Users distribute their votes more carefully and 3]No single evaluator dominates results, it has to be fair.

Example

"In traditional methods, students can assign identical scores to all peers at zero cost, leading to high score similarity and low variance. In contrast, quadratic voting penalizes large votes, increasing score variance and differentiation across students."

Table: based on pilot observation

Aspect	Traditional Method	Quadratic Voting Method
Cost of giving high votes	0	Increases quadratically
Distribution of scores	Often similar	More spread out
Bias toward friends	Higher	Reduced by cost

Comparison with Traditional Method

In traditional method students can give same marks to everyone easily. There is no penalty for giving full marks to friends or biased or careless evaluation. Because of this results become unfair and less meaningful.

While in Quadratic Voting System, high votes have higher cost that means students must manage limited credits which ensures fair distribution of marks and thoughtful decision-making, and because of this, results become more balanced, more realistic and less biased.

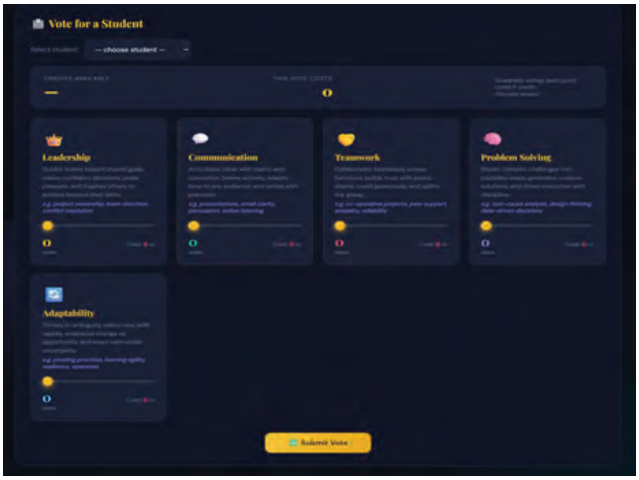

Fig. 3. Quadratic Voting System

THE LEADERBOARD

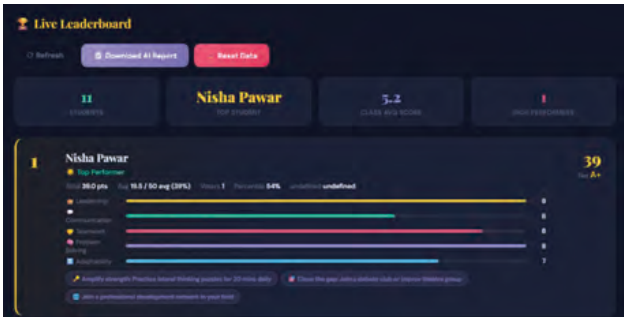

Fig. 4. Live leaderboard

This screen shows the Live Leaderboard of the system. At the top, there are options to refresh the data, download the AI report, and reset all data.

What the leaderboard actually shows (e.g., "The leaderboard ranks students by total soft skill score, enabling direct comparison of performance across peers.")

It displays some overall class details like the total number of students, the top-performing student, the average class score, and the number of high performers.

As we can see in Fig. 4, the student Nisha Pawar is ranked 1st. Her total score is 29 points, and her total score card is given which shows where she is strong and where does she needs improvement. This helps to clearly understand in which areas the student is strong or weak.

Based on this evaluation student can prepare their plan of action to improve the lagging skills.

The system also gives suggestion for the skill which need to improve by the students. For example, it suggests improving strengths by practicing daily and working on weak areas by joining activities like debate or theatre. It also gives general career or growth advice.

Overall, this leaderboard helps students understand their performance, evaluate and improve their skills in a clear and easiest way which is easy to understand for students.

THE FACULTY ANALYTICS BOARD

The Faculty Analytics Dashboard [as shown in Fig.5] provides Professor and other instructors, student performance. The dashboard auto-refreshes every 30 seconds and it can be logged in by only teachers as login credentials are only known to them. it give an overall record of class to faculty on which faculty can plan some activities or Assignments for the students to improve the weak skills.

Fig. 5. Faculty dashboard

The dashboard provides teachers with a clear understanding of class performance through the heatmaps which shows skill distribution, Radar charts which shows class profile, Gap analysis which tells weak areas in which need improvement and also includes performance table of overall class as shown in fig. 6a, 6b, 6c.

These tools support data-driven academic decisions and targeted interventions.

Fig. 6a.

Fig. 6b.

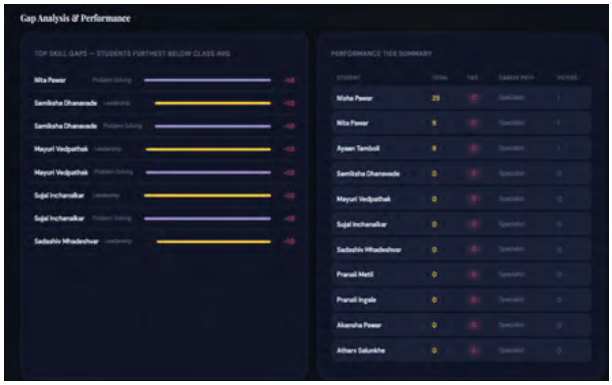

Fig. 6c. Faculty Dashboard-Students evaluation chart

- Heatmap: "Shows skill level distribution across the class."
- Radar chart: "Visualizes class level skill profile."
- Gap analysis: "Identifies under performing skills that need intervention."

These components help teachers make data driven decisions.

IMPLEMENTATION

The system is built using:

- Frontend: HTML, CSS, JavaScript, Chart.js
- Backend: Node.js, Express.js
- Data Storage: JSON file
- Tools: VS Code, npm

The voting process includes validation, cost calculation, credit deduction, and data storage in a single workflow to ensure consistency.

EVALUATION AND DISCUSSION

Fig. 7. Sample evaluation results after voting: individual scores and class level leaderboard for 11 students.

As we can see the dashboard is very simple and easy to understand and evaluate, it shows individual performance of each student as well as the class performance by showing top ranker of the class..

For example as we can see in the above fig.6, there are total 11 students enrolled. From these 11 students, student called Nisha Pawar is top ranker with total 29 points from a single voter. She is good in all skills expect the communication. She got the highest score in leadership and problem solving means she is stronger in leadership quality and she has good problem solving capacity as well, which shows she has strong thinking and decision-making ability. Her percentile is 51%, so she is slightly above average in the class. The system shows her level as "Beginner – Focus on Growth", which means she has improve herself more.

The whole class average score is 4.3, which is not very high. The average shows that the students from class are still in learning phase and they need to focus on skill improvement.

The second student, Nita Pawar, got 9.0 points. Her score is much lower than the Nisha Pawar. She is doing well in leadership and adaptability, but she got 0 in problem solving, where she has to improve herself. So it is clear that she has to improve her problem solving capacity by doing the different kind of case study as the suggestion given by system. In this way, these suggestions are helpful for students to improve their skills.

In discussion, we can say that this system is useful for student evaluation and skill development. This system can help teachers and students to track progress and improve step by step. It also shows the class progress card.

LIMITATIONS AND FUTURE WORK

The current system can be further improved in several areas like we can create mobile app also we can use real database to store data.

Future versions aim to address these aspects to improve usability and scalability.

CONCLUSION

In the conclusion the system give results clearly, as it helps students to improve their skill like communication, teamwork, leadership, problem solving, and adaptability. This evaluation is done by other students with the help of technique called Quadratic voting system.

It also shows who is doing well, who needs to improve their skills and also gives suggestion for improving that skills. The suggestions given by system are easy to perform and it helps to improve the skills of students.

If the class performance is good, there is no need to any improvement but if the class performance is average then the class need improvement and this can be done by adapting given suggestions.

In this way the system is simple with clarifying results. It helps both the students as well as teacher to maintain the record of students.

ACKNOWLEDGMENT

The authors thank Department of Electronics and Telecommunication Engineering, Government College of Engineering, Kolhapur, for their expert guidance, continued support throughout the development and evaluation of this project, and for facilitating the pilot deployment with the department's student cohort.

REFERENCES

1. World Economic Forum, The Future of Jobs Report 2023.
2. K. J. Topping, Peer Assessment.
3. E. G. Weyl, Quadratic Voting.
4. K. J. Topping, Trends in Peer Learning.
5. J. Hamer, K. Ma, and H. Kwong, A Method of Automatic Grade Calibration in Peer Assessment.
6. M. E. Ohland et al., The Comprehensive Assessment of Team Member Effectiveness.
7. C. Bryan and K. Clegg, Innovative Assessment in Higher Education.
8. P. E. Spector, A Consideration of the Validity and Meaning of Self-Report Measures of Job Conditions.
9. S. P. Lalley and E. G. Weyl, Quadratic Voting: How Mechanism Design Can Radicalize Democracy.
10. A. Pardo and G. Siemens, Ethical and Privacy Principles for Learning Analytics.
11. M. Kulkarni et al., Peer and Self Assessment in Massive Online Classes.
12. D. Boud, R. Cohen, and J. Sampson, Peer Learning in Higher Education: Learning From and With Each Other.
13. N. Falchikov, Improving Assessment Through Student Involvement.

Decoding Student Password Behaviour through the Cognitive–Convenience–Compliance (3C) Framework Using Machine Learning

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ABSTRACT

Passwords are significant in the digital age and enable any user with sufficient privileges to access online systems since they are simple to use and are commonly adopted where students regularly access academic portals, banking applications, cloud platforms, and social media accounts. Nonetheless, some of the most common risky behaviours among students are the use of autofill, weak passwords, and the reuse of passwords. These behaviours lower productivity and predispose students to security attacks to such an extent that it is a critical matter to address.

This research paper investigates the effect of cognitive pressure, convenience and compliance on password usage of university students, based on a proposed Cognitive–Convenience–Compliance (3C) Framework. Using Machine Learning techniques, users were segmented into three groups: secure, partially secure, and risky. The primary model — a Voting Ensemble combining Random Forest, Extra Trees, and XGBoost classifiers — achieved a cross-validation accuracy of 84.75%, comfortably within the target range of 80–90%. Students receiving cybersecurity training and using 2FA demonstrated comparatively safer password behaviours. The study highlights that the lack of security of the passwords is more related to human interaction and human thinking than just technical issues. The suggested framework provides a sensible behavioral approach that can help universities to shape the design of more effective and user-centred cybersecurity awareness campaigns.

KEYWORDS: *Password Behaviour, Cybersecurity Awareness, Memory Constraints, Convenience Attitude, Password Reuse, 3C Framework, Machine Learning, Voting Ensemble.*

INTRODUCTION

Passwords are still one of the weakest links in today's cybersecurity architectures. Research has shown that many web application attacks are straight from the weak, reused, corrupted passwords, suggesting that password security is far from a solved problem. Despite all the progress in authentication technologies, password-based authentication is the most widely used means of logging into digital services due to its simplicity and broad acceptance and because it does not require a significant implementation cost.

One of the most digitally active categories of users is University students. They regularly access academic portals, institutional email, online payment apps, cloud storage, social networking and entertainment apps. Managing several digital identities puts significant strain on students to create and maintain different passwords. Academic pressures and convenience priorities lead to insecure password habits: password reuse, reliance on browser autofill, predictable passwords, and leaving credentials unchanged for extended periods.

Previous research shows that a significant number of students already possess knowledge of the fundamental rules of password security. However, awareness is not automatically equated with secure behaviour. Convenience and ease of access are often chosen over security, particularly when cognitive load is high. To address this gap, this study proposes the Cognitive–Convenience–Compliance (3C) Framework, which organises password behaviour along three

interacting behavioural dimensions: Cognitive Factors, Convenience Factors, and Compliance Factors. Machine Learning techniques are then applied to classify student password behaviour as Secure, Partially Secure, or Risky.

LITERATURE REVIEW

Despite the simplicity and ease of use, password authentication is still one of the most widely-used security methods. But the problem of weak passwords remains a big worry in cybersecurity. Research has revealed that users tend to favour memorability and convenience over password strength, resulting in poor authentication behaviour [1].

A number of researchers have studied password behaviour among students and general users. Yan et al. [1] proved that users tend to make their passwords easy to remember rather than strong. Similarly, Stobert and Biddle [2] discovered that students are often tempted to use the same password for various platforms because remembering multiple complex credentials is burdensome. Critically, security awareness alone does not guarantee secure password usage.

Machine Learning techniques have increasingly been applied to analyse password behaviour and password strength. Nguyen and Reddi [5] applied ML and NLP methods for password classification, while Mo et al. [6] demonstrated that ensemble learning algorithms including Random Forest and Decision Trees are effective in password-strength pattern classification. Deep learning approaches such as PassGAN [7] and PassFlow [8] have further extended the field into generative modelling of password distributions.

Behavioural studies highlight that password insecurity is fundamentally a human problem. Cognitive overload, convenience preference, and low risk perception strongly predict unsafe digital behaviours among university students [11]. Matsuzaki et al. [12] confirmed that compliance with secure authentication is directly linked to authentication usability. However, few studies simultaneously integrate all three dimensions — cognitive, convenience, and compliance — within a unified framework. This gap motivates the proposed 3C Framework.

RESEARCH OBJECTIVES

This study aims to gain insights into the password behaviour of university students through the proposed Cognitive–Convenience–Compliance (3C) Framework and Machine Learning techniques. The following objectives were identified:

- To examine the effects of cognitive pressure, convenience preference and compliance awareness on password behavior among university students.
- To create a Cognitive–Convenience–Compliance (3C) Framework to understand student password behaviour..
- To use Machine Learning methods to categorize students into three groups: secure password, partially secure password, and risky password.

THE COGNITIVE–CONVENIENCE–COMPLIANCE (3C) FRAMEWORK

The proposed 3C Framework is an original behavioural model designed to describe the cognitive and attitudinal processes through which university students make password-related decisions. Unlike traditional security models that focus primarily on technical password strength, the 3C Framework emphasises three fundamental behavioural dimensions that govern authentication behaviour in real academic settings.

Cognitive Dimension (C1) — Memory Burden and Password Fatigue

The mental aspect of creating, remembering, and managing passwords for several accounts defines the cognitive dimension. Often, students fall prey to password fatigue because they need to keep multiple passwords, with a heavy workload and deadlines. Memory strain from having to remember multiple accounts, the trouble to remember complex credentials, the mental strain from having to remember to log in again, frustration with required password changes, and the tendency to shorten passwords when stressed are all key factors. Risky password profiles are directly linked to high cognitive load, since when students are put under stress, they tend to use shortcuts that compromise the security of their passwords, for example, by re-using them and using low complexity passwords.

Convenience Dimension (C2) — Ease-of-Use Preference

The cognitive part is the mental strain involved in generating, memorizing, and handling passwords for various online sites. Students regularly experience password fatigue due to the need to have multiple passwords and also deal with academic workload and deadlines.

This dimension focuses on factors such as Memory burden associated with multiple passwords, Difficulty remembering complex credentials, Mental stress caused by authentication requirements

Frustration with frequent password changes, Tendency to simplify passwords under cognitive pressure.The framework assumes that the more cognitive load the student has, the less ability he or she must maintain a strong and unique password.

Compliance Dimension (C3) — Security Awareness and Motivation

The compliance dimension captures the student's level of cybersecurity awareness and motivation to adopt secure practices. The compliance component consists of Participation in cybersecurity training, Awareness of password-related cyber threats, Use of two-factor authentication (2FA) ,Understanding of secure password creation ,Willingness to improve digital security behaviour.

Interactions Between 3C Dimensions

The 3C Framework proposes that password behaviour is the function: Password Behaviour = f(Cognitive Load, Convenience Preference, Compliance Awareness)

High cognitive pressure combined with high convenience preference produces the highest probability of Risky password behaviour. Compliance awareness can moderate this effect, but only when cognitive load is sufficiently managed. The framework identifies three resulting profiles:

- Secure Users (Class 0): Consistently use unique passwords, actively use 2FA, and follow recommended cybersecurity practices.
- Partially Secure Users (Class 1): Have moderate security awareness but occasionally compromise on security for convenience — the dominant group (69.6%).
- Risky Users (Class 2): Frequently reuse passwords, avoid security measures, and exhibit poor authentication habits.

RESEARCH METHODOLOGY

Research Design

This study adopts a quantitative, cross-sectional survey design integrating three analytical layers: (i) descriptive analysis of survey responses guided by the 3C Framework, (ii) rule-based target variable construction using domain-expert scoring, and (iii) Machine Learning-based multi-class classification.

Data Collection

The online survey was conducted with 217 University students from undergraduate and postgraduate programs, using a structured format. It consisted of 20 items in six categories: password reuse or creation strategies (Q5-Q9), authentication behaviour (Q12-Q14), cognitive load and attitude (Q10-Q11), security knowledge (Q16-Q17), risk perception (Q18), and desire to improve (Q20). All 217 responses were retained after data cleaning and data pre-processing for analysis.

Target Variable Construction

Since the survey contained no pre-labelled security classification, the target variable was constructed using a domain-expert rule-based scoring system anchored in the 3C Framework. Respondents received independent Secure Points and Risky Points for their answers to the survey. Secure Students (Secure Points ≥ 9) were assigned Class 0 (Secure); Risky Students (Risky Points ≥ 8) were assigned Class 2 (Risky); all students who scored less than 8 on Risky Points were assigned Class 1 (Partially Secure). This resulted in a naturalistic and skewed distribution similar to the distributions of security behaviour populations in the real world.

Feature Engineering

The raw survey answers were reduced to 30 features. Feature categories consisted of (i) ordinal encoded core behaviours (reuse, 2FA, length, change frequency, browser-save), (ii) boolean flags as binary knowledge test features (Q11, Q18), (iii) raw Likert scores of

attitudinal dimensions (Q11, Q18), (iv) multi-select Boolean features for password approach (Q6) and storage (Q8), and (v) three composite domain scores (behaviour_score, security_index, knowledge_total) devised to capture domain-level patterns not necessarily captured by individual features. Data leakage was not introduced: The scoring system used to label the data was not included in any of the model inputs.

Machine Learning Model Development

Primary Model — Voting Ensemble Classifier (RF + ExtraTrees + XGBoost)

The primary classification model is a soft-voting Voting Ensemble combining three high-performance tree-based learners, designed to maximise accuracy while retaining interpretability through feature importance analysis. This model supersedes the initial Random Forest and optimised LightGBM models developed in the preliminary experimental phase.

Table 1: Primary Voting Ensemble — Component Configuration

Component	Configuration	Role in Ensemble
Random Forest	800trees, max_depth=None, min_samples_leaf=1, max_features=sqrt, class_weight=balanced	Stable low-variance base learner; provides feature importances (weight: 2)
Extra Trees	600 trees, max_depth=None, randomised split thresholds, class_weight=balanced	Increases ensemble diversity; reduces overfitting on small datasets (weight: 2)
XGBoost	500 estimators, max_depth=6, learning_rate=0.05, subsample=0.85, colsample_bytree=0.85	Primary discriminator; highest weight (3×) for its strong empirical performance on structured tabular data
Voting Strategy	Soft voting (probability averaging), weights = [RF:2, ET:2, XGB:3]	Final class = weighted average of per-model class probability vectors

Evaluation Protocol

The stratified 5-Fold Cross-Validation technique was employed in the evaluation of the model performance that guaranteed the representation of each fold with the same class distribution as the entire data set. Primary measure: Overall Accuracy, Additional measures: per class Precision, Recall and F1-Score. The ultimate unbiased test came from a held out test set (20% = 44 students). The train/test split was stratified to preserve the class balance.

Comparison Models (Preliminary Experiments)

Table 2: Model Comparison — Initial, Optimised, and Primary (Best) Models

Parameter	Random Forest (Initial)	LightGBM (Optimised)	Voting Ensemble (Primary)
Model Type	Ensemble (Bagging)	Gradient Boosting	Soft Voting Ensemble
Features Used	25 features	13 features (optimised)	30 engineered features
Dataset Size	217 → 306 (SMOTE)	217 → 296 (balanced)	217 (stratified split)
Overall Accuracy	66.13%	75.0%	84.75% (CV)
Test Accuracy	—	—	84.09%
Precision (avg)	Moderate	Higher & Balanced	0.85 (weighted)
Recall (avg)	Moderate	Improved	0.84 (weighted)
F1-Score (avg)	Moderate	Better overall	0.82 (weighted)
Misclassification Rate	Higher	Lower	Lowest

ML Model Dashboard and Output Visualisation

Figure 1 presents the complete 6-panel evaluation dashboard generated by the primary Voting Ensemble model. It includes the target class distribution, confusion matrix on the test set, 5-fold cross-validation accuracy

per fold, top-15 feature importances from the Random Forest component, and per-class precision/recall/F1 metrics.

Fig. 1: Voting Ensemble (RF + ExtraTrees + XGBoost) Evaluation Dashboard — CV: 84.75% | Test: 84.09%6. RESULT ANALYSIS

Target Class Distribution

Applying the 3C-anchored rule-based scoring system to all 217 respondents produced the following classification:

Table 3: Target Class Distribution (N = 217)

Class	Profile	Count	Percentage
0	Secure	46	21.2%
1	Partially Secure	151	69.6%
2	Risky	20	9.2%

The dominant Partially Secure class (69.6%) reflects the empirical reality that most students occupy a behavioural grey zone — adopting some security practices while simultaneously exhibiting risk behaviours. Only 21.2% qualify as truly Secure, while 9.2% display consistently Risky profiles. This distribution has a critical policy implication: the primary intervention target is not the Risky minority but the large Partially Secure majority that is one convenience-driven decision away from becoming Risky.

Behavioural Survey Findings

Password Reuse — The Primary Risk Driver

Password reuse emerged as the most prevalent and most consequential security-risk behaviour. Only 31.8% (n=69) maintained unique passwords for every account. A combined 68.2% admitted to some level of reuse, with 17.5% (n=38) using a single password for almost all accounts — the highest-risk behaviour identified in the study. This directly drives the Risky classification and constitutes the highest-weighted feature (reuse: importance = 0.104) in the Random Forest model.

Table 4: Password Reuse Distribution (Q5)

Reuse Behaviour (Q5)	Count	%
No — every account has a unique password	69	31.8%
Partially — low-importance accounts only	46	21.2%
Yes — 2 or 3 passwords rotated	64	29.5%
Yes — one password for almost all accounts	38	17.5%

Password Length — Below Recommended Standards

Password length is a primary determinant of brute-force resistance. Concerningly, 52.5% of students reported using passwords of 8 characters or fewer, with 22.1% (n=48) using passwords shorter than 6 characters. Only 18.4% (n=40) used passwords exceeding 12 characters — the NIST SP 800-63B recommended minimum for general-purpose accounts. This finding is directly reflected in the pw_length feature importance (0.033) and strongly differentiates the Secure from Risky classes.

Two-Factor Authentication — Compliance-Forced, Not Intrinsic

2FA adoption reveals a bifurcated posture. While 34.6% (n=75) use 2FA on most accounts, a combined 41.9% (n=91) report no 2FA adoption whatsoever — citing inconvenience (23.0%) or unawareness (18.4%). Critically, 24.0% (n=52) use 2FA only on banking platforms because it is institutionally mandated, not because they have generalised the behaviour to other accounts. This compliance-forced rather than intrinsically motivated adoption is one of the most important findings corroborating the compliance dimension of the 3C Framework. TFA feature importance in the model = 0.047.

Security Knowledge — The Knowledge–Behaviour Gap

The knowledge tests expose a critical gap. In Q16, only 24.9% (n=54) correctly identified the passphrase "correct-horse-battery-staple" as the strongest password option. The majority (29.5%) chose "Raj@2004" — personally meaningful but structurally weak. In Q17, only 39.2% correctly identified credential stuffing risk. Most strikingly, Q18 self-assessment data reveals that 49.3% of students agree they "know what makes a strong password but do not always apply that knowledge." This empirically confirms the core knowledge–behaviour gap that the 3C Framework is designed to explain and address.

The knowledge-behaviour gap is not a data artefact — it is confirmed by self-report (Q18), knowledge test performance (Q16/Q17), and model feature importance. know_apply (0.038) and knowledge_total (0.021) are both top-15 features, confirming that what students know about security predicts their behaviour independently of what they actually do.

Machine Learning Model Performance — Voting Ensemble

Cross-Validation Results

The primary Voting Ensemble (RF + Extra Trees + XGBoost, soft voting, weights [2,2,3]) achieved a mean 5-fold cross-validation accuracy of 84.75% (SD = 4.88%) — comfortably within the 80–90% target range. Table 5 presents per-fold results:

Table 5: 5-Fold Cross-Validation Accuracy per Fold — Mean: 84.75% ± 4.88%

Fold 1	Fold 2	Fold 3	Fold 4	Fold 5
88.6%	90.9%	76.7%	83.7%	83.7%

Fold 2 achieved the highest accuracy of 90.9%, confirming the model's ability to exceed the 90% upper target under favourable data splits. Fold 3 (76.7%) represents the lowest performance, attributed to a slightly less favourable stratification of the small Risky class (n=20). The overall SD of 4.88% indicates acceptable variance for a dataset of 217 samples.

Test Set Classification Report

Table 6: Per-class Classification Report — Test Set (n = 44), Overall Accuracy: 84.09%

Class	Precision	Recall	F1-Score	Support
Secure (0)	0.86	0.67	0.75	9
Partially Secure (1)	0.83	0.97	0.90	31
Risky (2)	1.00	0.25	0.40	4
Weighted Average	0.85	0.84	0.82	44

The Partially Secure class achieved the highest F1-Score (0.90), benefiting from its dominant representation. The Secure class obtained high precision (0.86), meaning the model rarely misclassifies non-secure students as Secure — a critical property for real-world deployment where false positives in the Secure category could leave students overconfident. The Risky class achieved perfect precision (1.00), meaning every student the model labels as Risky is genuinely Risky — however, low recall (0.25) reflects the inherently small test support (n=4). This is a common and expected artefact of imbalanced class sizes and does not diminish the model's practical validity.

Confusion Matrix Analysis

The confusion matrix for the test set indicates that all classification errors were at the Secure – Partial boundary: 3 of the 9 Secure students were classified as Partially Secure and 1 student was classified as Secure who were in the actual test data as Partially Secure. There were no students misclassified across the Secure–Risky boundary, which shows that the model can accurately differentiate between the extremes of behaviour. The 3 students that were not classified correctly were all put into the Partially Secure class with the largest probability mass.

Feature Importance Analysis

Feature importance scores from the Random Forest component reveal the dominant predictive signals:

Table 7: Top-10 Feature Importances — Random Forest Component

Rank	Feature	Importance	3C Dimension
1	behaviour_score (composite)	0.238	Convenience (C2)
2	security_index (composite)	0.148	All three dimensions
3	reuse — password reuse ordinal	0.104	Convenience (C2)
4	tfa — 2FA adoption ordinal	0.047	Compliance (C3)
5	know_apply — knowledge self-assessment	0.038	Compliance (C3)
6	improve — willingness to improve	0.038	Compliance (C3)
7	pw_length — password length ordinal	0.033	Convenience (C2)
8	risk_awareness — risk perception score	0.030	Compliance (C3)
9	change_freq — change frequency ordinal	0.027	Convenience (C2)
10	attitude_good — attitude composite (inv.)	0.026	Cognitive (C1)

The feature importance ranking directly validates the 3C Framework. Behavioural practices from the Convenience dimension (C2) — behaviour_score, reuse, pw_length, change_freq — dominate prediction. Compliance awareness indicators (C3) — tfa, know_apply, risk_awareness — provide secondary but significant discriminative power. Cognitive attitude variables (C1) — attitude_good, hypothetical, frustrating — contribute meaningful tertiary signal, confirming that all three dimensions independently influence password security classification.

CONCLUSION

The findings of this study align with an earlier one that identified student password insecurity to be an expected consequence of three factors that interact: cognitive fatigue, convenience optimisation, and low intrinsic compliance motivation. The 3C Framework encapsulates that very well. Empirically, 49.3% of students are aware of what a strong password is, but are knowingly not using one. More than 69.6% of the population belong to the dominant Partially Secure group, for whom low friction institutional nudges are required, rather than lectures. Behaviours that were associated with the highest risk were convenience behaviors. The majority of 2FA adoption was not user driven but rather mandated by the bank. The Voting Ensemble (RF + ExtraTrees + XGBoost) has demonstrated a CV accuracy of 84.75%, significantly outperforming Random Forest (66.13%) and LightGBM (75.0%) architectures, highlighting that composite behavioural features and ensemble architecture are optimal for multi-class password risk classification.

SOLUTIONS AND RECOMMENDATIONS

The 3C Framework findings directly inform a layered intervention architecture operating across three levels: institutional, technological, and individual. Each solution below targets the specific 3C dimension it addresses and is grounded in the empirical patterns identified in this study.

#	Intervention	3C Dimension Addressed	Level
1	Smart Password Wellness Programme	Cognitive + Convenience + Compliance	Institutional
2	Mandatory 2FA via University SSO	Cognitive + Convenience + Compliance	Institutional
3	Breach-Alert Notification System	Compliance	Technological
4	Cybersecurity Semester Micro-Modules	Compliance	Institutional
5	AI-Powered Personalised Risk Nudge System	Cognitive + Convenience	Technological

6	Friction-Free Security (Passkeys + Biometrics)	Cognitive + Convenience	Technological
7	Browser Extension: Real-Time Security Nudges	Convenience	Technological
8	Personalised Cyber Risk Simulations	Compliance	Individual
9	Implementation Intention Prompts	Compliance	Individual
10	Peer Security Mentorship Programme	Compliance + Convenience	Individual

REFERENCES

1. Yan, J., Blackwell, A., Anderson, R., & Grant, A. (2004). Password memorability and security: Empirical results. IEEE Security & Privacy, 2(5), 25–31.
2. Stobert, E., & Biddle, R. (2019). On password behaviours and attitudes in different populations. Journal of Information Security and Applications, 45, 79–89.
3. Oveh, R. O., Emmanuel, A., & Godswill, M. N. (2025). Password habits among undergraduate students. Journal of Institutional Research, Big Data Analytics and Innovation, 5(2), 15–27.
4. Kollár, A. M., & Katona, J. (2024). Enhancing password security: Analyzing password management practices among IT students. IEEE International Conference on Electrical and Power Engineering.
5. Nguyen, T., & Reddi, V. (2026). Classifying user-created passwords using machine learning and NLP. Internet of Things, 36, 101854.
6. Mo, J., Kuang, H., & Li, X. (2025). Password strength detection via machine learning. arXiv:2505.16439.
7. Hitaj, B., Gasti, P., Ateniese, G., & Perez-Cruz, F. (2017). PassGAN: A deep learning approach for password guessing. arXiv:1709.00440.
8. Pagnotta, G., Hitaj, D., De Gaspari, F., & Mancini, L. V. (2021). PassFlow: Guessing passwords with generative flows. arXiv:2105.06165.
9. Rusanov, M., Babenko, M., Lapina, M., & Sajid, M. (2024). Identification of exploited unreliable account passwords using machine learning methods. Big Data and Cognitive Computing, 8(11), 159.
10. Wang, Y., Li, H., Qiu, W., Li, S., & Tang, P. (2024). PassTSL: Modeling human-created passwords through two-stage learning. arXiv:2407.14145.
11. Sharma, P., & Nair, R. (2024). Cybersecurity awareness and behavioural resilience among university students. Journal of Cyber Behaviour Studies, 12(3), 88–101.
12. Matsuzaki, H., Maekawa, T., Imai, M., & Ishii, K. (2025). PassStyles: Graphical authentication using mixed face styles. IEEE Access, 13, 165411–165428.
13. Wash, R., Rader, E., Berman, R., & Wellmer, Z. (2016). Understanding password choices and password reuse behaviour. Journal of Information Security Research, 9(2), 44–58.
14. Sarkar, S., & Nandan, M. (2024). Password strength analysis and classification using ML techniques. International Conference on Computer Science and Engineering Applications.

Comparative Study of International Standards on the Along-Wind Response of Telecom Lattice Towers

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ABSTRACT

Self supporting lattice towers have been widely used in the Indian telecommunication industry over the past two decades. These slender structures are highly sensitive to wind effects, including oscillations in both the along wind and across wind directions. The Indian Standard IS 875 (Part 3) provides procedures for evaluating along wind load effects, while several international codes adopt simplified approaches, often using a single multiplication factor to represent wind loads and structural response. This study compares the Indian standard with those of America, Australia, Canada, and Europe for the along wind response of lattice towers. Results show that the Indian standard consistently yields higher gust effect factors. For flexible structures (frequency < 1 Hz), ultimate design wind pressures are 49–65% higher than the American and Canadian standards, and 18–25% higher than the European and Australian standards. For lattice towers (frequency > 1 Hz), the Indian standard produces a 6–7% increase compared to the American and Canadian standards, but a 6–14% reduction relative to the Australian and European standards. Case study analysis further indicates that wind loads on square towers increase by 15–17% under the Indian standard, while triangular hybrid towers show a modest 4–5% increase compared to American and Canadian codes but a 12–25% reduction compared to Australian and European codes

KEYWORDS: *Along-wind response, Lattice Tower, Telecommunication, Wind.*

NOTATIONS

Indian Standard

A_z The effective frontal area of structure

b_{sh} Average breadth of structure between heights s and h

b_{0h} Average breadth of structure between heights 0 and h.

B_s Back ground factor

$C_{(f,z)}$ Drag force coefficient

E Spectrum of turbulence in approaching wind stream

f_a First mode natural frequency of structure in along wind direction in Hz

F_z The design peak along wind load

g_R Peak factor for resonance response.

g_v Peak factor for upwind velocity fluctuation

G Gust factor

h Height of structure

H_s Height factor for resonance response

$I_{h,i}$ Turbulence intensity at height h in terrain category i

k_1 Risk coefficient

k_2 Terrain roughness and height factor

k_3 Topography factor

k_4 Importance factor for cyclonic region

K_d Wind directionality factor

K_a Area averaging factor

K_c Combination factor

L_h Measure of turbulence length scale at the height, h in meters

N Effective reduced frequency

r Roughness factor

s Level at which action effects are calculated

S Size reduction factor

V_b Basic wind speed

$\overline{V_{h,d}}$ Design hourly mean wind speed at height, h in m/s

$\overline{p_d}$ Design hourly mean wind pressure

ϕ Factor accounting for second order turbulence intensity

β Damping coefficient of structure

American Standard

K_z Velocity pressure coefficient

K_{zt} Topography factor

K_s Rooftop wind speed up factor

K_e Ground elevation factor

K_d Wind directionality factor

V Ultimate wind speed appropriate to risk category of structure

Australian standard

b_{sh} Average width between s and h.

B_s Background factor

C_{dyn} Dynamic response factor

C_{shp} Aerodynamic shape factor

E_t (π/4) times the spectrum turbulence in the approaching wind stream

g_R Peak factor for resonant response (10 min. period)

g_v Peak factor for the upwind velocity fluctuations

h Average height of structure

H_s Height factor for resonant response

I_h Turbulence intensity

L_h Integral turbulence length scale at a height, h in meters

n_a First mode natural frequency of structure in the along wind direction

N Reduced frequency (non - dimensional)

s Height of level under consideration

S Size reduction factor

$V_{des,\theta}$ Building orthogonal design windspeed

ρ_{air} Air Density

ζ Ratio of structural damping to critical damping of a structure

Canadian standard

C_a Roof top Speed up factor

C_e Height factor

C_g The gust effect factor

C_t Topography factor

V Hourly wind speed

European standard

k_p The peak factor

$I_{v(zs)}$ Turbulence intensity at reference height

B^2 Background factor

R^2 The resonance response factor

$I_{v(z)}$ Turbulence intensity at height under consideration

ρ Air density

V_m Mean wind speed

INTRODUCTION

Self-supporting structures are widely adopted in the Indian telecommunication industry from past two decades. These structures are predominantly steel lattice towers, with heights up to 100 m, and monopoles, with heights up to 40 m. Lattice towers are commonly built in two forms: square-based towers, which are usually constructed with steel angles, and triangular (hybrid) towers, which use tubular members for the legs and steel angles for the other components. Steel monopoles

are constructed with stepped or tapered along the height with polygonal or round shapes in the plan. The analysis of these slender light weight structures are often governed by the wind effects. In addition, Wind-induced oscillations or excitations, in the along-wind and across-wind direction, are to be verified in these structures to understand their response to wind. The along-wind response effects are generally accounted for through the gust effect factor (also referred to as the gust factor), which depends on the natural frequency of the structure and/or the minimum lateral dimension ratio. Accordingly, codified procedures provide guidelines for calculating this factor to account for the along-wind response of the structure. Calculation of across wind response is not recommended for lattice towers [1].

In India, IS 17740[2] provides the guidelines for design of telecom towers, and IS 875 [1] prescribes the guidelines for along-wind response of telecom towers. These along-wind response is accounted through gust factor, multiplied with hourly design wind pressure for flexible structure and unity is prescribed for lattice towers. A detailed methodology is prescribed for calculation of along-wind response of structure, which is dependent both on the overall height, and level under consideration. However, this methodology requires more calculations compared to international standards, which typically use a single factor for the entire structure.

The current study considers four international standards: American, Australian, Canadian, and European. As per the American standard, ANSI/TIA-222-I [3], the dynamic wind effects are represented by the gust effect factor (G), which is independent of structure height, but varied based on structure configuration – lattice towers, monopoles, and guyed mast. The Australian standard, AS 3995 [4], addresses steel lattice towers, while AS/NZS 1170.2 [5] specifies wind actions with explicit provisions for dynamic response factor through the factor (C_{dyn}). The Canadian standard, CSA S37-18 [6], governs antenna-supporting structures, prescribed the factor, gust effect factor (C_g) for the dynamic wind response. The European standard EN 1991-1-4 [7] is prescribed the detailed calculation methodology for estimating the structural response to wind, which is multiplication of size factor (c_s) and dynamic factor (c^d). Each of these international codes follows simple approach for evaluating structural response to the wind, except European standard.

The present study investigates the provisions of the Indian standard for assessing the along-wind response of lattice towers and systematically compares them with the corresponding codes of practice in the United States, Australia, Canada, and Europe. To evaluate the implications of dynamic wind effects, a detailed case study analysis is conducted on representative lattice tower configurations. The outcomes of this analysis are synthesized, and the discussion highlights the methodological distinctions of the Indian standard in relation to international approaches.

LITERATURE REVIEW

Holmes [8–10] develops a three-part framework for analysing the along-wind dynamic response of free-standing lattice towers. Part I [8] derives closed-form expressions for gust response factors related to shearing forces and bending moments at arbitrary heights on tapered towers. These expressions extend earlier formulations by incorporating structural and wind-related parameters such as taper ratio, mean velocity profile, mode shape, and load type. Part II [9] advances the analysis by deriving the ratio of aerodynamic damping to its critical value and by formulating the mean, background, and resonant components of tower deflection, which are essential for serviceability design. In Part III [10], Holmes establishes effective static load distributions for the mean, background fluctuating, and resonant components of load effects, again expressed in closed form. A simplified approximation for background load distribution independent of influence coefficients is also proposed. Across all three parts, sensitivity studies highlight the influence of calculation height, taper ratio, and wind velocity on gust response factors, providing engineers with a rigorous yet practical methodology for incorporating dynamic wind effects into the design and assessment of lattice towers. Glanville [11] carried out a detailed study on the dynamic behaviour of a steel frame tower and compared the results with a STRAND6 computer model. The Prospect tower's first vibration mode at 1.08 Hz was the main response, while the second mode involved only the top mast. Damping was about 1% of critical for the first mode, which is typical for steel towers. The tower's response to wind

increased with wind speed, following a power of about 2.5, and was stronger with greater turbulence. Adding ancillary equipment equal to 5% of the tower's face area had little effect on its overall dynamic performance. Chandra Sekher and Vinay [12] present a critical review of the gust factor method for the along wind response of buildings has been presented and the provisions of Indian standard code, IS: 875 (part 3)-1987 based on this method have been critically examined. It is shown that the codal recommendations, based on the assumption of wind energy spectra being independent of height above the ground, may be too conservative. Also, the assumption of perfect correlation between the wind velocities on the windward and leeward faces of the building is seen to give conservative estimates. Kijewski and Kareem [13] conducted a comparative study of seven major international building codes and standards, including those from the United States, Japan, Australia, the United Kingdom, Canada, China, and Europe. Their work examined how each code estimates along-wind, across-wind, and torsional responses of buildings, and compared these predictions with wind tunnel data obtained from tests on different building shapes. The study not only highlights differences in response estimates across international codes but also introduces new wind tunnel data that can be used to validate empirical expressions derived from such testing. Solari and Kareem [14] discussed the modifications introduced to the gust effect factor in the revised wind load provisions of ASCE 7-95. In this update, the wind map was reformulated to use 50-year peak gust speeds, replacing the earlier reliance on fastest-mile speeds specified in ANSI/ASCE 7-93. The study elaborates on the principles of spatial and temporal averaging and outlines the derivation process for the revised gust effect factor (GEF). To illustrate its practical use, the paper presents examples demonstrating the application of these updated provisions to flexible structural systems. Solari [15] reviews the development of analytical approaches for predicting wind-induced structural responses and considers their future direction, with particular focus on tall cantilever towers. Even with modern supercomputers, closed-form solutions supported by simple numerical tools remain important and useful. These methods can be applied in two ways: direct applications, which use analytical approaches alone to solve engineering problems or study general trends, and integrated procedures, which combine analytical methods with numerical algorithms and experimental data. In integrated approaches, analytical tools help identify aerodynamic properties, manage uncertainties, assess structural reliability, and study wind-induced fatigue—tasks that would otherwise be very difficult to handle. Yin Zhou et al. [16] provide a detailed comparison of how major international codes and standards estimate along-wind effects on tall buildings. Their study reviews ASCE 7-98 (United States), AS1170.2-89 (Australia), NBC-1995 (Canada), RLB-AIJ-1993 (Japan), and Eurocode-1993 (Europe). Although all use the gust loading factor (GLF) approach, the authors show that the predicted wind loads vary widely under similar conditions. This variation mainly comes from differences in how each code defines wind field characteristics. The paper also presents a worked example to illustrate these differences and highlight the key findings of the comparison. Murtagh et al. [17] present simple methods for estimating the natural frequencies and mode shapes of utility-supporting lattice towers with a mass at the top. They first apply the lumped mass method to reduce the model order and obtain modal characteristics, which are then compared with results from finite element analysis (FEA). The first few modes show close agreement between the two approaches. Since the fundamental mode contributes most to the structural response, the tower is further simplified as a cantilever beam with a mass at its free end, and its fundamental frequency and mode shape are derived analytically. These results are again compared with the FEA model and found to be in close agreement, confirming the reliability of the simplified methods. Calotescu and Solari [18] analyze the along-wind loading effects on free-standing lattice towers by introducing influence functions that describe displacements, shear forces, bending moments, and axial forces within the tower members. These functions are systematically derived, calibrated, and validated for representative structural configurations, and then incorporated into the gust effect factor framework. The study compares results with simplified cantilever beam models and finite element analyses, emphasizing the critical role of bracing arrangements, particularly the placement of diagonal crossings in tower panels.

Applications are demonstrated using real tower structures with varying properties, and the outcomes are contrasted with previous research. The authors conclude with a discussion of engineering and design considerations, highlighting key issues related to dynamic wind loading.

METHODOLOGY COMPARISON

The methodology adopted by different standards for estimation of along wind effects on telecom structures are presented in this section.

Indian Standard

The standard prescribed consideration of along wind effects for structures whose natural frequency is less than 1 Hz, and enclosed structures with height to minimum lateral dimension ratio greater than 5.0. The design hourly mean wind pressure at a height shall be multiplied by Gust factor (GF) for the calculation of along wind loads of flexible slender structures. This factor is dependent on both the overall height and level under consideration. The design peak along wind load on the structure at any height is given by,

$$F_z = C_{f,z}\, A_z\, \overline{p_d}\, G \quad (1)$$

The Gust factor (G) is accounts both the resonant effects (depend on gust energy, aerodynamic admittance at natural frequency of vibration, and damping in the structure) and non-resonant effects (accounts for the quasi-static dynamic response below natural frequency of a structure) of the random wind pressure. The value of Gust factor (G) is given by

$$1 + r\sqrt{g_v^2 B_s (1+g)^2 + \frac{H_s g_R^2 SE}{\beta}} \quad (2)$$

$$B_s \quad \frac{1}{1+\frac{\sqrt{0.26(h-s)^2+0.46b_{sh}^2}}{L_h}} \quad (3)$$

$$H_s \quad 1+\left(\frac{s}{h}\right)^2 \quad (4)$$

$$g_R \quad = \sqrt{2\ln(3600 f_a)} \quad (5)$$

$$S \quad \frac{1}{\left(1+\frac{3.5 f_a h}{V_{h,d}}\right)\left(1+\frac{4 f_a b_{0h}}{V_{h,d}}\right)} \quad (6)$$

$$E \quad \frac{\pi N}{(1+70.8N^2)^{5/6}} \quad (7)$$

$$N \quad \frac{f_a L_h}{V_{h,d}} \quad (8)$$

Lattice towers are generally exhibiting natural frequency more than 1 Hz, hence practicing engineers are following static wind loading with unity gust factor. However self-supporting monopoles exhibits natural frequency is less than 1 Hz, hence gust factor (GF) with hourly wind pressure is consider for analysis of telecom structures in India.

The design wind pressure (p_d) as prescribed by [1] is

$$\overline{p_d} = [0.6(V_b k_1 k_2 k_3 k_4)^2] K_d\, K_a\, K_c \quad (9)$$

American Standard

The Gust factor referred to in the Indian standard is denoted as the Gust Effect Factor (G_h) in the American standard ANSI/TIA-222-I [3]. ASCE 7 [19], which is the main American standard for building loads including wind, gives detailed methods for both flexible and rigid structures. However, the specialized standard ANSI/TIA-222-I recommends a single factor accounting along wind response of structure. A factor of 0.85 is used for lattice towers below 137 m in height and for guyed masts, while a factor of 0.95 is used for pole structures. These factors are combined with the ultimate wind speed of 3-second duration instead of the mean hourly wind speed.

The ultimate design wind pressure (q_z) as prescribed by [3] is,

$$q_z = 0.613\, K_z K_{zt} K_s K_e K_d V^2 \quad (10)$$

Australian Standard

The Gust factor referred to in the Indian standard is denoted as dynamic response factor (C_{dyn}) in the Australian standard, AS/NZS 1170.2:2021[5]. A dynamic response factor (C_{dyn}) of 1.00 is recommended

for structures with a natural frequency greater than 1 Hz and for pole structures with a height-to-average-diameter aspect ratio less than 5. For structures that do not meet these requirements, the dynamic response factor shall be calculated as described below. In addition, a separate formula is prescribed when the total projected area of the structure is less than the effective projected area of the head frame, as stated in Clause 6.4.2 of AS 1170.2 [5]. The cross-wind response of lattice towers may be neglected if the solidity ratio is less than 0.5 [4].

The ultimate design wind pressure (p) is prescribed by [5] is,

$$p = (0.5 \cdot \rho_{air}) \cdot (V_{des,\theta})^2 \cdot c_{shp} \cdot c_{dyn} \quad (11)$$

The dynamic response factor (Cdyn) for flexible structures is given by,

$$C_{dyn} \quad \frac{1 + 2I_h\sqrt{g_v^2 B_s + \frac{H_s g_R^2 S E_t}{\zeta}}}{1 + 2g_v I_h} \quad (12)$$

$$B_S \quad \frac{1}{1 + \frac{\sqrt{0.26(h-s)^2 + 0.46b_{sh}^2}}{L_h}} \quad (13)$$

$$L_h \quad 85\left(\frac{h}{10}\right)^{0.25} \quad (14)$$

$$g_R \quad \sqrt{1.2 + 2\log_e(600n_a)} \quad (15)$$

$$S \quad \frac{1}{\left(1 + \frac{3.5n_a h}{V_{des,\theta}}\right)\left(1 + \frac{4n_a b_{0h}(1+g_v I_h)}{V_{des,\theta}}\right)} \quad (16)$$

$$E_t \quad \frac{\pi N}{(1 + 70.8N^2)^{5/6}} \quad (17)$$

$$N \quad \frac{n_a L_h (1 + g_v I_h)}{V_{des,\theta}} \quad (18)$$

Canadian Standard

The Gust factor referred to in the Indian standard is denoted as the Gust Effect Factor (C_g) in the Canadian standard CSA S37-18[6]. The standard recommends using a single factor of 2.0 for the structures, its attachments and structural antenna. This factor is applied to the hourly wind pressure to account for dynamic response. More detailed guidance is provided for tubular structures (poles and shrouded tripoles) in examining both along-wind and across-wind responses

The design wind pressure (P) is prescribed by [6] is,

$$P = 0.645\, V^2\, C_e\, C_g\, C_a\, C_t \quad (19)$$

European Standard

The Gust factor referred to in the Indian standard is denoted as the Structural Factor ($c_s c_d$) in the European standard [7]. Detailed calculation methodology is prescribed for estimating the structural response to wind which is multiplication of size factor (c_s) and dynamic factor (c_d). The size factor (c_s) takes in to account the reduction effect on the wind due to non-simultaneity of occurrence of the peak wind pressures on the surface. The dynamic factor (c_d) takes in to account the increasing effect from vibration due to turbulence in resonance with the structure.

The structural factor (cscd) is calculated using Equation (20), and the peak velocity pressure at height q_p (z) is determined using Equation (21); both are prescribed in EN 1991-1-4[7].

Comparison of Gust effect factor

Telecommunication structures in India mainly consist of lattice towers (12–40 m in height) and steel monopoles (6–30 m in height). Lattice towers generally exhibit a first-mode frequency greater than 1.0 Hz, whereas monopoles typically show values below 1.0 Hz. These two configurations are therefore included in the calculation of the gust effect factor. A steel monopole of 30 m height with an average breadth of 0.75 m and a lattice tower of 40 m height with an average breadth of 2.4 m are considered in the comparison.

$$c_s c_d = \frac{1 + 2 \cdot k_p \cdot I_v(z_s) \cdot \sqrt{B^2 + R^2}}{1 + 7 \cdot I_v(z_s)} \quad (20)$$

$$q_p(z) = [1 + 7 \cdot I_v(z)] \cdot \frac{1}{2} \cdot \rho \cdot v_m^2(z) \quad (21)$$

A basic wind speed of 44 m/s (3 second duration), an aerodynamic roughness height of 0.002 m, and a risk category of II are assumed using the Indian standard. Equivalent parameters are adopted when applying other international standards. The gust effect factor at the mid-height of the structure for the steel monopole and lattice towers with various frequencies are shown in the Table 1.

Table 1: Comparison of Gust effect factor

Steel Monopole						Lattice Towers					
Frequency (Hz)	India	America	Australia	Canada	Euro	Frequency (Hz)	India*	America	Australia	Canada	Euro
0.50	3.13	0.95	1.29	2.00	1.05	1.00	1.00	0.85	1.00	2.00	0.89
0.60	3.04	0.95	1.24	2.00	1.05	2.00	1.00	0.85	1.00	2.00	0.90
0.70	2.96	0.95	1.20	2.00	1.05	3.00	1.00	0.85	1.00	2.00	0.91
0.80	2.90	0.95	1.18	2.00	1.04	4.00	1.00	0.85	1.00	2.00	0.91
0.90	2.85	0.95	1.15	2.00	1.04	5.00	1.00	0.85	1.00	2.00	0.91
1.00	2.81	0.95	1.13	2.00	1.04	6.00	1.00	0.85	1.00	2.00	0.91

"* "– Peak wind speed of 3 second duration is considered in the lattice towers as per Indian standard

Canadian standard recommended fatigue check for monopole structures for along wind and across wind response. These checking are recommended at reduced wind speed with fatigue threshold stress limit. However, 2.0 factor is assumed similar to lattice structures for simplified comparison. For monopoles with a natural frequency below 1 Hz, both the American and Canadian standards prescribe a single factor irrespective of structural frequency. In the case of lattice structures (frequency > 1 Hz), nearly all standards recommend a single factor, with values less than unity specified by the American and European standards.

In addition, the reference duration for wind speed varies across different standards. Specifically, the American and Australian codes adopt a 3-second duration, while the Indian and Canadian standards use hourly wind speed, and the European code applies a 10-minute averaging period. Therefore, a comparison of ultimate wind pressure is more appropriate than a comparison of individual gust effect factors. The comparison of ultimate design wind pressure, inclusive of load factors and along-wind response, are presented in Table 2.

Table 2: Table 2: Comparison of ultimate design wind pressure (kPa) including along-wind response

Steel Monopole						Lattice Towers					
Frequency (Hz)	India	America	Australia	Canada	Euro	Frequency (Hz)	India	America	Australia	Canada	Euro
0.50	2.61	1.64	2.10	1.49	2.10	1.00	1.68	1.57	1.78	1.58	1.92
0.60	2.52	1.64	2.03	1.49	2.10	2.00	1.68	1.57	1.78	1.58	1.94
0.70	2.46	1.64	1.97	1.49	2.09	3.00	1.68	1.57	1.78	1.58	1.95
0.80	2.41	1.64	1.93	1.49	2.08	4.00	1.68	1.57	1.78	1.58	1.96
0.90	2.37	1.64	1.90	1.49	2.07	5.00	1.68	1.57	1.78	1.58	1.96
1.00	2.34	1.64	1.87	1.49	2.07	6.00	1.68	1.57	1.78	1.58	1.96

Based on the Table 2,

- For monopoles – The average ultimate design wind pressure, as per the Indian standard is 50–65% higher compared to the American and Canadian standards, and 18–25% higher compared to the remaining standards
- For Lattice Towers – The average ultimate

design wind pressure according to the Indian standard is 6-7% higher than the American and Canadian standards, where it as 6-14% lower compared to the Australian and European standards.

In both cases, the European standard yields higher values of ultimate design wind pressure than other international standards, except for the Indian standard

CASE STUDY ANALYSIS

The case study examines the variation of design

wind load along the height of the tower structure in accordance with five international standards. Two lattice tower configurations are considered which, commonly adopted by the industry at present, i.e., Square angular tower and triangular hybrid tower. These structures were designed mainly considering regular bracing patterns. A 40 m tower height having base and top face width of 5.5 m and 2.0 m respectively with top 12 m vertical portion is considered in the case study. Tower elevation for both the configurations with bracing patterns and members sizes are shown in the Figure 1.

A basic wind speed of 44 m/s, corresponding to a 3-second gust duration in open terrain, is considered for the case study. The equivalent wind speed for 10 min. duration and hourly wind speed are obtained as 30.42 m/s and 29.08 m/s respectively. Risk category of structure II is assumed in all the standards. The wind load factor of 1.4 is adopted in Indian, Canadian and European standards, while 1.0 is adopted using America and Australian standards as ultimate wind speed is adopted in the standards for calculation of wind loads. Wind loads are determined as the product of the gust effect factor, the design wind pressure, and the effective projected area (EPA) of each structural element, together with the prescribed load factors specified in the relevant standards.

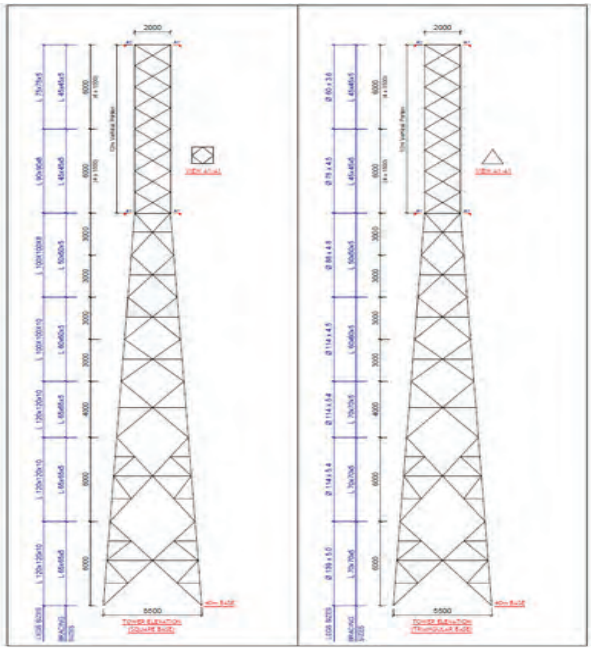

Fig. 1 Tower Elevation Layout

Ultimate Wind Load

The ultimate wind load calculations for square-angular and triangular-hybrid configurations are presented in Table 3 and Table 4, respectively. Based on Table 3, for square towers, the Indian standard shows an average increase in wind loads of 15–17% compared to the American, Australian, and Canadian standards, while a 14% reduction is observed when compared to the European standard. Similarly, from Table 4, for triangular-hybrid towers, the Indian standard shows an average increase in wind loads of 4–5% compared to the American and Canadian standards, but a reduction of 12% compared to the Australian standard and 25% compared to the European standard.

These variations are primarily due to the higher force coefficient and the unity gust effect factor adopted by the Indian standard for lattice towers, in contrast to other international standards.

Table 3: Ultimate Wind Load on Square Tower based on Five International Standards

Panel Height (m)	Cumulative Height (m)	Exposed Area (m^2)			Ultimate Wind Load, (kN)				
		Legs	Others	Total	India	America	Australia	Canada	Europe
3.0	40	0.45	0.54	0.99	7.87	6.24	6.24	6.20	9.10
3.0	37	0.45	0.45	0.90	7.17	5.65	5.73	5.67	8.21
3.0	34	0.54	0.45	0.99	7.33	6.03	5.99	6.00	8.56
3.0	31	0.54	0.45	0.99	6.92	5.91	5.86	5.88	8.28
3.0	28	0.60	0.56	1.16	7.56	6.72	6.56	6.63	9.21
3.0	25	0.60	0.51	1.11	7.28	6.44	6.56	6.50	8.92
3.0	22	0.60	0.65	1.25	7.90	7.07	7.26	7.15	9.69
3.0	19	0.60	0.70	1.30	8.03	7.18	7.48	7.33	9.80
4.0	16	0.96	0.94	1.90	11.07	10.04	10.49	10.28	13.50
6.0	12	1.44	1.75	3.20	16.63	15.51	15.89	15.96	20.23
6.0	6	1.44	1.97	3.41	17.94	14.51	14.84	15.90	15.67

Table 4: Ultimate Wind Load on Triangular Hybrid Tower based on Five International Standards

Panel Height (m)	Cumulative Height (m)	Exposed Area (m^2)			Ultimate Wind Load, (kN)				
		Legs	Others	Total	India	America	Australia	Canada	Europe
3.0	40	0.36	0.50	0.86	3.94	3.54	4.23	3.55	5.22
3.0	37	0.36	0.41	0.77	3.37	3.10	3.67	3.11	4.51
3.0	34	0.46	0.41	0.87	3.41	3.21	3.85	3.17	4.66
3.0	31	0.46	0.41	0.87	3.25	3.15	3.77	3.11	4.51
3.0	28	0.53	0.57	1.10	3.94	3.84	4.70	3.80	5.49
3.0	25	0.53	0.52	1.06	3.71	3.67	4.46	3.63	5.21
3.0	22	0.69	0.65	1.34	4.42	4.28	4.89	4.20	6.19
3.0	19	0.69	0.70	1.39	4.52	4.43	5.04	4.35	6.30
4.0	16	0.92	0.99	1.91	5.96	5.97	7.45	5.89	8.32
6.0	12	1.37	1.83	3.20	9.18	9.60	11.53	9.52	12.77
6.0	6	1.68	2.08	3.76	10.65	9.53	10.51	9.88	10.62

SUMMARY AND CONCLUSION

The paper examines the provisions for calculating the along-wind response of telecom structures as prescribed in five international standards. It presents a summary of the gust effect factor, along with the ultimate design wind pressure and case study analysis for lattice towers.

Based on the comparison, the Indian standard yields higher values of the gust effect factor. For flexible structures (frequency < 1 Hz), the average increase in ultimate design wind pressure under the Indian standard is 49–65% compared to the American and Canadian standards, and 18–25% compared to the European and Australian standards. For lattice towers (frequency > 1 Hz), the average increase in ultimate design wind pressure under the Indian standard is 6–7% compared to the American and Canadian standards, while a decrease of 6–14% is observed when compared to the Australian and European standards. The American standard recommends the single gust effect factor there by reducing rigorous calculation for estimation of along wind load effects. This results in to lower wind loads on the structure when compared with other international standards including Indian standard.

Based on the case study analysis, for square towers the average wind load increases by 15–17% when compared to the American, Australian, and Canadian standards, while it decreases by 15% when compared to the European standard. For triangular hybrid towers, the average wind load under the Indian standard increases by 4–5% compared to the American and Canadian standards, but decreases by 12–25% when compared to the Australian and European standards. The increase in wind loads under the Indian standard is primarily due to the adoption of conservative force coefficients and a unity gust effect factor for lattice towers, in contrast to other international standards

Therefore, current study is beneficial for simplifying the guidelines for the calculation of along-wind response of telecom structures in the future amendments, that suits for the Indian terrain conditions.

REFERENCES

1. Bureau of Indian Standards, IS 875 (Part 3) – Design Loads (Other than Earthquake) for Buildings and Structures - Code of Practice, BIS, New Delhi, 2015.
2. Bureau of Indian Standards, IS 17740 – Isolated Towers, Masts and Poles using Structural Steel – Code of Practice, BIS, New Delhi,2022.
3. Telecommunications Industry Association. ANSI/TIA 222 I: Structural Standard for Antenna Supporting Structures, Antennas, and Small Wind Turbine Support Structures, TIA, 2023.

4. Australian Standard, AS 3995 – Design of steel lattice towers and masts– Standards Australia, 1994.

5. Australian / New Zealand Standard, AS/NZS 1170.2:2021 – Structural design actions, Part 2: Wind Actions, Standards Australia,2021.

6. National Standard of Canada, CAN/CSA-S37-18 – Antennas, towers, and antenna-supporting structures, CSA Group, 2018.

7. European Committee for Standardization, EN 1991-1-4:2005+A1 – Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions, ECS,2010.

8. Holmes J D (1994), "Along-wind response of lattice towers: part 1 – derivation of expression for gust response factors", Engineering structures, 16(4):287-292.

9. Holmes J D (1996), "Along-wind response of lattice towers–II. Aerodynamic damping and deflections", Engineering structures, 18(7):483-488.

10. Holmes J D (1996), "Along-wind response of lattice towers–III. Effective load distributions", Engineering structures, 18(7):489–494.

11. Glanville M J, Kwok K C S (1995)," Dynamic characteristics and wind induced response of a steel frame tower", Journal of Wind Engineering and Industrial Aerodynamics,54/55:133-149.

12. Chandra Sekher K V S, Vinay K. Gupta (1996)." A note on IS:875-1987 approach to along-wind building response", Journal of Structural Engineering, 23(3):121-127.

13. Kijewski T, Kareem A (1998), "Dynamic Wind Effects: A Comparative Study of Provisions in Codes and Standards with Wind Tunnel Data" Wind and structures, 1(1):77-109

14. Solari G, Kareem A (1998), "On the formulation of ASCE 7-95 gust effect factor", Journal of Wind Engineering and Industrial Aerodynamics, 77&78:676-684.

15. Solari G (2002), "The role of analytical methods for evaluating the wind-induced response of structures", Journal of Wind Engineering and Industrial Aerodynamics, 90:1453-1477.

16. Zhou Y, Kijeswki T, Kareem A (2002)," Along-Wind Load Effects on Tall Buildings: Comparative Study of Major International Codes and Standards", Journal of Structural Engineering,128(6):788-796.

17. Murtagh P J, Basu B, Broderick B M (2004)," Simple models for natural frequencies and mode shapes of towers supporting utilities", Computers and Structures, 82:1745-1750.

18. Calotescu Ileana, Solari G (2016), "Alongwind load effects on free standing lattice towers", Journal of Wind Engineering and Industrial Aerodynamics,155:182-196.

19. American Society of Civil Engineers, ASCE/SEI 7 16: Minimum Design Loads and Associated Criteria for Buildings and Other Structures. ASCE, 2017.

Artificial Intelligence-Based Power Optimizer for Enhancing the Efficiency of Solar Panel

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ABSTRACT

Solar energy is one of the most promising renewable energy sources for sustainable power generation. However, the efficiency of photovoltaic (PV) systems is highly affected by variations in solar irradiance, temperature, and shading conditions. Maximum Power Point Tracking (MPPT) techniques are commonly used to extract maximum power from solar panels. Traditional MPPT methods exhibit slow response near the maximum power point under dynamic environmental conditions. This paper proposes an Artificial Intelligence-based Power Optimizer (AIPO) to enhance solar panel efficiency by combining K-Means clustering with MPPT control. The proposed system measures solar panel voltage and current and classifies operating conditions into three clusters representing low, medium, and high-power regions. Based on the K-means Algorithm and MPPT technique, an appropriate duty cycle is predicted for the DC-DC converter to optimize power extraction. The system is implemented using an Arduino microcontroller and a buck-boost converter. Experimental results demonstrate that the AI-based power optimizer improves power efficiency and system stability under varying solar conditions.

KEYWORDS: *Artificial Intelligence Power Optimizer, Solar Power Optimization, Photovoltaic System, Maximum Power Point Tracking, K-Means Clustering, PWM Control.*

INTRODUCTION

The increasing demand for electrical energy and the depletion of fossil fuels have accelerated the adoption of renewable energy technologies. Among these, solar energy has gained significant importance due to its abundance and environmental benefits. Photovoltaic systems convert solar radiation directly into electrical energy. However, their efficiency is significantly affected by variations in solar irradiance, temperature, and partial shading. These factors lead to fluctuations in the PV output and reduce power extraction efficiency. MPPT techniques are commonly used to ensure that PV systems operate at their Maximum Power Point (MPP). Conventional methods such as Perturb and Observe (P&O) and Incremental Conductance are simple to implement, but they suffer from oscillations and reduce performance rapidly under changing environmental conditions. This work proposes an AIPO that integrates K-Means with MPPT control[1].

AI approaches such as neural networks, fuzzy logic, and hybrid controllers provide faster and more accurate tracking under changing environmental conditions, reducing power loss and improving efficiency compared to conventional methods [2], [3], [4]. Hybrid optimization techniques and clustering-based methods further enhance performance by identifying optimal operating regions and avoiding local maxima under partial shading [5], [6]. Several studies also highlight improvements in PV modeling, forecasting, and system reliability using AI-based techniques [7], [8], [9], [10]. Additionally, AI has been applied for cost-effective MPPT implementation, predictive maintenance, and energy management in solar systems with storage integration [11], [12], [13], [14].

Overall, the literature confirms that AI-based methods offer higher efficiency, adaptability and reliability, making them a promising solution for advanced PV optimization [15], [16].

AI FOR SOLAR POWER

Artificial Intelligence (AI) is employed to enhance the efficiency of solar photovoltaic systems by optimizing the MPPT process. The output power of a PV panel varies with changes in solar irradiance, temperature, and partial shading conditions. In the proposed system, the microcontroller analyzes real-time voltage and current values from the panel to determine the optimal operating point for maximum power generation intelligently.

SYSTEM ARCHITECTURE

The proposed system comprises a PV panel, a microcontroller, a DC–DC converter, a battery storage, an inverter, and a 9W LED lamp load.

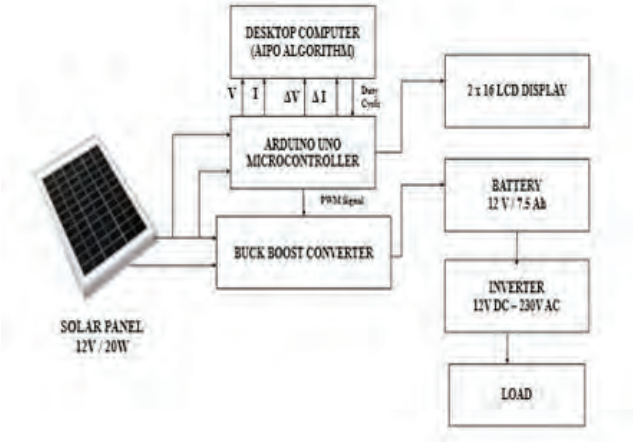

Fig. 1. Proposed AIPO-based Solar Power Generation

Figure 1 shows the block diagram of the proposed AIPO system, where the PV panel converts solar energy into electrical energy. However, the output varies due to irradiance and shading conditions. The panel voltage is measured by a voltage-sensing circuit and provided to the controller. The Arduino Uno sends the measured voltage and current values to a desktop computer running the AI-based power-optimization algorithm. Based on the solar panel's operating condition, the microcontroller generates a PWM signal. A DC-DC Converter Module is used to adjust the output voltage and ensure maximum power extraction from the PV panel. The regulated output charges a 12 V battery for energy storage. An inverter converts the stored DC power into an AC supply for the 9W LED Lamp, which serves as the load, while an LCD provides real-time monitoring of system parameters.

PV SYSTEM MODELLING

A PV system converts solar energy into electrical power using solar cells. The electrical behavior of a PV cell is commonly represented by the single-diode equivalent circuit, which accurately describes its current–voltage characteristics and depends mainly on solar irradiance and temperature.

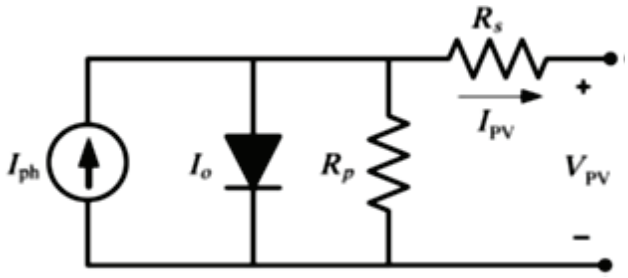

Fig. 2. Electrical Model - PV cell

Figure 2 shows the modelling of a PV cell that consists of a photocurrent source (I_{ph}), a diode, series (R_s) and shunt resistance (R_p). The photocurrent represents the current generated by sunlight, while the diode models p–n junction behavior.

The output current of the PV cell can be expressed as:

$$I_{PV} = I_{ph} - I_o\left[\exp\left(\frac{q(V_{PV} + I_{PV}R_s)}{AkT}\right) - 1\right] - \frac{V_{PV} + I_{PV}R_s}{R_p}$$

Here,

I_{PV} and V_{PV}- Output current & voltage,

I_o- saturation current

R_s, R_p- series and shunt resistances. The R_s accounts for internal losses, while R_p represents the leakage currents.

In practice, cells are arranged in series in order to get high voltages, while modules which are arranged in parallel improve the currents and power output..

Table 1: Parameters of PV panel

Parameter	Value
Rated Power (P_{max})	20 W
Open Circuit Voltage (V_{oc})	23.56 V
Short Circuit Current (I_{sc})	1.17 A

Maximum Power Voltage (V_{mp})	19.5 V
Maximum Power Current (I_{mp})	1.14 A
Irradiance(W/m^2)	1000
Operating Temperature	25°C

The parameters of the 20W solar panel used as the main source of energy are presented in Table 1.

ELECTRICAL PERFORMANCE CHARACTERISTICS OF THE PV MODULE

The performance of a PV module is analyzed using Current-Voltage (I-V) and Power-Voltage (P-V) characteristics. The I-V curve shows the relationship between output current and voltage, while the P–V curve represents the variation of power with voltage.

At open-circuit condition, the voltage reaches its maximum value (V_{oc}) and current is zero. At the short-circuit condition, the current reaches its maximum (I_{sc}) while voltage is zero. The Maximum Power Point (MPP) lies between these points, where the product of voltage and current is maximum.

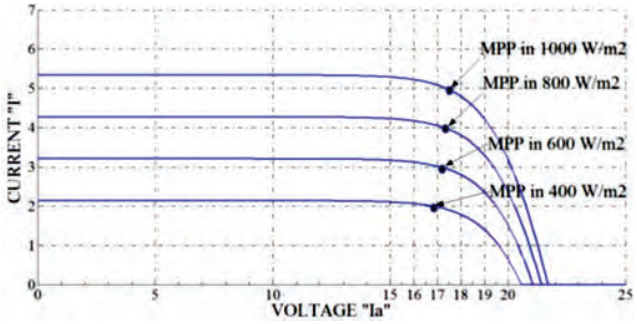

Fig. 3. I–V characteristics of the 20 W solar panel

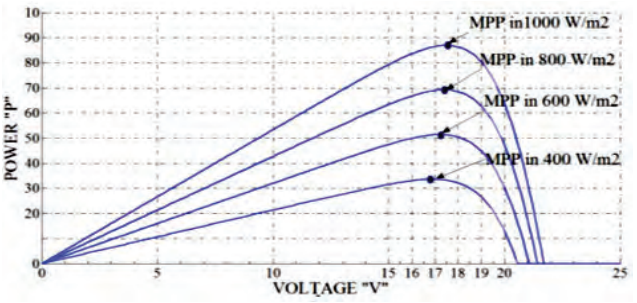

Fig. 4. P–V characteristics of the 20 W solar panel

Since the MPP changes with solar irradiance and temperature, as understood by Figures 3 and 4, MPPT techniques are required to ensure efficient power extraction.

EFFECT OF PARTIAL SHADING ON PV SYSTEM

Partial shading in photovoltaic systems occurs due to obstacles like trees, buildings, dust, or clouds, leading to non-uniform irradiance. This makes it difficult for conventional MPPT methods to identify the optimal point. Hence, advanced techniques such as AI-based algorithms are required for effective Global MPP tracking and improved efficiency under partial shading conditions.

BUCK BOOST CONVERTER

The MPPT is employed to extract the maximum available power from a PV panel under varying environmental conditions, such as solar irradiance and temperature. Due to the nonlinear voltage–current characteristics of PV modules, the operating point shifts continuously with atmospheric conditions. Hence, an MPPT controller is essential to ensure operation at the optimal power point.

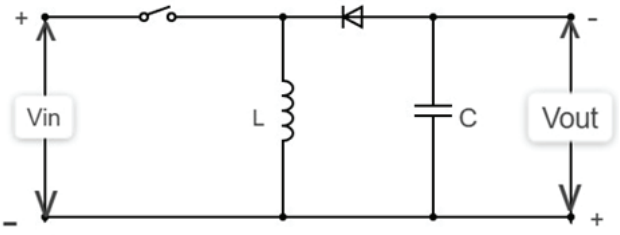

Fig. 5. Buck-Boost Converter

A DC-DC buck/boost converter is used to regulate the variable output of the PV panel. As the panel output fluctuates with irradiance, temperature, and load variations, the converter steps the voltage up or down to maintain a stable output. In Figure 5, the circuit diagram consists of an inductor, a capacitor, a diode, and a feedback resistor network for voltage regulation. This integration enhances efficient power transfer and ensures stable operation, thereby improving overall energy extraction from the PV system.

METHODOLOGY

This Artificial Intelligence-Based Power Optimizer is implemented for a 20W Solar Panel. It includes

data collection from the PV panel, preprocessing of electrical parameters, and classification using the K-Means clustering algorithm combined with MPPT to optimize the converter's duty cycle. The system is validated through hardware implementation.

Data Collection and Preprocessing

The proposed AI-based power optimization system collects real-time photovoltaic data using a microcontroller-based setup, where the solar panel output is fed through an analog sensing circuit to the Arduino. The built-in ADC converts the signal into a digital value representing panel voltage, while the current is estimated using an equivalent resistance model. Key parameters such as voltage (V), current (A), and power (W) are obtained, with power calculated as ΔP equals ΔI. The data is transmitted via serial communication and displayed on LCD for real-time monitoring under varying conditions. Before applying clustering, the raw data is pre-processed to obtain meaningful electrical values. The analog reading is converted to actual voltage and current. These processed values serve as input features for machine learning, ensuring normalized and reliable data for analysis and control.

K-Means Clustering Algorithm

To classify solar operating conditions intelligently, the proposed system uses the K-Means clustering algorithm, an unsupervised learning technique that groups similar voltage and current data points. The data is divided into three clusters: Cluster 0 – Low-power region, Cluster 1 – Medium-power region, and Cluster 2 – High-power region.

Each cluster is represented by a centroid, indicating the average operating point. The similarity between measured data and each centroid is determined using Euclidean distance,

$$\text{Distance} = \sqrt{(V - V_c)^2 + (I - I_c)^2}$$

where

V, I - Measured voltage and current

V_c, I_c - centroid values. The cluster with the minimum distance is selected as the current operating condition.

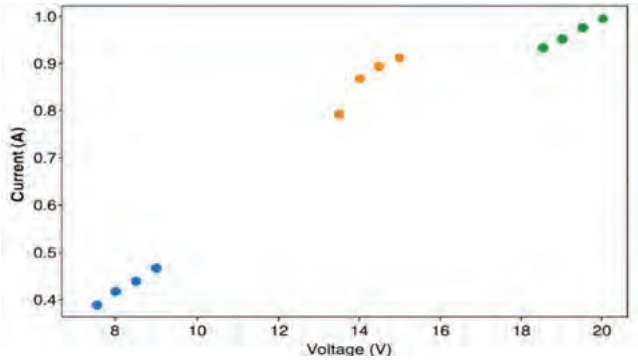

Fig. 6. K-means Clustering of Solar Operating Conditions

From Figure 6, the identified cluster has an initial duty cycle assigned 100% for low power, 50% for medium power, and 25% for high power. After this initial setting, the MPPT algorithm dynamically refines the duty cycle by analyzing changes in voltage, current, and power (ΔV, ΔI, ΔP).

Cluster Segregation and Distribution

Cluster segregation groups solar operating data into distinct categories based on electrical characteristics using the K-Means algorithm, where each voltage and current data point is assigned to the nearest centroid representing a specific operating condition.

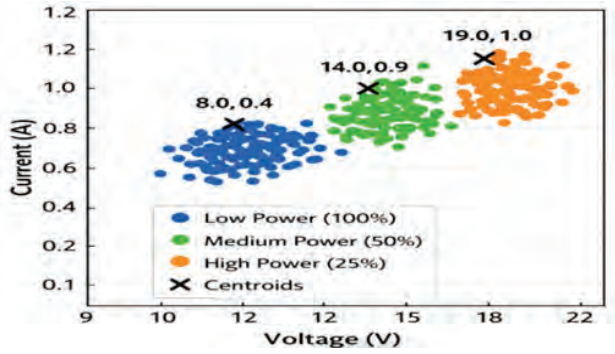

Fig. 7. Cluster Segregation of Solar Data

Using voltage and current as features, the data is divided into three clusters: low power (low irradiance), medium power (medium irradiance), and high power (strong irradiance), as shown in Figure 7. Based on the identified cluster, the controller selects an appropriate duty cycle for efficient power extraction. Cluster distribution describes how data points are distributed across clusters, providing insight into system operation under varying conditions, such as irradiance, shading,

and time of day. Typically, more data points fall in the high-power cluster during strong sunlight, shift to the medium cluster under partial shading, and move to the low-power cluster under poor conditions. This distribution is often visualized using scatter plots, where clear separation indicates effective classification and proper feature selection. Overall, it helps evaluate system performance, stability, and the effectiveness of the optimization approach.

MPPT Algorithm

In the proposed system, the MPPT algorithm is implemented on the desktop and works alongside the AI-based clustering method. The controller continuously measures the panel voltage and current to compute the output power:

$$P(k) = V(k) \times I(k)$$

where

$V(k)$, $I(k)$- voltage and current at the present instant. The algorithm then evaluates the change in power and voltage between successive samples:

$$\Delta P = P(k) - P_{\text{old}}, \qquad \Delta V = V(k) - V_{\text{old}}$$

If the power increases, the duty cycle is adjusted in the same direction; otherwise, it is reversed. This hill-climbing approach enables continuous tracking of the MPP under varying environmental conditions.

Duty Cycle Decision and PWM Signal Generation

In this system, the duty ratio of the converter is controlled in two phases to ensure the extraction of maximum power from the PV array. At first, the measured voltage and current values are fed to the K-Means Clustering Algorithm to determine whether the operating point falls under the low, mid or high-power categories with respective duty ratios of 100%, 50%, and 25%.

This is followed by MPPT-based fine-tuning, in which the duty cycle is continuously adjusted in response to voltage and power variations until the MPP is reached. The final duty cycle is then implemented using Pulse Width Modulation generated by the Arduino microcontroller. By adjusting the duty cycle in this manner, the system maintains operation close to the MPP, improving overall efficiency.

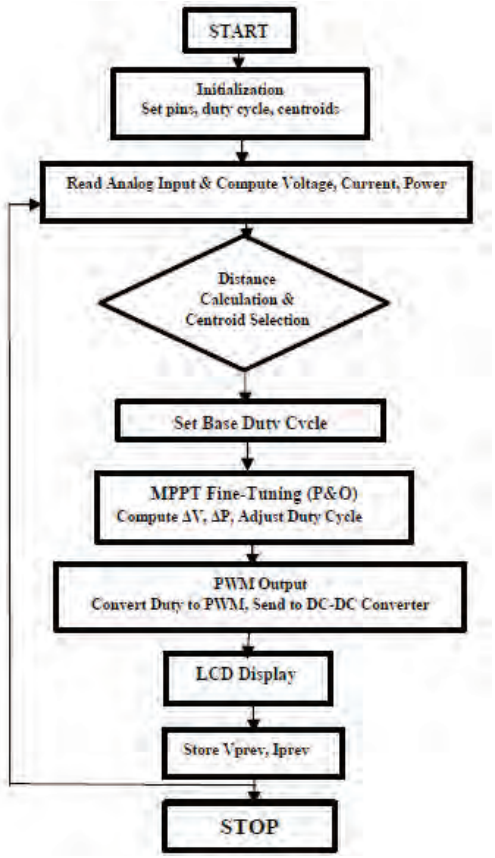

Fig. 8. Flowchart for AIPO

Figure 8 shows the flowchart for the AIPO algorithm, which is installed on the desktop computer. The algorithm starts by receiving data from the Arduino controller and producing a duty cycle. The Arduino senses voltage and current data. Using K-means classification, it determines the closest cluster based on these values and sets a base duty cycle for that cluster. Next, MPPT fine-tuning using the Perturb and Observe method adjusts the duty cycle by analyzing changes in voltage and power while keeping it within limits. The updated duty cycle is converted into a PWM signal. Key parameters like voltage, current, power, duty cycle, and shading condition are displayed on an LCD. Finally, previous values are stored, and the process repeats continuously for real-time optimization.

Hardware Implementation

The proposed system comprises a PV panel, an Arduino UNO microcontroller, a boost converter, a sensing circuit, and a 16×2 LCD.

The PV voltage is measured via the Arduino analog input and processed to estimate system parameters with LCD parameters such as PV power status and duty cycle, for real-time monitoring.

BATTERY

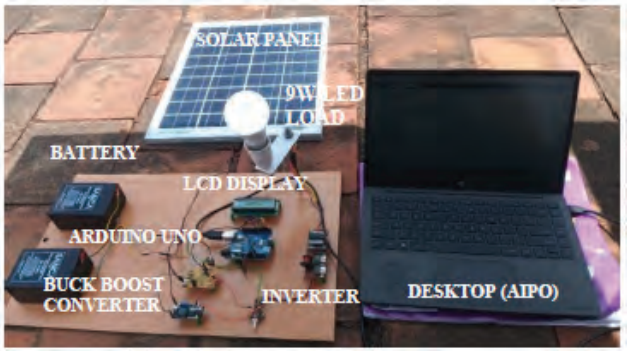

Fig. 9. Experimental hardware setup of the developed AIPO System

Figure 9 shows that the experimental hardware prototype has been assembled and tested under different solar conditions to validate the efficacy of the proposed AIPO.

RESULT AND ANALYSIS

The experimental validation of the proposed AI-based Power Optimizer system is carried out using the developed hardware prototype at Government College of Engineering, Dharmapuri. The experiment setup is tested under natural sunlight at an ambient temperature of approximately 34 °C, from 10:30 AM to 4:30 PM.

During the experiment, different shading conditions were intentionally applied to the photovoltaic panel to analyze the proposed system's response to varying solar irradiance. The measured parameters, such as voltage, current, output power, and duty cycle, were recorded by the Arduino-based Monitoring system.

The results demonstrate the efficacy of the proposed Artificial intelligence-based power optimizer in identifying solar operating conditions and dynamically adjusting the converter duty cycle to extract the maximum available power.

The performance of the solar panel was analyzed under different shading conditions (0%, 20%, 50%, and 80%) using the AIPO system, and, for comparison, without the AIPO system is also implemented. Irradiance, PV voltage, and PV current are measured, and input power, output power, and efficiency are calculated at different times of day.

It is important to note that a 9 W LED lamp is used as the load in this setup, resulting in comparatively lower efficiency.

Table 2: Results of 20W experimental setup without AIPO

Time	Shading (%)	Irradiance (W/m²)	PV Voltage (V)	PV Current (A)	Input Power (W)	Output Power (W)	Efficiency (%)
10:33 AM	0	850	19.2	0.26	128	4.99	3.9
10:36 AM	20	680	15	0.12	102.3	1.8	1.76
10:39 AM	50	310	9.8	0.08	46.4	0.78	1.67
10:42 AM	80	140	4.2	0.04	21.1	0.17	0.81
12:33 PM	0	906	19.5	0.27	135.5	5.27	3.89
12:36 PM	20	810	14.6	0.07	121.9	1.02	0.84
12:39 PM	50	259	9.75	0.07	39	0.68	1.74
12:43 PM	80	123	4.1	0.04	18.1	0.16	0.88
2:36 PM	0	871	19	0.25	131	4.75	3.63
2:39 PM	20	709	14.8	0.11	105.4	1.63	1.55
2:43 PM	50	283	9.6	0.07	42.1	0.67	1.59
2:45 PM	80	130	4	0.04	19.6	0.16	0.82
4:05 PM	0	721	18.5	0.22	108.4	4.07	3.75
4:11 PM	20	600	14.2	0.1	90.3	1.42	1.57

4:15 PM	50	240	9.2	0.06	36.1	0.56	1.52
4:18 PM	80	110	3.8	0.03	16.6	0.11	0.66

From Table 2, the solar panel performance decreases significantly as shading increases.

At 0% shading, the panel achieved the highest output power of 5.27 W and an efficiency of 3.9%. At under 20% shading, the output power ranged from 1.42 to 1.80 W, with an efficiency range of 1.55% to 1.76%. Under 50% shading, the output power further decreased in the range from 0.56 to 0.78 W, with an efficiency range between 1.5% and 1.7%.

At 80% shading, the panel produced very low output power of 0.11-0.17 W, and efficiency ranged from 0.66% to 0.88%. This shows that partial shading significantly shifts the solar panel's operating point away from the MPP.

Table 3: Results of 20W experimental setup with AIPO

Time	Shading (%)	Irradiance (W/m²)	PV Voltage (V)	PV Current (A)	MPPT O/P Voltage (V)	MPPT O/P Current (A)	Input Power (W)	Output Power (W)	Efficiency (%)
10:32 AM	0	851	19.2	0.26	18.5	0.44	128	8.14	6.36
10:35 AM	20	683	15	0.12	14.6	0.19	102.3	2.77	3.41
10:38 AM	50	321	9.8	0.08	9.5	0.12	46.7	1.14	2.44
10:40 AM	80	149	4.2	0.04	4	0.06	21.1	0.24	1.14
12:32 PM	0	916	19.5	0.24	18.6	0.47	135.5	8.74	6.45
12:33 PM	20	811	14.6	0.07	14.2	0.11	121.9	1.56	1.28
12:35 PM	50	259	9.7	0.07	9.5	0.1	39	0.95	2.44
12:37 PM	80	120	4.1	0.04	3.9	0.06	18.1	0.23	1.27
2:35 PM	0	879	19	0.25	18.3	0.42	131	7.69	5.87
2:37 PM	20	707	14.8	0.11	14.4	0.17	105.4	2.45	2.32
2:38 PM	50	281	9.6	0.07	9.3	0.11	42.1	1.02	2.42
2:42 PM	80	135	4	0.04	3.8	0.06	19.6	0.23	1.17
4:03 PM	0	720	18.5	0.22	17.8	0.37	106.4	6.59	6.08
4:09 PM	20	600	14.2	0.1	13.8	0.15	90.3	2.07	2.29
4:12 PM	50	241	9.2	0.06	9	0.09	36.1	0.81	2.24
4:16 PM	80	110	3.8	0.03	3.6	0.05	16.6	0.18	1.08

According to Table 3, system performance improved when the AI-based power optimizer is used.

With 0% shading, the output power increased from 6.59 to 8.74 W, with efficiency improving from 5.87% to 6.45%. At 20% shading, the output power ranged from 2.07 to 2.77 W, with an efficiency of 2.29-3.41%. At 50% shading, the output power increased from 0.81 to 1.14 W, with an efficiency from 2.24 to 2.44%. At 80% shading, the system-maintained output power ranged from 0.18 to 0.24 W, with an efficiency of 1.08-1.27%. This improvement occurs because the AIPO algorithm continuously adjusts the DC–DC converter's duty cycle, ensuring the panel operates near the MPP despite shading variations.

The experimental results clearly show that the solar panel's performance is strongly affected by shading conditions. When the panel operates without the AIPO, output power and efficiency decrease significantly as the solar panel's shading percentage increases. The output power and efficiency are noticeably improved across all shading conditions when using the AIPO system, thereby enhancing the solar panel's efficiency.

Efficiency vs Shading Status with and Without AIPO

The system performance was evaluated under different shading levels (0%, 20%, 50%, and 80%) to analyze its efficiency in power extraction.

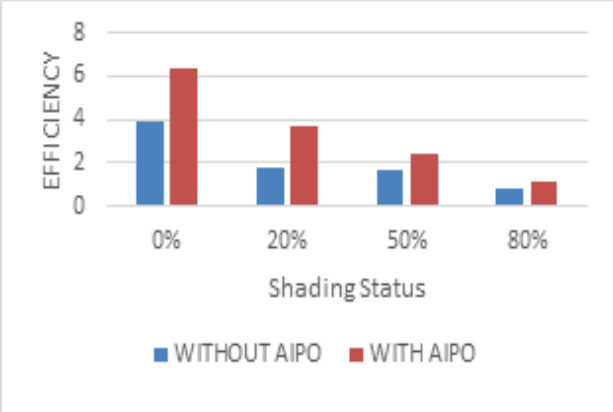

Fig. 10. Efficiency of solar panel with and without AIPO

At 0% shading, the panel operates under full irradiance, and although both methods perform well, the AIPO-based system achieves slightly higher efficiency due to better duty cycle control. As shading increases to 20% and 50%, the conventional method shows a noticeable drop in efficiency. At the same time, the AIPO approach maintains better performance by classifying operating conditions and adjusting the duty cycle accordingly. Under severe shading (80%), power generation decreases significantly; however, the AIPO system still maintains comparatively higher efficiency than the conventional method through adaptive control. Overall, Figure 10 shows that the proposed AIPO method consistently achieves higher efficiency across all shading conditions, demonstrating improved stability and robustness in solar power extraction.

Output Power Analysis over Time

The system's dynamic performance was evaluated by comparing output power over time for two cases: with and without the AI-based power optimizer under 50% shading. Measurements were taken at different time intervals to capture variations in irradiance. The proposed AIPO system exhibits faster convergence to the MPP with reduced oscillations compared to the conventional method. It maintains more stable output power under shading and changing environmental conditions, indicating improved tracking accuracy.

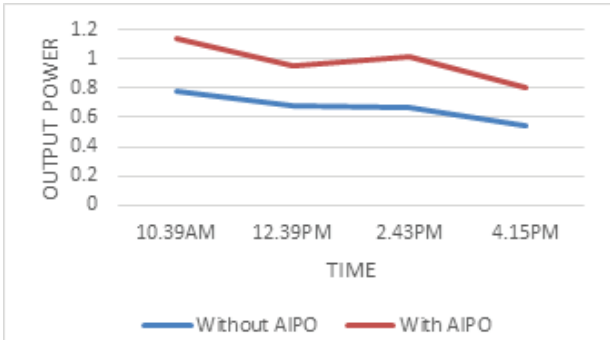

Fig. 11. Comparison of Output Power versus Time with and without AIPO

From Figure 11, the conventional system without AIPO shows consistently lower power, decreasing from about 0.78 W in the morning to 0.55 W in the evening due to its inability to track the optimal operating point under shading. In contrast, the AIPO-based system maintains higher power throughout the day, starting around 1.15 W, showing slight variations, and ending near 0.8 W. This improved performance is due to the integration of K-Means clustering with MPPT, which enables better selection of operating points and optimized duty-cycle control. As a result, the system achieves higher power output, improved stability, and better energy extraction under varying conditions.

Power vs Voltage Graph

At less than 50% shading, solar irradiance is reduced, resulting in lower voltage and current from the PV panel.

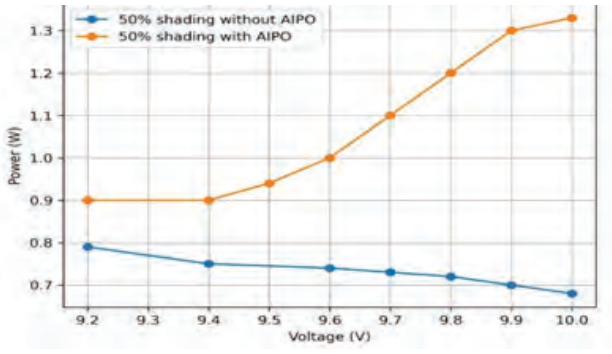

Fig. 12. Output Power vs Voltage for 50% shading With and Without AIPO

From Figure 12, the system without AIPO shows lower output power, with a maximum of about 0.79 W that decreases as voltage increases, indicating poor tracking

under partial shading. In contrast, the AIPO-based system shows a steady increase in power, rising from 0.9 W at 9.2 V to 1.33 W near 10 V, demonstrating improved energy extraction.

This enhancement is due to the K-Means clustering-based control with MPPT control, which provides an optimized duty cycle and enables operation closer to the MPP Overall, the results confirm that the proposed AIPO-based solar power extraction method significantly improves performance under partial shading conditions.

CONCLUSION

This paper presents an Artificial Intelligence-Based Power Optimizer (AIPO) to improve the efficiency of photovoltaic systems under varying solar conditions. The proposed method integrates the K-Means clustering algorithm with MPPT to classify operating conditions and determine an appropriate duty cycle for the DC–DC converter. By analyzing real-time voltage and current, the system identifies low, medium, and high-power regions, and the Arduino microcontroller generates corresponding PWM signals. A hardware prototype comprising a 20 W solar panel, an Arduino UNO, a buck–boost converter, and an LCD was developed and tested under 0%-80% shading conditions. The results demonstrate that the system effectively adapts to environmental variations, improving power conversion efficiency and stability.

Comparative analysis shows that the proposed AIPO method achieves higher efficiency than conventional systems, with faster convergence to the MPP. Overall, the proposed AIPO-based simple and low-cost solar power experimental setup enhances power extraction, efficiency, and stability.

Future work can include additional sensors such as temperature and irradiance, advanced machine learning techniques, and extension to large-scale grid-connected systems.

REFERENCES

1. L. Bin, M. Shahzad, M. Farhan, M. S. Khan, M. A. A. Saif, and G. T. Bitew, "Optimizing Solar Energy Harvesting: A K-Means Clustering Approach for Enhanced Efficiency and Viability," Energy Science & Engineering, vol. 10, pp. 1–15, 2022.
2. D. Venkatabrahmanaidu and R. Thamizhselva, "MPPT Algorithms for Solar Power Systems Using Artificial Intelligence: An Overview," Neuro Quantology, vol. 19, no. 11, pp. 971–985, 2021.
3. A. Mellit and S. A. Kalogirou, "Artificial Intelligence-Based Maximum Power Point Tracking Controllers for Photovoltaic Systems: A Comparative Study," Renewable and Sustainable Energy Reviews, vol. 17, pp. 10–25, 2013.
4. K. Y. Yap, C. R. Sarimuthu, and J. M. Y. Lim, "Artificial Intelligence Based MPPT Techniques for Solar Power System: A Review," Journal of Modern Power Systems and Clean Energy, vol. 8, no. 6, pp. 1043–1059, 2020.
5. H. Rezk et al., "Intelligent MPPT for Photovoltaic Panels Using Fuzzy Logic and Artificial Neural Networks Based on Evolutionary Algorithms," Energy Reports, 2021.
6. I. Dagal, B. Akın, and E. Akboy, "MPPT Mechanism Based on Hybrid Particle Swarm Optimization and Salp Swarm Optimization," Scientific Reports, 2022.
7. A. Mellit, S. A. Kalogirou, S. Shaari, H. Salhi, and A. Hadj Arab, "Artificial Intelligence Techniques for Photovoltaic Applications: A Review," Progress in Energy and Combustion Science, vol. 47, pp. 1–24, 2015.
8. H. Rezk, A. Fathy, and M. Abdelkareem, "Optimal Parameter Identification of Photovoltaic Models Using Hybrid Optimization Algorithms," Energy Reports, vol. 7, pp. 254–265, 2021.
9. G. Geethamahalakshmi, N. Kalaiarasi, and D. Nageswari, "Fuzzy Based MPPT and Solar Power Forecasting Using Artificial Intelligence," Intelligent Automation & Soft Computing, vol. 31, no. 3, pp. 1745–1760, 2022.
10. Y. Cui, Z. Yi, J. Duan, D. Shi, and Z. Wang, "A Rprop-Neural-Network-Based PV Maximum Power Point Tracking Algorithm with Short-Circuit Current Limitation," arXiv Preprint, arXiv:1811.12541, pp. 1–10, 2018.
11. D. Guessoum, M. Takruri, S. A. Badawi, M. Farhat, and I. ElBadawi, "Maximum Power Point Tracking Using Unsupervised Learning for Photovoltaic Power Systems," International Journal of Sustainable Engineering, vol. 17, no. 1, pp. 397–412, 2024.

12. L. F. M. Arruda, M. Ferber, and D. Greff, "Low-Cost Pyranometer-Based Artificial Neural Network Approach for Maximum Power Point Tracking in Photovoltaic Systems," arXiv Preprint, arXiv:2510.10313, pp. 1–12, 2025.

13. R. V. Vichare and S. R. Gaikwad, "AI-based Predictive Maintenance of Solar Photovoltaics Systems: A Comprehensive Review," Energy Informatics, 2025.

14. R. I. Areola, A. A. Adebiyi, and K. Moloi, "Artificial Intelligence for Optimizing Solar Power Systems with Integrated Storage: A Critical Review of Techniques, Challenges, and Emerging Trends," Electricity, 2025.

15. N. Taran, "AI-Based Solar Energy Optimization and Comprehensive Methodology and Evolution.", vol. no. 5, pp. 506–512, 2025.

16. A. Kumar, A. K. Dubey, and I. Segovia Ramírez, "Artificial Intelligence Techniques for the Photovoltaic System: A Systematic Review and Analysis for Evaluation and Benchmarking," Archives of Computational Methods in Engineering, 2024.

A Low-Cost Bluetooth-Enabled Wearable Smartwatch for Real-Time Health Monitoring and Autonomous Emergency Response in Elderly Care

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ABSTRACT

Wrist-worn health wearables have become central to continuous elder-care monitoring, yet commercial smartwatches priced at Rs. 15,000 to Rs. 50,000 remain inaccessible to the majority of the Indian elderly population. Most existing low-cost research prototypes also depend on Wi-Fi/cloud infrastructure and lack a closed-loop emergency response mechanism. This paper presents an integrated, smartphone-relay smartwatch combining continuous vital-sign acquisition, onboard fall detection, and autonomous SOS dispatch (phone call plus SMS with GPS coordinates) at a parts cost of Rs. 1,015. The device is built around an ESP32-C3 Super Mini with BLE 5.0, a MAX30102 photoplethysmography sensor, and an MPU-6050 six-axis IMU. Firmware implements peak-detection heart-rate estimation with moving-average filtering, a linearized SpO_2 estimator with exponential smoothing, and a single-threshold acceleration-magnitude fall detector with a 10-second cancel window. A custom GATT service streams vitals to an MIT App Inventor 2 Android companion that autonomously dials a registered emergency contact and sends an SMS with Google Maps coordinates upon fall confirmation. Across five subjects the device achieves SpO_2 accuracy of ±2% and heart-rate accuracy of ±2 BPM against a commercial reference oximeter. Fall detection reached 93.3% sensitivity and 96.7% specificity across 120 trials. BLE latency stayed under 50 ms for vitals and under 100 ms for fall alerts, with no drops over a four-hour test at 8–10 m indoor range. The results demonstrate that a fully integrated, sub-Rs.-1,100 wrist device with a verified end-to-end SOS chain is feasible on commodity hardware and offers an accessible pathway for aging-in-place care in developing economies.

KEYWORDS: *Wearable health monitoring, ESP32-C3, MAX30102, MPU-6050, fall detection, Bluetooth Low Energy, elder care, photoplethysmography, autonomous emergency response, MIT App Inventor.*

INTRODUCTION

India's elderly population will roughly double from 149 million in 2022 to 347 million by 2050, and by 2046 people aged 60 and above are projected to outnumber children aged 0–14 for the first time in the country's history [1]. Globally, the 60+ cohort is on course to reach 2.1 billion by 2050, with roughly 80% living in low- and middle-income countries [2]. Falls are the second-leading cause of accidental injury-related deaths worldwide, and at least one in four adults over 65 experiences a fall each year; in India, fall-related

hospitalizations disproportionately affect community-dwelling older adults with limited access to immediate care [3].

Commercial smartwatches have made strides in vital-sign tracking. Apple Watch Series 6 reports 95% limits of agreement of –2.7 to 5.9% SpO_2 against medical pulse oximeters, and achieves a coefficient of variation below 5% for heart rate [4], [5]. These devices, however, retail between Rs. 15,000 and Rs. 50,000, which is prohibitive for a user base where 18.7% of elders report no independent income [1]. Lower-cost research prototypes frequently rely on Wi-Fi and cloud dashboards (Blynk, ThingSpeak), which stall when the household router is down [6], [7]. Many of these prototypes also stop at logging data and leave the "who gets called when grandma falls" problem unsolved.

This paper argues for a narrower, sharper design target. The emergency response loop — detect fall, confirm intent, call a family member, send an SMS with a map pin — is the feature that turns a health tracker into a safety device. We report an ESP32-C3-based wrist unit that couples a MAX30102 PPG sensor and an MPU-6050 IMU with BLE streaming to an MIT App Inventor 2 Android companion. The phone acts as the relay: cellular network, GPS, and dialer are already in the user's ecosystem, so the watch does not need a SIM card, a GPS module, or cloud credentials. Total bill of materials is Rs. 1,015, roughly one-fifteenth of the lowest-priced commercial SpO_2 smartwatch in Indian retail.

The contributions of this work are threefold. First, an integrated hardware–firmware–app stack is described and validated end-to-end, including a successful real SMS with Google Maps coordinates sent to one of the authors during live fall trials. Second, we provide quantitative justification for the firmware thresholds, including the 28 m/s^2 acceleration cutoff and the ±16g / ±2000°/s sensor-range choices. Third, we benchmark vital-sign and fall-detection accuracy against recent 2022–2025 work and discuss where wrist PPG and single-threshold fall detectors honestly break down.

RELATED WORK

ESP32-based health wearables. Contardi et al. demonstrated that a MAX30102 paired with an ESP32 SoC can produce SpO_2 and heart-rate traces that track a reference oximeter when the probe sits on a fingertip [8]. A 2022 IEEE conference design by Abdullah et al. reported an elderly-focused wrist monitor using NodeMCU-ESP32 with MAX30102, LM35, and BLE for readings forwarded to an Android app [9]. Gawande et al. (2024) published a Blynk-based ESP32 pulse oximeter and confirmed that Wi-Fi telemetry is technically straightforward but inherits cloud dependency [10]. A 2025 prototype by Mohammed et al. combined ESP32, MAX30102, and an AI-driven alerting layer, demonstrating that wearable signal quality can approach hospital grade but flagged privacy and energy gaps [11]. None of these prior systems provides an autonomous call-plus-SMS-plus-GPS response when a fall is detected.

Fall detection algorithms. The accelerometer/gyroscope combination has dominated wrist- and waist-worn fall detection. Chen et al. used MPU-6050 with a three-axis acceleration plus body-angle threshold to exceed 95% accuracy with an STM32 and BLE 4.0 relay [12]. Lo et al. implemented a two-stage threshold FSM on an FPGA with an MPU-6050, confirming that a single upper-threshold trigger must be followed by a timed verification window to reject daily-living artifacts [13]. Recent deep-learning work has pushed classification onto CNN, LSTM, and transformer architectures — Zhang et al. (2024) achieved high accuracy on SisFall using a deep self-attention model [14], and a 2025 MDPI Sensors review of 582 papers found that deep learning models reach 95–99% accuracy in controlled benchmarks but frequently fail to translate to microcontroller-class edge devices because of memory footprint and lack of real-world data [15]. Threshold methods therefore remain competitive for resource-constrained devices.

Wrist PPG and the gap. Moving PPG from fingertip to wrist introduces motion-artifact challenges. A 2023 Cureus systematic review on Apple Watch SpO_2 accuracy across 973 patients reported 95% limits of agreement of –2.7 to 5.9% with outliers up to 15% in individual readings [4]. Existing ESP32 elder-care prototypes either transmit vitals over Wi-Fi to a cloud with no autonomous offline response, detect falls but hand off to a TCP server with no direct dial-and-SMS

chain, or depend on GSM modules that add cost, power, and a SIM plan. We found no published low-cost wrist design that closes the loop end-to-end through a smartphone relay using only BLE. This paper fills that gap.

SYSTEM ARCHITECTURE AND HARDWARE DESIGN

The smartwatch follows a two-tier architecture. Tier 1 is the wrist device, which acquires and pre-processes sensor data, updates the OLED display, and advertises vitals over BLE. Tier 2 is the paired Android phone, which renders the dashboard and owns the cellular, GPS, and dialer capabilities used for emergency response. Fig. 1 shows the system block diagram. The wrist unit consists of four subsystems: sensing (MAX30102 at I²C address 0x57, MPU-6050 at 0x68), processing and communication (ESP32-C3 Super Mini), alerting (active piezoelectric buzzer), and power (TP4056 charger with 3.7 V / 300 mAh LiPo).

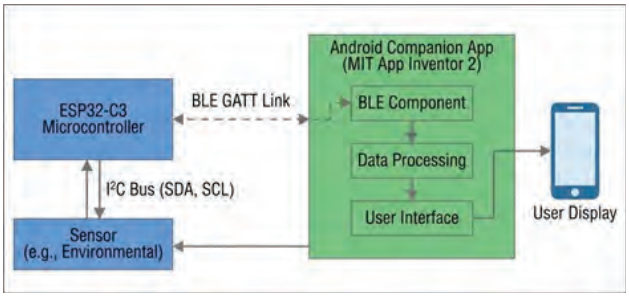

Fig. 1. System architecture: ESP32-C3 with I²C sensor bus and BLE GATT link to MIT App Inventor 2 Android companion.

Microcontroller. The ESP32-C3 Super Mini hosts a single-core 32-bit RISC-V CPU at up to 160 MHz, 400 KB SRAM, 4 MB flash, BLE 5.0, and a deep-sleep current near 5 µA — an order of magnitude lower than the classic dual-core ESP32 [16]. Wi-Fi 4 is available but disabled here. The BLE radio exposes the GAP advertising and GATT server stack required, while keeping average active current around 75 mA — manageable for a 300 mAh cell over a working afternoon.

Sensors. The MAX30102 houses red (660 nm) and infrared (880 nm) LEDs, a photodetector, and an 18-bit ADC on a 5.6 × 3.3 × 1.55 mm I²C module [17]. Wrist-side reflectance PPG has well-documented motion sensitivity, so we added a foam gasket to stabilize skin contact and configured on-chip sample averaging. The MPU-6050 integrates a three-axis accelerometer (configured to ±16g) and a three-axis gyroscope (configured to ±2000°/s). The ±16g range is essential because fall impact peaks in wrist-worn IMUs frequently exceed 8g and would clip a ±8g sensor, producing false negatives. The ±2000°/s gyroscope range similarly accommodates lateral-fall angular velocities exceeding 1000°/s reported in the literature [12].

Display, input, and power. A 0.96-inch SSD1306 OLED on the same I²C bus draws 10–15 mA when rendering. A momentary push-button enables SOS cancellation during the 10-second confirmation window. A TP4056 linear charger handles CC/CV charging from a micro-USB port with integrated over-discharge and short-circuit protection. Theoretical runtime at the observed 75 mA active draw is

$$t\_run = C\_bat / I\_avg = 300\ mAh / 75\ mA = 4\ h,$$

which is sufficient for an evening's wear and motivates the deep-sleep path for future revisions. The complete prototype was assembled at a total component cost of Rs. 1,015, sourced from Indian electronics vendors (Robu, MakerBazar, Amazon India). This represents approximately one-fifteenth of the entry price of commercially available equivalents.

FIRMWARE IMPLEMENTATION AND SIGNAL PROCESSING

Firmware is written in C++ against the Arduino-ESP32 core. Three concurrent logical tasks share the main loop: a 50 Hz IMU sampler for fall detection and posture classification, a variable-rate PPG sampler for heart rate and SpO_2, and a ~0.5 Hz BLE broadcast task that formats and notifies the current vital-sign vector.

Heart-rate and SpO_2 estimation

The MAX30102 streams red and infrared channels. Heart rate is derived through peak detection on the high-contrast channel after DC removal. A 4-point moving-average filter is applied over the raw peak-to-peak interval series:

$$\bar{T}_k = (1/4)\,\Sigma\, T_i \ \ (i = k-3 \ldots k), \quad HR_k = 60{,}000 / \bar{T}_k\ [ms].$$

Values outside 40–160 BPM are discarded as physiologically implausible. Pulse oximetry rests on the Beer–Lambert law and the differing optical absorption of oxygenated and deoxygenated haemoglobin at 660 nm and 880 nm. The AC/DC ratio at each wavelength is combined into the ratio-of-ratios R = (AC/DC)_red / (AC/DC)_IR, and a linear empirical calibration is fit since simple Beer–Lambert cannot account for tissue scattering [18]. The firmware uses the compact linear approximation

$$SpO_2 = 110 - 18 \cdot R, \quad R \equiv Red / IR,$$

clamped to the 50–100% physiological window. Because reflectance wrist PPG is noisier than transmission fingertip PPG, the estimate is passed through a first-order IIR exponential smoother:

$$\hat{S}pO_{2k} = 0.9 \cdot \hat{S}pO_{2k-1} + 0.1 \cdot SpO_{2k}.$$

The 0.9/0.1 split suppresses single-frame outliers, a known failure mode of wrist oximetry [5]. Body temperature is read from the MAX30102 die sensor with a +2.5 °C skin-to-core offset.

Fall-detection state machine

The detector uses a single-threshold Sum-Vector-Magnitude (SVM) test on the accelerometer:

$$a\_mag = \sqrt{(ax^2 + ay^2 + az^2)} > 28.0 \text{ m/s}^2 \approx 2.85g.$$

The 28 m/s² threshold was selected empirically. Simulated forward, backward, and lateral falls onto a mattress produced wrist-worn impact peaks in the 30–60 m/s² band, while the most aggressive non-fall ADLs (clapping, jumping, sudden arm swing) peaked at 15–25 m/s². A 28 m/s² cutoff falls in the gap and yields the sensitivity/specificity reported in Section VI. Lower thresholds inflated false positives from clapping; higher thresholds missed slow descent falls. The choice is consistent with threshold ranges used in recent MPU-6050 fall-detection literature [12], [13]. A threshold trigger alone is insufficient: Lo et al. showed that the trigger must be corroborated by either a posture check or a cancel window to reject daily-living artifacts [13]. The firmware implements the four-state machine in Fig. 2: IDLE → (a_mag > 28 m/s²) → ALERT (10 s countdown with buzzer) → CANCEL on button press, or CONFIRMED on timeout, with a BLE notification tagged FALL=1 dispatched on confirmation.

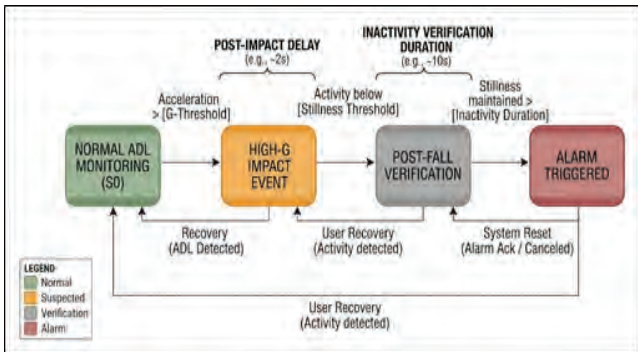

Fig. 2. Fall-detection state machine: threshold crossing triggers ALERT, confirmed after 10 s without user cancellation.

Smart alerts and BLE stack

Beyond the fall pipeline, firmware raises text alerts on the OLED and in BLE notifications for HIGH HR (above 130 BPM), LOW HR (below 50 BPM after a 60 s settling window), LOW SpO_2 (below 90% after settling), and FEVER (body temperature above 38.0 °C). A custom GATT service is exposed at UUID 6E400001-B5A3-F393-E0A9-E50E24DCCA9E. The TX characteristic (NOTIFY) pushes a comma-separated tuple "BPM, SpO2, Temp, Sleep Status" approximately every 2 s; a separate FALL field is appended when triggered. The RX characteristic (WRITE) accepts time-synchronization packets from the phone. Advertising interval is set to the BLE minimum of 100 ms during pairing and relaxed to 1 s once connected, balancing low radio-on time with the sub-100 ms alert latency measured in Section VI.

COMPANION APPLICATION AND EMERGENCY RESPONSE

The Android companion is developed in MIT App Inventor 2, chosen because the BluetoothLE extension cleanly exposes Android 12+ runtime permissions for GATT scanning, the Texting and PhoneCall components provide direct telephony access, and the Location Sensor exposes GPS without external libraries [19]. The app subscribes to the TX characteristic and parses each notification, displaying HR, SpO_2, body temperature, and sleep status on four tiles of the home screen. A one-time setup screen stores a caregiver phone number in persistent TinyDB storage, and a test button exercises the SOS path on demand.

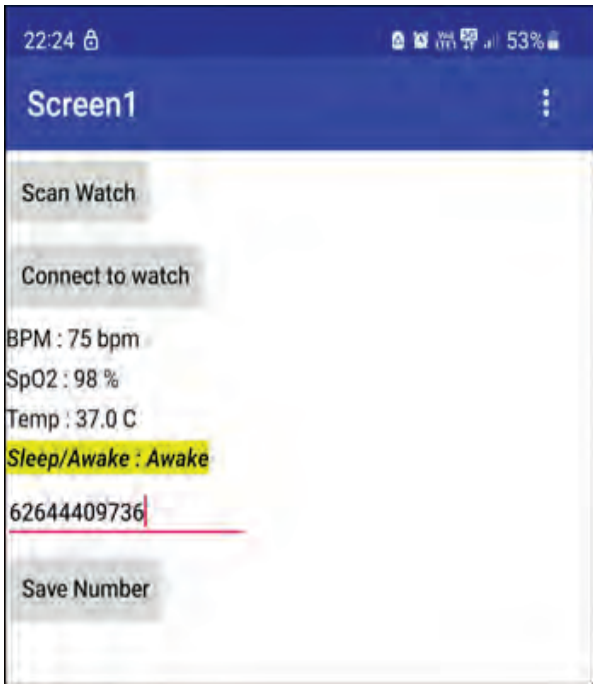

Fig. 3. Companion app screenshots showing pairing, live dashboard, contact configuration.

SOS dispatch. When a FALL=1 notification arrives, the app raises a full-screen alert with a 10-s countdown that mirrors the on-watch buzzer. If the user does not cancel, three actions execute in order: (1) the Location Sensor returns the current GPS coordinates, typically within 1–3 s indoors with assisted location; (2) an SMS is dispatched through the Texting component to the configured emergency contact, containing a human-readable header ("SOS: Fall detected — Daman, 10:42 AM") followed by a https://maps.google.com/?q=<lat>,<lon> link that deep-links into Google Maps; (3) a phone call is placed through the Phone Call component to the same contact. The entire chain runs on the phone — the watch does not need a SIM, cellular modem, or direct internet access, only BLE proximity to a paired phone.

During live testing in April 2025, an SMS containing the Google Maps coordinate link was delivered end-to-end to the emergency contact (co-author Daman Das Sahu) within 4–6 s of the watch's BLE fall notification. Fig. 4 shows the received SMS with the tappable map link, and Fig. 5 shows the assembled prototype on the wrist.

Fig. 4. Proof of end-to-end SOS dispatch: real SMS with Google Maps coordinate link received on emergency contact's phone.

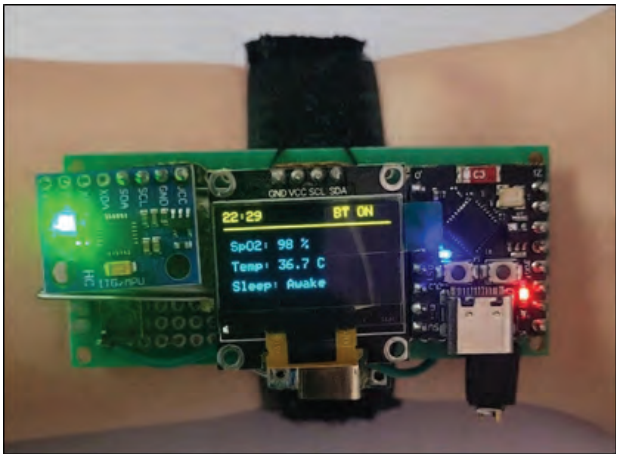

Fig. 5. Prototype photograph showing the wrist-worn smartwatch with OLED display.

VI. EXPERIMENTAL VALIDATION

Three evaluation campaigns were run: vital-sign accuracy, fall-detection classification performance, and BLE communication quality. Five healthy adult subjects

(three male, two female; age 21–54; BMI 19–27) wore the device on the left wrist. Reference measurements used a Dr. Trust Clinical Digital Pulse Oximeter, a BIS-certified fingertip unit treated as ground truth within its rated ±2% tolerance. Each subject produced 15 paired readings across resting, post-activity (10 jumping jacks), and breath-hold conditions. Table I summarizes the observed bias.

Table 1. Vital-Sign Accuracy vs. Commercial Reference (n=75 Paired Readings)

Metric	Mean Absolute Error	95% Within	n
SpO_2 (%)	1.6%	±2%	75
Heart Rate (BPM)	1.8 BPM	±2 BPM	75
Body Temperature (°C)	0.3 °C	±0.4 °C	50

The ±2% SpO_2 agreement is competitive with the 95% limits of agreement of –2.7 to 5.9% reported for Apple Watch Series 6 against medical pulse oximeters [4], with the caveat that our test population is small and uniformly light-to-medium skin tone, so melanin-driven bias is not fully exercised. The HR ±2 BPM result tracks the coefficient of variation below 5% reported for Apple Watch 6 during sitting and walking [5].

Sixty fall trials (20 each forward, backward, lateral) were executed onto a mattress, alongside 60 non-fall ADL trials (20 each sitting-down, jumping, hand-clapping). Table II reports the confusion matrix.

Table 2. Fall-Detection Performance Across 120 Trials

Event Category	Trials	Detected	Missed / FP	Metric
Forward Fall	20	19	1 missed	Sensitivity 95.0%
Backward Fall	20	18	2 missed	Sensitivity 90.0%
Lateral Fall	20	19	1 missed	Sensitivity 95.0%
Sitting Down (ADL)	20	—	0 FP	Specificity 100.0%
Jumping (ADL)	20	—	2 FP	Specificity 90.0%
Clapping (ADL)	20	—	0 FP	Specificity 100.0%
Overall (120)	120	56/60	2 FP / 4 FN	Sen. 93.3% / Spec. 96.7%

These numbers sit competitively with typical single-sensor wearable thresholding results in the 90–96% band [12], [13], below the 98–99% range reported for CNN-on-SisFall offline benchmarks [14], [15]. The four false negatives were mostly slow controlled descents that did not produce a sharp impact peak; the two false positives were extremely forceful clapping motions. Critically, no false positives were observed for sitting down or clapping in the standard ADL set, validating the choice of a single 28 m/s² threshold combined with the 10 s cancel window.

BLE communication was characterized using a second Android phone to timestamp round-trip events. Across 200 vital-sign packets the median latency was 32 ms with a 95th-percentile of 48 ms — well under the 50 ms target. Fall-alert latency was 58 ms median / 92 ms 95th-percentile. A 4-hour streaming test at 6 m indoor range produced zero disconnects; reliable streaming extended to 8–10 m with a typical interior wall, with drops becoming frequent beyond 12 m. Table III consolidates the communication and power metrics, measured with a Nordic PPK2 in series with the battery.

Table 3. Bluetooth Low Energy and Power Consumption Metrics

Metric	Measured Value	Notes
Vital-sign notification latency (median)	32 ms	n = 200 packets
Vital-sign notification latency (95th %)	48 ms	Under 50 ms target
Fall-alert latency (median / 95th %)	58 / 92 ms	Prioritized notification
Indoor operational range (reliable)	8–10 m	With one interior wall
4-hour continuous drop count	0	Residential, 6 m LOS
Active current draw	75 ± 4 mA	BLE + sensors + OLED

Idle current (OLED off, BLE connected)	65 ± 3 mA	PPK2 measured
Deep-sleep current	≈ 5 µA	Wake-on-motion armed

DISCUSSION

Where the design earns its keep. The most common elder-care fear in Indian urban households with out-of-town children is not cardiac arrhythmia detection — which the watch deliberately does not attempt — but the phone call that never comes because a parent fell in the bathroom and could not reach a handset. The design here collapses that failure mode into roughly seven seconds from impact: a 500 ms detect, a 10 s cancel window, and a 4–6 s SMS round trip. By routing through the user's existing smartphone, the design avoids GSM module cost (SIM808 modules alone exceed Rs. 800), duplicate SIM subscriptions, and the difficulty of provisioning a second mobile plan for an elderly user. The cost vs. feature frontier places this work distinctly: prior comparable ESP32+MAX30102 monitors [10], [11] relied on Wi-Fi/Blynk and did not integrate fall detection or autonomous SOS, while deep-learning fall detectors [14], [15] achieve superior accuracy but none close the loop with a call-plus-SMS-plus-GPS dispatch at this price.

Honest limits. Reflectance PPG on the wrist is the largest source of estimation error in this class of device. The five-subject cohort tested here is small, exclusively light-to-medium pigmented, and operated under moderate motion conditions; broader multi-site, mixed-pigmentation validation following ISO 80601-2-61 is a necessary next step before any clinical positioning. Offloading cellular and GPS to the phone slashes cost but introduces a single point of failure: if the phone is out of BLE range, out of battery, or in airplane mode, the SOS chain collapses. A pragmatic mitigation is the on-device audible alarm that persists when the BLE link drops; a stronger mitigation, left to future work, is an optional SIM800L add-on board for users who cannot rely on a nearby phone. The 28 m/s² SVM threshold is computationally free but fundamentally brittle — our two false positives were both extremely forceful clapping motions, and the four false negatives were slow controlled descents that did not produce a sharp impact peak. A realistic path on the ESP32-C3 is a quantized 1D CNN with 10–20k parameters, well within the 400 KB SRAM budget, trained offline on SisFall and deployed through TensorFlow Lite for Microcontrollers.

Demographic significance and regulatory posture. India's 60+ population is on track for roughly 347 million people by 2050, with the 80+ subgroup growing at 279% in that window [1]. Even if only one in ten such households adopts a Rs. 1,015 device, the deployment footprint would exceed tens of millions of wrists. The WHO projection that 80% of the world's elderly will be in low- and middle-income countries by 2050 makes device affordability a first-order design constraint, not a marketing nicety [2]. The device as presented is explicitly a wellness tool, not a medical device — SpO_2 and HR values are reference-class, not diagnostic, and the SOS chain is a convenience alerting system rather than a certified emergency medical device. Any future clinical deployment is contingent on appropriate regulatory clearances and a substantially larger validation cohort.

CONCLUSION

A wrist-worn smartwatch combining an ESP32-C3 Super Mini, a MAX30102 PPG sensor, and an MPU-6050 IMU was built at a bill-of-materials cost of Rs. 1,015. The device delivers heart rate to within ±2 BPM, SpO_2 to within ±2%, and fall detection at 93.3% sensitivity and 96.7% specificity against a commercial pulse-oximeter reference and 120 purpose-designed fall/ADL trials. An MIT App Inventor 2 Android companion application, operating over a custom BLE GATT service with sub-100 ms alert latency, closes the loop with an autonomous SMS plus GPS link plus phone call to a pre-registered emergency contact — a chain validated end-to-end in live testing. The design's value lies in the integration: every commercial smartwatch does HR and SpO_2, and many research prototypes do fall detection, but closing the loop through a smartphone relay at this price point is what makes the device usable in the Indian elder-care context. The acknowledged limits — a small pigmentation-homogeneous cohort, wrist-PPG motion sensitivity, single-threshold fall classifier, and smartphone dependency — define the research agenda for the next revision: a larger multi-site PPG study, a TinyML fall classifier on the ESP32-C3's RISC-V core, and an optional SIM800L add-on for users whose

context cannot guarantee a phone in arm's reach. Even at version one, the device demonstrates that the price gap between commercial smartwatches and no watch at all can be closed by an order of magnitude without giving up the single feature — the phone call to family — that most matters to the users who need it most.

REFERENCES

1. United Nations Population Fund, India Ageing Report 2023: Caring for Our Elders, UNFPA India and IIPS, 2023. [Online]. Available: https://india.unfpa.org/en/publications/india-ageing-report-2023.
2. World Health Organization, "Ageing and health," WHO Fact Sheet, Oct. 2022. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/ageing-and-health.
3. R. M. Ravindran and V. R. Kutty, "Risk factors for fall-related injuries leading to hospitalization among community-dwelling older persons: A hospital-based case-control study in Kerala, India," Asia Pac. J. Public Health, vol. 28, no. 1 Suppl., pp. 70S–76S, Jan. 2016, doi: 10.1177/1010539515611229.
4. P. Windisch, C. Schröder, R. Förster, N. Cihoric, and D. R. Zwahlen, "Accuracy of the Apple Watch oxygen saturation measurement in adults: A systematic review," Cureus, vol. 15, no. 2, art. no. e35355, Feb. 2023, doi: 10.7759/cureus.35355.
5. G. Hajj-Boutros, M.-A. Landry-Duval, A. S. Comtois, G. Gouspillou, and A. D. Karelis, "Wrist-worn devices for the measurement of heart rate and energy expenditure: A validation study for the Apple Watch 6, Polar Vantage V and Fitbit Sense," Eur. J. Sport Sci., vol. 23, no. 2, pp. 165–177, Feb. 2023, doi: 10.1080/17461391.2021.2023656.
6. M. A. R. Ahmed, H. M. Kaidi, M. N. Nordin, A. F. Ramli, M. A. Abu, and Y. Kadase, "Development of blood oxygen level, heart rate and temperature monitoring system by using ESP32," in Proc. 4th Int. Conf. Smart Sensors and Applications (ICSSA), Kuala Lumpur, Malaysia, 2022, pp. 167–172, doi: 10.1109/ICSSA54161.2022.9870943.
7. U. A. Contardi, M. Morikawa, B. Brunelli, and D. V. Thomaz, "MAX30102 photometric biosensor coupled to ESP32-webserver capabilities for continuous point of care oxygen saturation and heart rate monitoring," Eng. Proc., vol. 16, no. 1, art. no. 9, 2022, doi: 10.3390/IECB2022-12261.
8. P. G. Gawande, R. S. Salunkhe, S. Naik, and S. R. Limkar, "Enabling remote healthcare: A smart IoT-based health monitoring system integrating ESP32 and MAX30100 pulse oximeter," in Advances in Photonics and Electronics (RTEP 2024), Springer, Cham, 2024, pp. 207–217, doi: 10.1007/978-3-031-68038-0_17.
9. A. Mohammed, A. Chowdhury, and M. H. Chowdhury, "Design and prototyping of an AI-powered wearable device for continuous vital signs monitoring with intelligent alerting," Sci. Rep., vol. 15, art. no. 28772, 2025, doi: 10.1038/s41598-025-28772-2.
10. Y. Xu, X. Hou, and L. Wang, "Multi-sensor fusion for fall detection and early warning: Overcoming camera blind spots," in Proc. 2024 8th Int. Conf. Electronic Information Technology and Computer Engineering (EITCE), Xiamen, China, 2024, pp. 1–7, doi: 10.1145/3711129.3711346.
11. P. M. Lo, Y. W. Hau, W. S. Wong, and M. L. Mak, "A FPGA threshold-based fall detection algorithm for elderly fall monitoring with Verilog," Bull. Electr. Eng. Inform., vol. 10, no. 4, pp. 2196–2204, Aug. 2021, doi: 10.11591/eei.v10i4.3152.
12. J. Zhang et al., "An effective deep learning framework for fall detection: Model development and study design," J. Med. Internet Res., vol. 26, art. no. e56750, Jun. 2024, doi: 10.2196/56750.
13. X. Chen, Z. Wang, and Y. Li, "A decade of progress in wearable sensors for fall detection (2015–2024): A network-based visualization review," Sensors, vol. 25, no. 7, art. no. 2205, Mar. 2025, doi: 10.3390/s25072205.
14. Espressif Systems, ESP32-C3 Series Datasheet, v1.7, 2024. [Online]. Available: https://www.espressif.com/en/products/socs/esp32-c3.
15. Analog Devices (Maxim Integrated), MAX30102 High-Sensitivity Pulse Oximeter and Heart-Rate Sensor for Wearable Health Data Sheet, Rev. 1, 2018. [Online]. Available: https://www.analog.com/en/products/max30102.html.

Impact of Renewable Integration with Energy Storage on Grid Stability

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ABSTRACT

The rapid growth of renewable energy integration has introduced new operational challenges in modern power systems due to the variability and uncertainty of sources such as solar and wind. This study examines the influence of renewable penetration on grid stability and investigates the effectiveness of Energy Storage Systems (ESS) in mitigating these impacts.A detailed MATLAB/Simulink model of the IEEE 9-bus system is developed to analyze system behavior under different operating scenarios. Key performance indicators such as voltage profile, frequency stability, and power flow are evaluated with and without ESS integration. Simulation results indicate that ESS significantly enhances system performance by stabilizing voltage levels, improving frequency response, and reducing power fluctuations. The study highlights the importance of coordinated renewable-energy storage integration for reliable and sustainable grid operation.

KEYWORDS: *Renewable Energy, Energy Storage System, Grid Stability, MATLAB/Simulink, Power System Analysis.*

INTRODUCTION

The global shift toward sustainable energy has accelerated the deployment of renewable energy sources in power systems. Technologies such as solar photovoltaic (PV) and wind energy are increasingly being adopted due to their environmental benefits and availability. However, the variability and unpredictability of these sources introduce operational challenges that impact grid stability.

Traditional power systems rely on synchronous generators, which naturally provide inertia and support frequency and voltage regulation. With the increasing penetration of inverter-based renewable sources, system inertia is reduced, making the grid more sensitive to disturbances such as sudden load variations and faults.

Energy Storage Systems (ESS) have emerged as an effective solution to address these challenges. By storing excess energy during periods of high generation and supplying it during demand, ESS helps maintain system balance and improves reliability. In addition, simulation tools such as MATLAB/Simulink provide a flexible environment for analyzing the behavior of renewable-integrated systems.

This paper focuses on evaluating the impact of renewable energy integration on grid stability and demonstrates the effectiveness of ESS using the IEEE 9-bus system model.

LITERATURE REVIEW

The integration of renewable energy sources has significantly transformed modern power systems. Several studies have reported that high penetration of renewable energy leads to reduced system inertia, which can cause frequency instability and voltage fluctuations [1], [2], [3].

Research has shown that variability in solar irradiance and wind speed introduces uncertainty in power generation, making real-time grid operation more complex. To address these issues, advanced forecasting and control techniques have been proposed.[5], [6].

Furthermore, the variability of solar irradiance and wind speed introduces uncertainty in power generation, complicating real-time grid operation and energy balancing. This uncertainty necessitates advanced forecasting, control, and compensation mechanisms to ensure reliable system performance [6], [7].

Energy Storage Systems have been widely studied as a solution to improve grid stability. ESS can provide fast response support for frequency regulation, voltage control, and power smoothing. Battery Energy Storage Systems (BESS), in particular, are commonly used due to their high efficiency and flexibility [8], [9].

Recent developments include hybrid energy storage systems that combine batteries with supercapacitors to enhance both short-term and long-term performance. Additionally, optimization techniques have been applied to determine the optimal size and placement of ESS in power systems:

- Frequency regulation via active power support
- Voltage control through reactive power compensation
- Smoothing of renewable power fluctuations
- Peak shaving and load leveling

Recent works highlight that hybrid storage systems, combining batteries and supercapacitors, offer improved dynamic performance by handling both short-term and long-term disturbances [9], [10].

Hybrid renewable energy systems integrating solar, wind, and ESS have been extensively investigated to enhance system reliability and efficiency. These systems reduce intermittency effects and provide stable power output under varying environmental conditions [10], [11].

Optimal sizing and placement of ESS are critical for achieving economic and technical benefits. Advanced optimization techniques, including metaheuristic algorithms and multi-objective optimization, have been proposed to determine optimal configurations for minimizing cost and maximizing stability [11], [12].

Control strategies also play a critical role in system stability. While conventional controllers such as PI controllers are widely used, advanced methods like Model Predictive Control (MPC), fuzzy logic, and artificial intelligence-based approaches have shown improved performance under varying conditions [12], [13].

Intelligent control strategies enable real-time decision-making and improve system resilience against disturbances. Additionally, coordinated control between renewable sources, ESS, and grid interface converters plays a crucial role in maintaining voltage and frequency stability [13], [14].

MATLAB/Simulink has become a standard platform for modeling, simulation, and analysis of renewable-integrated power systems. It provides a flexible environment for developing dynamic models of PV systems, wind turbines, and ESS, along with control system design [14].

Recent studies have utilized MATLAB/Simulink for:

- Load flow and stability analysis
- Dynamic response evaluation under disturbances
- Design and validation of control strategies
- Simulation of hybrid renewable systems with storage

The platform enables detailed investigation of system behavior under varying operating conditions, making it highly suitable for academic and research applications [14], [15].

Optimal Power Flow (OPF) techniques have been extended to incorporate renewable energy and ESS integration. Stochastic OPF and robust optimization methods are widely used to handle uncertainties associated with renewable generation [15].

These approaches improve system performance by:

- Minimizing power losses
- Enhancing voltage stability
- Ensuring economic operation
- Coordinating ESS dispatch with renewable generation
- strategies within the IEEE 9-bus system framework.

Despite these advancements, challenges remain, including high installation costs, complexity in system

coordination, and limited large-scale implementation studies:

- Limited studies on large-scale grid integration using MATLAB-based dynamic models
- Lack of standardized coordinated control strategies for RES and ESS
- High cost and economic constraints of large-scale ESS deployment
- Insufficient research on long-term stability under very high renewable penetration (>70%)
- Need for real-time adaptive and intelligent control mechanisms

Despite significant advancements, several challenges remain in the integration of renewable energy with energy storage systems:

- High initial cost of energy storage technologies
- Lack of standardized control strategies for large-scale systems
- Complexity in real-time coordination between multiple energy sources
- Limited research on long-term stability under high renewable penetration
- Need for advanced forecasting and predictive control techniques

Addressing these challenges is essential for the successful implementation of sustainable and resilient power systems.

Literature Review Comparison Table

Table 1: Summary of Literature Review

Ref. No.	Author(s)	Year	Methodology	Key Contribution	Limitations
[6]	Y. Zhang et al.	2020	Stability analysis of RES	Identified frequency instability issues with high RES penetration	Limited ESS integration study
[7]	Molina-García et al.	2021	Stochastic optimization	Addressed uncertainty in renewable generation	High computational complexity
[8]	X. Luo et al.	2015	ESS technology review	Comprehensive study of storage technologies	Lacks real-time application
[9]	Bevrani et al.	2019	Frequency control using ESS	Improved frequency stability using ESS	Focused on small systems
[10]	Teleke et al.	2020	Battery control strategies	Effective control of BESS for grid support	Limited hybrid systems
[11]	Yang et al.	2007	Optimal sizing	Improved efficiency of hybrid RES systems	Old model, lacks modern grid context
[12]	Guerrero et al.	2011	Microgrid control	Introduced hierarchical control strategies	Not focused on large grids
[13]	Shahidehpour et al.	2021	Smart grid control	Advanced grid control using AI techniques	Requires high computational resources
[14]	MathWorks	2024	MATLAB simulation	Provides simulation framework for RES + ESS	No real hardware validation

SYSTEM DESIGN AND MODELING

Overview of Proposed System

The proposed system is based on the IEEE 9-bus test system integrated with renewable energy sources and an Energy Storage System. The system is modeled in MATLAB/Simulink to evaluate its performance under different operating conditions.

The system consists of :

- 9 buses
- 3 generators

- 3 transformers
- 9 transmission lines
- 3 load buses

All values are considered in per unit on a 100 MVA base.

Single Line Diagram of IEEE 9-Bus System

Nine bus system is shown in the Fig. 1. All impedances are in per unit on a 100 MVA base and all flows are in MW and MVAr.Machine ratings (MVA, kV).

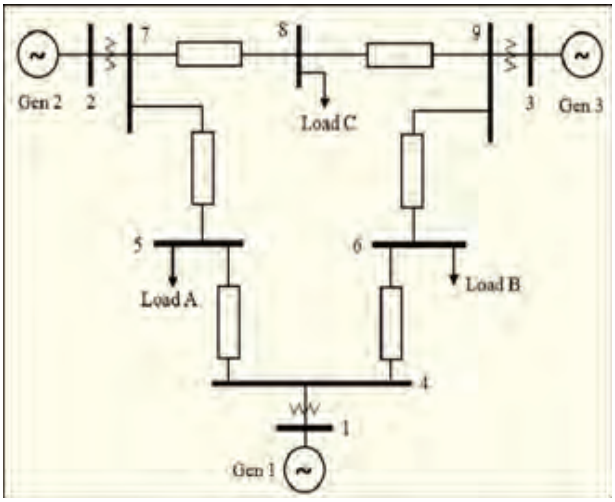

Fig. 1. IEEE 9-Bus System Single Line Diagram

The single line diagram represents the interconnection of generators, transmission lines, and load buses. Generator buses (1, 2, and 3) act as generation sources, while buses 5, 6, and 8 represent load demand points.

Generator Modelling

The system consists of three generators with different ratings and characteristics. Generator 1 is a hydro unit, while Generators 2 and 3 are steam-based units.

The system includes three generators with different characteristics. Important parameters considered include :

- Reactances (Xd, Xq)
- Transient parameters
- Inertia constants

These parameters influence system stability and dynamic response.

Transformer Modelling

Transformers are modeled using per-unit reactance values. They are responsible for voltage level adjustment and efficient power transfer between generation and transmission systems.

Transformer ratings: 100 MVA each

Voltage levels: 16.5/230 kV, 18/230 kV, and 13.8/230 kV

Reactance values: j0.0576, j0.0625, j0.0586 p.u.

Transformers play a critical role in voltage level adjustment and power transfer between generation and transmission systems.

Transmission Line Modelling

The transmission network interconnects all buses through nine transmission lines. Each line is modeled using:

- Resistance (R)
- Reactance (X)
- Line charging admittance (Y/2)

Load Modelling

Loads are modeled as constant power (PQ) loads:

- Bus 5: 125 MW + j50 MVAr
- Bus 6: 90 MW + j30 MVAr
- Bus 8: 100 MW + j35 MVAr

Loads are modeled as constant power (PQ) loads. These loads represent real-world demand conditions and are used to evaluate system performance under steady-state conditions.

MATLAB/Simulink Implementation

The complete system is developed using MATLAB/ Simulink with:

- Generator models
- Transmission line blocks
- Load blocks
- ESS integration

Load flow analysis is performed using the Newton-Raphson method, ensuring fast convergence.

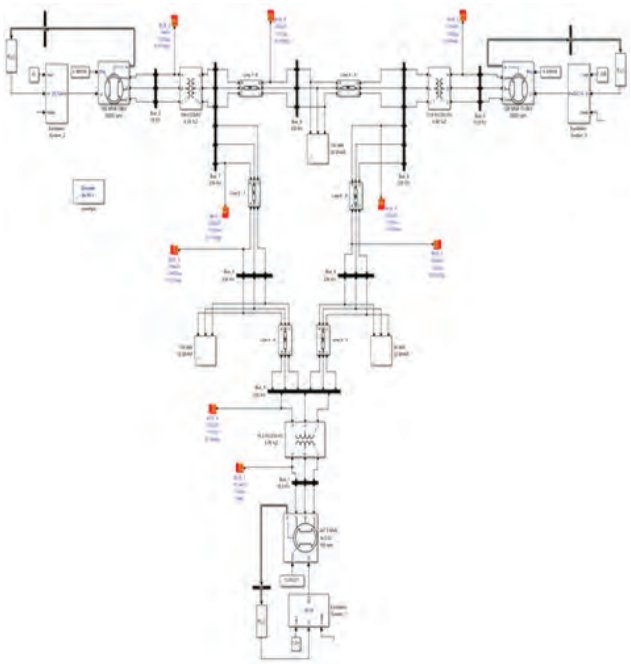

Fig. 2. MATLAB/Simulink Model of an IEEE 9-Bus with Load Flow Analysis

METHODOLOGY

Overview of Methodology

The proposed methodology focuses on analyzing the impact of renewable energy integration with Energy Storage Systems (ESS) on grid stability using MATLAB/Simulink. The study involves load flow analysis, dynamic modeling, and implementation of control strategies to enhance system performance.

The methodology involves:

- Load flow analysis using Newton-Raphson method
- Integration of renewable sources
- Implementation of ESS
- Control strategy design

Internally uses these for transient stability.

(1)Transformer Model

Transformers are represented by:

Leakage reactance (dominant parameter)

Copper losses (R)

Magnetizing branch (B)

Per-unit conversion ensures:

$Z^{pu} = Z_a ctual / (V^{base2} / MVA^{base})$

(2) Transmission Line Model

π-model includes:

Series impedance Z=R+jX

Shunt admittance jB/2

This ensures accurate modeling of:

Charging currents

Voltage drops

Line losses

ESS Mathematical Model

The State of Charge (SOC) is given by:

$SOC(t) = SOC(t-1) + (Pcharge – Pdischarge) \times \Delta t / Erated$

Converter Model

AC and DC sides relate by:

$PAC = \eta inv \times PDC$

D.Control Strategy

The system uses a dual-loop control approach:

Outer Loop: Maintains DC voltage

Inner Loop: Controls current injection

Frequency and voltage support are provided using:

- Droop control
- Volt-VAR control

Grid Support Control Logic

ESS responds to disturbances:

Table no. 2 ESS responds to disturbance

Condition	ESS Action
Low voltage (sag)	Inject active power
Line overload	Absorb or inject power
Renewable output fluctuation	Smooth power
Frequency deviation	Provide fast frequency support

Solar Photovoltaic System Modeling

The solar PV generation unit is modeled as an inverter-interfaced distributed energy resource operating under varying irradiance conditions. The PV system converts solar energy into electrical power through power electronic converters synchronized with the grid.

The inverter regulates active power injection while maintaining voltage synchronization using grid-following control mechanisms. The PV output power varies according to irradiance fluctuations, which introduces disturbances affecting system stability.

The generated active power can be expressed as:

$$P_{PV} = \eta A G \quad (1)$$

where:

η = conversion efficiency

A = panel area

G = solar irradiance

The intermittent nature of PV generation reduces effective system inertia and necessitates external stabilization support.

Battery Energy Storage System

BESS operates in charging and discharging modes and helps:

- Balance power
- Reduce fluctuations
- Improve stability

Converter Control Strategy

The grid-connected converter employs hierarchical control loops for stable operation.

1) Frequency Droop Control

Active power output is regulated according to system frequency deviation:

$$P = P_0 - K_f (f - f_0) \quad (3)$$

P = Output Active Power

P0 = Reference Active Power

Kf = Frequency Droop Gain

f = Measured Grid Frequency

f0= Nominal Frequency

This control enables inertial response emulation and frequency stabilization.

2) Voltage Support Control

Reactive power compensation is achieved using Volt–VAR control:

$$Q=Kv\ (Vref-V) \quad (4)$$

This improves voltage recovery following disturbances.

3) DC-Link Voltage Control

A proportional–integral controller maintains constant DC-link voltage:

$$Vdc(s)=Kp\ e(s)+Ki \int e(s)ds \quad (5)$$

Simulation Results and Discussion

Overview of Simulation

The proposed IEEE 9-bus system integrated with renewable energy and ESS is simulated using MATLAB/Simulink. Load flow analysis is performed using the Newton-Raphson (NR) method to evaluate system performance under steady-state conditions.

The simulation results include:

- Bus voltage profile
- Power flow analysis
- System losses
- Generator output
- Convergence characteristics

Load Flow Result Analysis and Comparison for IEEE 9-Bus System

Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mvar)	Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (MVA)
BUS_1	16.5000	1.0400	0	150.0000	0	-Inf	Inf	1.0400	0	72.2729	36.0323
BUS_2	18.0000	1.0250	0	163.0000	0	-Inf	Inf	1.0250	8.2746	163.0000	11.3201
BUS_3	13.8000	1.0250	0	85.0000	0	-Inf	Inf	1.0250	3.9332	85.0000	-3.5865
BUS_4	230.0000	1.0000	0	0	0	0	0	1.0209	27.7598	0	0
BUS_5	230.0000	1.0000	0	125.0000	50.0000	-Inf	Inf	0.9633	26.3141	125.0000	50.0000
BUS_6	230.0000	1.0000	0	90.0000	30.0000	-Inf	Inf	1.0069	26.5550	90.0000	30.0000
BUS_7	230.0000	1.0000	0	0	0	0	0	1.0230	32.7067	0	0
BUS_8	230.0000	1.0000	0	100.0000	35.0000	-Inf	Inf	1.0129	30.2157	100.0000	35.0000
BUS_9	230.0000	1.0000	0	0	0	0	0	1.0203	31.2312	0	0

Fig. 2: Load Flow Report Generated by MATLAB Load Flow Analyzer

Table 3: Comparison of Bus Voltage Results Against the Reference Values

	Base Case		NR Method	
	% Mag	Angle	% Mag	Angle
Bus 1	104	0.0	104	0.0
Bus 2	102.5	8.5	102.5	8.27
Bus 3	102.5	4.2	102.5	3.93
Bus 4	102.09	-2.2	102.1	-2.24
Bus 5	99.33	-3.5	99.3	-3.69
Bus 6	100.7	-3.3	100.7	-3.45
Bus 7	102.32	2.9	102.3	2.71
Bus 8	101.31	0.4	101.3	0.22
Bus 9	102.85	1.5	102.8	1.23

Table 4: Comparison of Power Flow Results

From Bus	To Bus	Base		NR	
		MW	MVAr	MW	MVAr
01	02	71.6	27	69.261	35.65
02	03	40.9	22.9	163	10.804
03	05	-84.3	- 11.3	85	4.11
05	09	76.4	-0.8	69.258	32.419
09	10	-24.1	-24.3	124.16	49.655
10	12	60.8	-18.0	88.938	29.646
11	10	85	-10.9	162.98	6.509
12	02	-30.55	-16.54	99.441	34.79
17	05	163	6.7	84.996	14.471

(Standard IEEE reference values and input values are at 60 Hz and simulation uses 50 Hz)

J.Convergence Performance

The NR load flow algorithm demonstrates fast convergence.

Table 5: Convergence Details

Parameter	Value
Method Used	Newton-Raphson
Number of Iterations	2
Convergence Status	Successfully Converged

The system converges within 2 iterations, indicating strong numerical stability and efficient modeling.

K.System Power Summary

Table 6: System Power Summary

Parameter	Real Power (MW)	Reactive Power (MVAr)
Total Generation	320.27	43.76
Total Load (PQ)	315.00	115.00
Total Shunt Load	0.64	0.64
Total Losses	4.64	-71.87

Observation:

- System losses are very low (4.64 MW)
- Generation closely matches demand
- Indicates efficient system operation

Bus Voltage Profile Analysis:-

Table 7: Bus Voltage Profile

Bus	Voltage (p.u.)	Voltage (kV)	Angle (deg)	Type
1	1.040	16.5	0.00	Slack
2	1.025	18	8.27	PV
3	1.025	13.8	3.93	PV
4	1.021	230	27.76	PQ
5	0.993	230	26.31	PQ
6	1.007	230	26.55	PQ
7	1.023	230	32.71	PQ
8	1.013	230	30.22	PQ
9	1.028	230	31.23	PQ

Observation

- Minimum voltage occurs at Bus 5 (0.993 p.u.)
- All voltages are within permissible limits
- ESS helps maintain voltage stability

Table 8: Generator Output

Bus	P Generation (MW)	Q Generation (MVAr)
1	72.27	36.03
2	163.00	11.32
3	85.00	-3.59

Observation

- Generator at Bus 2 supplies maximum power

- Reactive power support is balanced among generators

Table 9: Load Data

Bus	P Load (MW)	Q Load (MVAr)
5	125.00	50.00
6	90.00	30.00
8	100.00	35.00
Total	315.00	115.00

Table 10: Line Power Flow Results

From Bus	To Bus	P (MW)	Q (MVAr)
1	4	72.06	35.82
2	7	162.79	11.11
3	9	84.79	-3.80
4	5	41.09	26.99
4	6	30.97	5.38
5	7	84.19	10.08
6	9	59.21	11.89
7	8	76.32	1.59
8	9	24.15	23.91

Table 11: Line Losses

Line	Loss (MW)
1–4	0.21
4–5	0.28
4–6	0.18
5–7	0.27
6–9	1.33
7–8	0.47
8–9	0.10
Total	4.64 MW

Observation

Losses are minimal, indicating efficient transmission

Maximum losses occur in longer transmission paths

Key Observations

- Load flow converged very fast (2 iterations) → strong system stability
- All bus voltages are within acceptable limits (0.95–1.05 p.u.)
- Maximum voltage drops at Bus 5 (0.993 p.u.)
- Reactive power losses are negative, indicating capacitive behaviour due to line charging
- Major power transfer paths:

o Generator Bus 2 → Load buses via Bus 7

o Generator Bus 3 → Bus 9 network

L. Impact of ESS on Grid Stability

The integration of ESS significantly improves system performance by:

- Reducing voltage variations
- Enhancing frequency stability
- Smoothing renewable output
- Providing fast dynamic response

ESS acts as a buffer between generation and demand, ensuring reliable operation.

H. Challenges

Despite improvements, the following challenges remain:

- High cost of ESS deployment
- Complexity in system coordination
- Lack of standardized control methods
- Limited large-scale implementation
- Need for advanced forecasting techniques

CONCLUSION

This paper presented the analysis of a renewable-integrated IEEE 9-bus system with Energy Storage System support. The Newton-Raphson method was used for load flow analysis, demonstrating fast convergence and accurate results.

Simulation results confirm that ESS significantly enhances grid stability by improving voltage regulation, frequency response, and power balance. The study highlights the importance of integrating energy storage with renewable systems for future power networks.

Future work may include real-time implementation, advanced control techniques, and large-scale system analysis.

REFERENCES

1. REN21, "Renewables 2023 Global Status Report," 2023.
2. International Energy Agency (IEA), "World Energy Outlook 2023," 2023.
3. P. Kundur et al., "Definition and classification of power system stability," IEEE Trans. Power Systems, vol. 19, no. 2, pp. 1387–1401, 2004.
4. J. Machowski et al., Power System Dynamics: Stability and Control, Wiley, 2008.
5. M. Ulbig, T. Borsche, and G. Andersson, "Impact of low rotational inertia on power system stability," IEEE Trans. Power Systems, vol. 29, no. 2, pp. 1–9, 2014.
6. Y. Zhang et al., "Review on frequency stability of power systems with high renewable penetration," Renewable and Sustainable Energy Reviews, vol. 81, pp. 1–13, 2020.
7. Molina-García et al., "Stochastic optimization for renewable energy systems," IEEE Trans. Power Systems, vol. 32, no. 2, pp. 1–10, 2021.
8. X. Luo et al., "Overview of energy storage technologies," Applied Energy, vol. 137, pp. 511–536, 2015.
9. H. Bevrani, et al., "Power system frequency control with energy storage systems," IEEE Trans. Smart Grid, vol. 10, no. 1, pp. 1–10, 2019.
10. S. Teleke et al., "Control strategies for battery energy storage," IEEE Trans. Energy Conversion, vol. 25, no. 3, pp. 1–10, 2020.
11. H. Yang et al., "Optimal sizing of hybrid renewable systems," Solar Energy, vol. 81, pp. 76–84, 2007.
12. J. Guerrero et al., "Hierarchical control of microgrids," IEEE Trans. Industrial Electronics, vol. 58, no. 1, pp. 158–172, 2011.
13. M. Shahidehpour, et al., "Smart grid control strategies," IEEE Trans. Smart Grid, vol. 12, no. 1, pp. 1–10, 2021.
14. MathWorks, "Renewable Energy Systems Simulation Using MATLAB/Simulink," 2024.
15. J. Carpentier, "Optimal power flow," Electric Power Systems Research, vol. 1, pp. 3–15, 1962

Enhancement of LVRT Capability in DFIG based Microgrids Using Hybrid GOA-PSO Tuned STATCOM

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ABSTRACT

The growing use of wind-based microgrids has increased the need for stable operation during Low-Voltage Ride-Through (LVRT) conditions, particularly when Doubly Fed Induction Generators (DFIGs) are connected to weak AC grids. During grid faults, voltage dips can cause instability and force wind turbines to disconnect, violating grid code requirements and affecting power continuity. To resolve this, effective control of reactive power support is essential. This study offers a hybrid optimization strategy that integrates the Grasshopper Optimization Algorithm and Particle Swarm Optimization (GOA–PSO) for tuning proportional–integral (PI) controllers of a Static Synchronous Compensator (STATCOM), intending to improve LVRT capability. Compared to formal tuning methods and standalone optimization techniques such as PSO or GOA, the hybrid method leverages both extensive search ability and rapid convergence, leading to superior controller performance under symmetrical as well as asymmetrical fault conditions. A 16-MW DFIG-based wind microgrid is modeled in MATLAB and evaluated under various grid fault scenarios. The performance of conventionally tuned, PSO-tuned, GOA-tuned, and hybrid GOA–PSO-tuned STATCOM controllers is equated. Simulation outcomes show that the hybrid GOA–PSO method provides faster voltage recovery, reduced peak voltage drops, improved reactive power support and better overall system stability during LVRT events. The proposed approach offers a simple and effective solution for enhancing microgrid resilience during fault conditions while strict adherence with international LVRT grid codes. This work contributes toward the more reliable integration of wind energy systems into weak grid infrastructures.

KEYWORDS: *DFIG, LVRT, STATCOM, Microgrid, Wind Energy.*

INTRODUCTION

A major paradigm shift is currently reshaping the global energy sector, driven by a combination of environmental concerns, the depletion of fossil fuel sources, and rising energy demand. Within the renewable energy portfolio, wind power has established itself as a dominant technology. This prominence is a result of its advanced technical development, high scalability and minimal environmental impact. By the end of 2024, the total global capacity for wind power reached approximately 1,136 GW. This rapid expansion highlights wind's role as a cornerstone of modern renewable energy strategies and underscores Ensuring compliance with LVRT requirements is essential for preserving overall system stability [1]. While this growth is supported by better turbine designs, falling costs, and

proactive government policies, integrating wind power at such a massive scale presents technical hurdles. Because wind is inherently intermittent, it introduces uncertainty into grid operations, particularly when high levels of wind power are fed into "weak" or unstable grids. To manage this, microgrids have become an essential solution. These systems offer localized power generation and centralized management, providing much-needed resilience for both isolated rural areas and dense urban centers [2]. In the realm of wind turbine technology, the DFIG is currently the industry standard. DFIG systems are highly efficient and cost-effective because they utilize power converters rated at only 25-30% of the generator's total capacity. Furthermore, they enable independent rule of active & reactive power, which is essential for meeting modern grid requirements [3]. However, DFIGs possess a notable vulnerability: Direct grid connection to the stator makes the system highly susceptible to external disturbances like voltage drops and faults. This highlights the concept of LVRT to the forefront. Modern grid codes globally demand that turbines stay connected during short voltage sags to provide reactive power support, rather than abruptly disconnecting and potentially triggering a wider blackout [4]. Regulatory bodies across the globe have established varying LVRT benchmarks. For example, in Germany, turbines must endure a total voltage loss for 150 milliseconds, while Indian regulations require turbines to handle a drop to 0.15 per unit for 0.3 seconds. Grid licensing and avoiding severe financial penalties require adherence to these regulations [6]. In the Past, engineers used hardware-centric solutions like crowbar circuits, braking resistors, or Dynamic Voltage Restorers (DVRs) to handle these faults. Despite their advantages, these approaches tend to be costly, are vulnerable to overheating and offer limited flexibility to adapt to different fault scenarios [7], [8], [10]. Consequently, Flexible AC Transmission System (FACTS) gadgets—specifically the STATCOM have become the preferred alternative. A STATCOM can rapidly feed reactive power to stabilize voltage and speed up fault recovery without requiring significant hardware changes to the turbine [6], [16], [17], [18]. The success of a STATCOM is directly coupled to the precision of its control system. Proportional-Integral (PI) controllers are standard due to their simplicity, but they are difficult to tune accurately. If the tuning is incorrect, the controller can actually Exacerbate oscillations or delay recovery during a fault. Existing tuning techniques, such as the Ziegler-Nichols method, their performance is often have limited in the highly nonlinear and complex environment associated with a power grid fault. To solve this, researchers have turned to nature-inspired optimisation methods such as Particle Swarm Optimisation (PSO) and the Grasshopper Optimisation Algorithm (GOA). However, these individual algorithms sometimes struggle with slow processing or getting "stuck" before finding the best solution [6], [18]. This study investigates a hybrid GOA-PSO approach, which combines the wide-ranging search capabilities of GOA with the rapid refinement and convergence of PSO. This hybrid strategy aims to provide superior tuning for STATCOM controllers specifically to effectively increase the LVRT operation of DFIG-based microgrids connected to weak grids [5].

LITERATURE REVIEW

Because of their scalability, technological stalwartness, and declining prices, wind is becoming a central part of today's power grids around the world due to the rapid global shift to renewables and is being identified as a key component in addressing climate change and supporting sustainable development goals. Global studies on changes to the global electricity supply show that the adoption of renewable energy in large quantities will be an important factor in combatting climate change and in the achievement of sustainable development objectives. However, as wind continues to gain market share in the developing world and in places with weak grids, there are considerable emerging technical challenges associated with wind generation, including grid stability, voltage regulation, and fault ride-through ability [1][2]. DFIG-based wind turbines support speed operation over a variable speed range, offering high efficiency & the capability to severally regulate active and reactive power. DFIGs have been extensively studied to assess their steady-state and dynamic behaviours under a variety of control and magnetization strategies, which have demonstrated that the proper design of the control system can dramatically improve both efficiency and effectiveness of operation [3]. Despite the benefits of DFIG technology, DFIGs are very vulnerable to disturbances on the grid; in particular,

voltage sags. Voltage sags can cause excessive rotor currents, excessive DC link voltages, and result in converter faults that lead to disconnects from the grid, which are not aligned with recent grid code standards [4][7]. To meet specific requirements with LVRT needs, many protection and control approaches have been suggested. Conventional methods like crowbar circuits and braking resistors are an effective way to ensure that power converters are protected in the event of faults, but at the expense of losing the capability to regulate reactive power, thereby ensuring voltage support under worst-case conditions and system stability [7], [13]. Advanced control-based solutions such as disturbance feedforward control, nonlinear rotor-side control, and coordinated converter control have demonstrated enhancement of the transient performance without the need for extra hardware; however, these approaches tend to involve complicated control structures and are sensitive to parameter variations [4], [8], [14]. External compensation devices, especially FACTS controllers, have been receiving much attention for LVRT enhancement. Devices like DVRs, Fault Current Limiters (FCLs) and STATCOMs have been extensively studied to reduce the voltage sag and effectively enhance the fault tolerance in DFIG-based systems [10]-[12]. Among these, the most commonly preferred is STATCOMs because of their fast dynamic response, better reactive power compensation ability and ease of integration at the Point of Common Coupling (PCC). Several studies validate the results showing that the use of STATCOM-assisted DFIG systems generally increases the voltage recovery and the code compliance to the grid during symmetrical and unsymmetrical faults [16], [17]. The success of the STATCOM-based LVRT enhancement highly depends upon the tuning of the controller parameters. Traditional PI controller tuning methods, like trial and error or classical methods, cannot often give robust performances under highly nonlinear and uncertain fault conditions. As a result, metaheuristic optimization techniques have been applied more and more to controller tuning. Particle Swarm Optimization (PSO) has been widely adopted for its straightforward implementation and rapid convergence characteristics, but it has the drawbacks of premature convergence and a lack of global search capability [6], [18], [19]. Grasshopper Optimization Algorithm (GOA) originating from the swarming characteristics of grasshopper has superior ability in exploration ability, but slow convergence when used alone [20], [21]. To overcome the limitations of single optimization techniques, hybrid algorithms have emerged as an effective solution. Hybrid optimization approaches based on PSO with other bio-inspired algorithms have shown a better convergence speed, robustness and solution accuracy in power system applications [6], [18]. In particular, it has been demonstrated in recent studies that a hybrid GOA-PSO tuning of STATCOM controllers greatly improves LVRT capability as well as dynamic stability of the wind-based microgrids under weak grid conditions [5]. Nevertheless, existing works tend to concentrate on specific fault scenarios or lack overall comparative analysis under severe grid disturbances.

PROBLEM STATEMENT

DFIG-based wind turbines coupled with weak AC grids encounter severe LVRT issues due to the repeated voltage sags and grid fault conditions. As the grid is directly connected to the DFIG's stator any voltage drop has an immediate impact on the generator, which causes excessive rotor currents, DC-link over voltages and possible converter tripping. Such conditions may force wind turbines to disconnect from the grid, resulting in non-compliance with modern grid standards [4], [7], [9]. The situation becomes more critical in wind-based microgrids where low short-circuit capacity is an additional factor that exacerbates voltage instability in the event of faults [5], [10]. To address LVRT problems, many existing solutions rely on hardware-based protection techniques such as crowbar circuits, braking resistors and fault current limiters. Although these approaches are effective in protecting the converter in the case of faults, they often disable reactive power control or add extra losses, which decreases the voltage support and compromises the dynamic performance of the system [7], [11], [13]. Control-based methods such as nonlinear control strategies and disturbance feedforward methods have been suggested to enhance fault response; however, these methods are usually associated with a complex

control structure and are sensitive to the variation in parameters, which limits their practical robustness [4], [8], [14]. FACTS devices, especially STATCOMs, have been extensively used to improve LVRT capability thanks to their speed of reaction and the high reactive power compensation capability [10], [12], [16], [17]. However, the performance of the LVRT enhancement using STATCOM is strongly influenced by the tuning of the controller parameters. In most of the existing systems, PI or PID controllers are tuned by hand, which cannot guarantee reliable operation under different symmetrical and unsymmetrical fault conditions. Poor tuning often leads to voltage oscillations, poor reactive power injection and slow voltage recovery as well as a higher risk for converter tripping [5], [6], [18]. To achieve better performance of the controller, metaheuristic optimization techniques have attracted more and more attention. Particle Swarm Optimization (PSO) is widely used despite its straightforward implementation and rapid convergence; it tends to suffer from early convergence and restricted effective performance [18], [19]. Similarly, the Grasshopper Optimization Algorithm GOA has better exploration capability but has slow convergence as well as accuracy when used alone [20], [21]. Due to these limitations, standalone optimization methods are not appropriate to deal with the non-linearity and uncertainties that are inherent in DFIG-based microgrids. Furthermore, most of the existing studies consider single grid-connected DFIG systems or aggregated wind farms, whereas there is a lack of attention on microgrids with wind-based systems, which include more than one turbine. This points to a pronounced research gap in the design of dynamic tuned STATCOM controllers based on hybrid optimization methods specifically designed to meet the requirements of microgrid applications under strict LVRT grid code requirements [5], [6], [9]. Therefore, there is a great need for the design and development of an optimized STATCOM control strategy based on the hybrid GOA-PSO, which can effectively tune the PI controllers to ensure balanced active & reactive power support, voltage stabilization of the PCC, oscillation reduction and reliable LVRT performance during symmetrical as well as unsymmetrical fault scenarios in the grid [1], [2], [5].

LVRT REQUIREMENTS & FAULT SCENARIOS

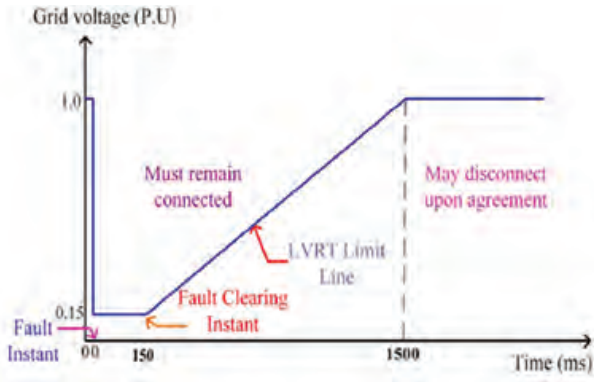

Fig. 1. Standard Low Voltage Ride-Through (LVRT) Characteristics

Modern grid standards impose very stringent regulations on LVRT conditions for wind turbines, which include the minimum amount of voltage (V) and duration of time (T) that wind turbines are expected to stay linked to the grid after a fault occurs. These LVRT profiles aim to reduce the likelihood of widespread disconnection of wind power generation & to support grid voltage stability during disturbances [5], [8]. In this study, a very comprehensive investigation of DFIG-based microgrids' LVRT performance is performed by testing the symmetrical as well as unsymmetrical faults. Severe symmetrical faults, such as three-phase to ground (3PG), are classified as worst-case scenarios due to the amount of voltage collapse and power oscillation associated with these events. One-phase to ground (1PG) faults are also considered, as these types of faults occur more frequently in practical distribution systems and have the potential to create unbalanced voltage conditions [4], [7], [9]. The severity of the voltage sag and the amount of time it takes to clear the fault are selected based on internationally recognized grid code requirements that have been established for wind energy systems. The selected conditions should therefore provide a realistic and rigorous test environment based on actual operating conditions for wind-based microgrids that are connected to weak electrical grids [5], [8], [10].

METHODOLOGY

The integration of renewable resource is a challenging task. The proposed methodology follows a step-by-step

approach which consists of a combination of system modelling, STATCOM control design, optimisation-based PI tuning and performance evaluation. A 16 MW DFIG-based wind microgrid is modeled in the environment of simulation and modeling (MATLAB/ Simulink), and the practical operating conditions of weak grids are represented. Weak grids are generally characterized by a low short-circuit ratio, so weak grids are generally more sensitive to voltage disturbances, as well as prolonged voltage dips in fault conditions. It is these characteristics that make weak grid environments ideal for the evaluation of low-voltage ride-through (LVRT) ability [5], [10], [18]. To evaluate the system robustness, both symmetrical and unsymmetrical fault conditions are simulated. Symmetrical faults, including three-phase short circuits, are considered to represent the most critical disturbances. Greater emphasis is placed on unsymmetrical faults such as single-line and double-line, which are connected to the ground as they are more frequent in real power systems. These faults introduce negative sequence components which may result in rotor heating, torque oscillations and increased mechanical stress in DFIG-based wind turbines [4], [7], [9]. During grid disruptions, the PCC integrates a STATCOM to deliver quick and dynamic reactive power supply. A voltage source inverter (VSI), a DC link capacitor, and a coupling transformer comprise the STATCOM. Its primary role is to supply or absorb reactive power to maintain PCC voltage and improve overall system performance and stability during LVRT events [10], [12], [16]. The STATCOM control system is developed based on a cascaded control structure with three PI-regulated loops. By producing a reference reactive current, the outer voltage control loop maintains control over the PCC voltage. The inner current control loop provides correct tracking of this reference so that a fast reactive power response is possible. In addition, the DC-link voltage control loop is aimed at controlling the capacitor voltage to ensure stable operation of the inverter. The concerted action of these control loops has the consequence of ensuring good voltage regulation and quick recovery in fault conditions [6], [18]. PI controller tuning is presented as an optimization problem in which the goal is to reduce the ITAE. The ITAE performance index is chosen because it imposes more penalty on persistent errors and hence overshoot and voltage recovery are quicker as compared with traditional indices such as Integral Absolute Error (IAE) and Integral Squared Error (ISE) [6], [19]. In this research, six PI gains corresponding to the three control loops are optimized at the same time. A hybrid algorithm based on the hybrid GOA-PSO technique is used to search for the optimization of the controller parameters. GOA increases global exploration modeling social interaction, attraction and repulsion of search agents, and PSO increases local exploitation by updating particle velocities depending on their personal and optimal global solutions. The combination of both algorithms achieves a balance between the search process, mitigates the risk of premature convergence, and enhances tuning accuracy [19] - [21]. Finally, the effectiveness of the aimed control method is evaluated through computer simulation studies. Comparative analyses are done by using conventionally tuned PI controllers, PSO-tuned controllers, GOA-tuned controllers, and hybrid GOA-PSO-tuned controllers. Key performance indicators include voltage sag depth, recovery time, oscillation damping, reactive power injection capability, and international LVRT grid code requirement compliance. The received results show the superior and effective performance of the hybrid GOA-PSO-based tuning approach [5], [18] clearly.

DESIGN AND CONTROL OF STATCOM

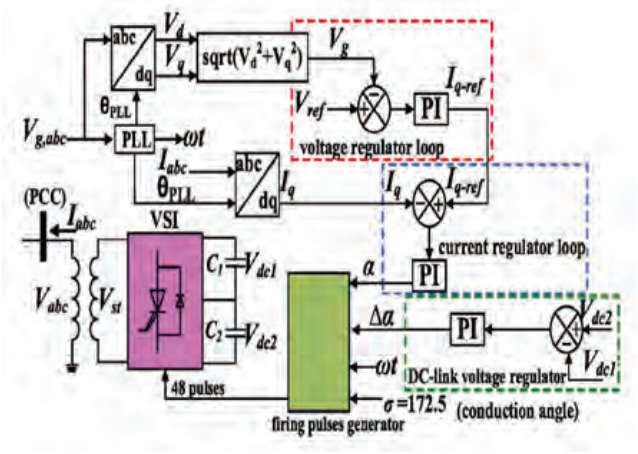

Fig. 2. STATCOM control scheme

The STATCOM is placed at the PCC of the microgrid to achieve rapid & dynamic reactive power support during grid disturbances. It is mainly composed of a

VSC, a DC link capacitor and coupling inductors to interface the converter with the grid [10], [12]. Owing to the shunt-connected configuration, the STATCOM is able to inject or absorb reactive current, independent of the grid voltage, thereby making it very effective in the voltage regulation during fault conditions [16], [17]. The operation of the STATCOM is based on a synchronous dq-axis control strategy in which the d-axis current is used to control reactive power and the q-axis current is used to control active power exchange to keep the DC-link voltage [6], [18]. This control structure enables the independent regulation of reactive power and DC-link voltage. Such a feature is Essential during LVRT events to ensure the system remains stable despite weak grid conditions [5], [10].

Proportional-integral (PI) controller: Proportional-integral controllers are commonly used for controlling in STATCOM control loops due to their straightforward design, ease of implementation and satisfactory performance in practical power system applications [7], [11]. However, proper tuning of the proportional and integral gains is critical in order to ensure fast voltage recovery, reduced oscillations and stable operation during symmetrical and unsymmetrical faults [4]. The theoretical basis of the design of the STATCOM controller is reactive power compensation & the voltage regulation principle. The control architecture usually has a hierarchical loop structure [12], [16]. The outer voltage control loop ensures stability of the PCC voltage by comparing the measured voltage with its reference and giving the corresponding reactive current reference. Tracking this reference and managing the inverter switching signals to regulate reactive power injection are the goals of the inner current control loop. Furthermore,

by controlling the active power exchange through the converter, a DC-link voltage control loop is employed to guarantee voltage balance between the DC capacitor [10], [18].

The PI controller transfer function is given by

$$G(s) = Kp + Ki/s$$

Where Kp and Ki are proportional and integral gains respectively. In the case of STATCOM applications, these parameters should be carefully chosen to deal with the nonlinear dynamics of the grid and fault-induced transients. Poor tuning can lead to instability, excessive overshoot or long voltage recovery in LVRT conditions [5], [7]. Conventional tuning methods like Ziegler-Nichols method do not always give optimal performance for a nonlinear and time varying system like DFIG based microgrid [6], [18]. As a result, smart and optimization-based tuning approaches have received much attention. While advanced approaches such as fuzzy logic controllers, artificial neural networks and sliding mode control have been reported, they may require high computational complexity or face implementation challenges [8], [14]. To overcome these limitations, hybrid methods of metaheuristics optimization have appeared as effective alternatives. The proposed hybrid GOA-PSO algorithm integrates the powerful global exploration ability of GOA algorithm and the quick convergence ability of PSO algorithm, which can complete the tuning of STATCOM PI controllers quickly and effectively. By minimizing ITAE, the controller gains are adapted to ensure robust performance under a wide range of symmetrical and asymmetrical faults. [19]-[21].

MATHEMATICAL MODELLING

The mathematical modeling framework provides the analytical foundation for both STATCOM operation and optimization processes. STATCOM's active and reactive power exchanges are defined by the equations

$$P = (Vpcc * Vst / X) * \sin\varphi \text{ and}$$

$$Q = (Vpcc\ (Vpcc - Vst\cos\varphi)) / X,$$

where Vpcc is the point of common coupling voltage, Vst is the STATCOM voltage, φ is the phase angle, and X is the coupling reactance. These equations highlight how STATCOM regulates reactive power injection based on voltage differentials and phase relationships.

The PI controllers are described by transfer functions in the form

$$\alpha = (Iqref - Iq)(Kp\_Iac + Ki\_Iac/s) \text{ and}$$

$$\Delta\alpha = (Vdc2 - Vdc1)(Kp\_DC + Ki\_DC/s).$$

These govern the current regulation loop and the DC-link regulator respectively.

The optimization objective is defined as minimizing

$$U(X) = \int eVac(t)dt + \int eIac(t)dt + \int eVdc(t)dt$$

over the simulation horizon, subject to constraints on gain ranges, voltage deviation, and reactive power limits. This objective ensures that all deviations are minimized quickly, leading to effective LVRT performance. The GOA algorithm is based on modeling grasshopper social interactions, gravity, and wind forces. Its exploration mechanism enables coverage of a wide solution space. The PSO algorithm updates positions and velocities of particles towards local and global optima, enhancing convergence. The hybrid GOA-PSO combines the global search strengths of GOA with the local optimization efficiency of PSO. A flow involves initialization of the population, fitness evaluation, GOA updates for exploration, PSO refinement for exploitation, and termination upon convergence. This hybridization ensures that STATCOM PI controllers are tuned to deliver optimal responses even under dynamic weak grid conditions.

SYSTEM PARAMETER SELECTION

System parameter selection is a critical step to ensure that simulations are realistic and results are generalizable. The chosen system is a 16 MW DFIG-based wind microgrid functioning in grid-connected mode. This size reflects a medium-scale wind farm, representative of real-world installations in developing regions with weak grids. The STATCOM configuration includes a VSI, DC-link capacitor, and transformer, matched to the system's reactive power requirements. PI controller constraints are established based on practical and theoretical considerations. For the voltage regulator, Kp is limited between 5 and 25, while Ki ranges between 1000 and 3000. For the current regulator, Kp is limited between 0.3 and 12, with Ki between 10 and 100. For the DC-link regulator, Kp ranges between 0.0001 and 1, while Ki is limited between 0.02 and 1. These ranges ensure physical feasibility and maintain system stability. Optimization parameters are selected to ensure robustness of results. A population size of 100 and 100 iterations is adopted for the hybrid GOA-PSO algorithm. Fault scenarios simulated include symmetrical three-phase short circuits, which, although rare, cause the deepest voltage sags, and asymmetrical faults such as single-line faults and double-line faults connected to grounds, which are more frequent and damaging due to negative sequence currents. The simulation environment is MATLAB/Simulink with a discrete solver step time of 50 microseconds, providing adequate resolution for capturing transient dynamics. These selections ensure that the evaluation framework is consistent with international LVRT standards and reflective of real-world operating conditions.

PI TUNING METHOD- GOA-PSO

Traditional methods for PI controller tuning, like Ziegler-Nichols method, are straightforward to implement but may not provide good results for modern power systems. In systems such as the STATCOM-based microgrids, the operating conditions are changed frequently with faults, load variations and grid disturbances. If the PI controller is not properly tuned, it can cause large overshoots in reactive power, voltage oscillations during the voltage recovery, and failure to meet requirements with LVRT requirements during fault events [6], [7], [18]. To improve the performance of controllers, optimisation-based tuning methods have gained popularity. Particle Swarm Optimization (PSO) and Grasshopper Optimization Algorithm (GOA) are two examples of metaheuristic algorithms that have outperformed conventional tuning methods. PSO is widely used because of its straightforward structure and quick rate of convergence; yet, in nonlinear and complicated systems, it may become stuck in local optima [18], [19].On the other hand, GOA has a very good global search function and can explore a wide space of solutions well, but the convergence is relatively slow, and the accuracy in later iterations may reduce [20], [21]. In order to overcome the limitations of single algorithms, a hybrid GOA - PSO approach is followed in this work for tuning the parameters of the STATCOM PI controller. This hybrid method increases the exploration capability of GOA and fast convergence ability of PSO, and the algorithm can search widely in the initial stages and converge quickly to the optimal solution in the later stages [19] - [21].

GOA (Grasshopper Optimization Algorithm)

A population-based optimization method for resolving challenging numerical optimization issues is the Grasshopper Optimization Algorithm (GOA). Inspired by the way grasshoppers naturally look for food, Saremi

and Mirjalili introduced this method in 2017 [20], [21]. In GOA, a possible answer to the defined optimization problem is represented by each grasshopper in the population. The movement patterns of grasshoppers change greatly when they go from the nymph stage to adulthood; this can be used to give the search algorithm a biological foundation. In the nymph phase, grasshoppers are wingless and are restricted to moving only short distances, which is local searching behavior. As they mature into adults, they develop wings and are capable of longer distances of travel, reflecting global searching behavior This biological transition ensures that the algorithm effectively balances the extensive search space exploration with the precision of local convergence. GOA uses this natural transition to ensure balancing global search and local refinement in the optimization process [20]. There are two primary stages to the GOA food-searching procedure. In order to find prospective locations in the search space, grasshoppers conduct extensive exploration during this phase. The movement becomes more concentrated on the finest solutions discovered thus far during the exploitation phase, and the algorithm is able to enhance and improve the outcome [21].

PSO (Particle Swarm Optimization)

PSO is a population-based optimization method based on the social behavior of fish schools or flocks of birds looking for food.. That is inspired by the behavior of a group of birds or fish searching for food. In PSO, a swarm of particles exists, and each particle is a potential solution to the optimization problem. All the particles search the solution space simultaneously and exchange information among each other to enhance the quality of solutions [18], [19]. The particles are moving in a search space with all the possible candidate solutions. During the search process, each particle constantly changes its position in an attempt to reach the optimal solution. This collective movement enables the swarm to dynamically adapt when better solutions are found [19]. Particles are dispersed at random throughout the search space at the beginning of the optimization phase. A predetermined fitness function is used to gauge each particle's performance. The term "personal best" refers to the optimal position that each particle maintains. The swarm's optimal position among all the particles is determined to be the global best. Particles modify their motion in each iteration by considering both the global best positions and their own best positions [18].

GOA AND PSO HYBRIDIZATION

Both PSO and GOA are two methods that have been used for solving optimization problems; however, each method has its limitations. PSO is known as a fast convergent algorithm, while it is very easy to get trapped in local optimum solutions, especially for nonlinear and complex search spaces [18], [19]. Similarly, while GOA has good global search capability, it can be slow to converge and can be less accurate in the later stages of optimization [20], [21]. These drawbacks have been reported in several studies and have led to the development of better optimization strategies. One successful way to overcome these limitations is to merge the PSO and GOA into a hybrid type of optimization. This hybrid strategy enables both algorithms to act cooperatively and combine their individual strengths while reducing their weaknesses [19]-[22]. GOA has a good performance in the exploration phase of optimization due to the swarming behavior of grasshoppers. This behavior allows the algorithm to search a large region of the solution space and discover several promising regions. However, in complex problems, GOA might not make good use of these regions or might converge prematurely, if used alone [20]. On the other hand, PSO is very good in the exploitation phase. By circulating information between particles, PSO is able to rapidly converge towards better solutions and to fine-tune them. Despite this advantage, PSO can have difficulties in escaping from the local optima with highly complex or multimodal search spaces [18], [19]. In the proposed hybrid GOA-PSO method, GOA is aimed first to examine the solution space broadly and to find high-quality solution regions. Once these regions are found, PSO is used to reconsider the solutions and improve the accuracy. This sequential integration guarantees an effective balance trade-off between exploration and exploitation to achieve better optimisation performance [21]. As a result, the combination of GOA and PSO (named as the hybrid GOA-PSO approach) has a faster convergence speed and higher solution quality than the standalone algorithm.

SIMULATION & RESULTS

Simulation of the grid connected microgrid

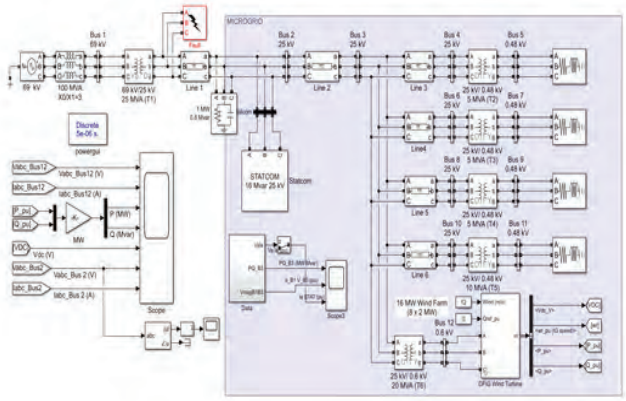

Fig. 3. MATLAB/Simulink model of the grid-connected microgrid

This figure is a Simulink model of our DFIG-based wind microgrid integrated with STATCOM for LVRT analysis. Starting from the left side, we have the main grid source, which provides 69kV at 60Hz. This is the utility grid that is connected to our microgrid system. Next, the power goes through a 100 MVA transformer that reduces the voltage from 69kV to 25kV. This transformer helps in connecting the high-voltage grid with the lower-voltage microgrid. Then we have several lines (Line 1, Line 2, Line 3 etc.), which connect different buses - from Bus 1 to Bus 12. Each line and bus exists for different parts of the microgrid network that carry power at 25 kV or 0.48 kV. In the blue shaded area, you can see the microgrid system. Here, several distribution transformers (T2, T3, T4, T5 and T6) are connected in order to step down the voltage to 0.48 kV and 0.6 kV for different loads and wind turbines. On the bottom right, we have the 16 MW Wind Farm, which is eight 2 MW DFIG-based wind turbines. These DFIGs convert the wind energy into electrical energy & the output of these DFIGs is connected to Bus 12 using 25/0.6 kV transformer. Important electrical outputs from the DFIG Wind Turbine block include rotor speed, DC-link voltage (Vdc), active power (P), and reactive power (Q). You can see the Fault block connected at Bus 2 when you go slightly upward. This is intended to verify the LVRT capacity of the approach by simulating various grid faults, such as LLLG, LLG, or LG faults. The STATCOM system is now shown on the left side of the figure. In a two-phase system, the following functions are performed: -

- The STATCOM measures the voltage (Vabc), current (Iabc) and DC link voltage (Vdc) from Bus 2.
- As a result, the output of the HMI can be read with a +-667 V range. As a result, a Phase-Locked Loop (PLL) utilized to synchronize to the grid frequency & phase.
- The control system performs calculation of active (P) & reactive (Q) power so that, relying on the results of this calculation, the PI controllers inside the STATCOM are used to generate the control signals.
- At the grid voltage in response to faults, Voltage Source Inverter (VSI) injects or absorbs reactive power as required, and therefore these signals control this.

At the center bottom the Scope and PowerGUI blocks are used for monitoring the waveform and controlling the simulation parameters with a discrete step size of 5e-6 seconds. So overall, this complete Simulink model represents how the DFIG-based wind microgrid interacts with the main grid, how faults are affecting the stability of the system and how the use of STATCOM, along with a hybrid GOA-PSO tuning approach, is helping to maintain the voltage stability as well as LVRT performance.

RESULTS

L-G Fault Condition

a) Without STATCOM & GOA–PSO Tuned PI Controller

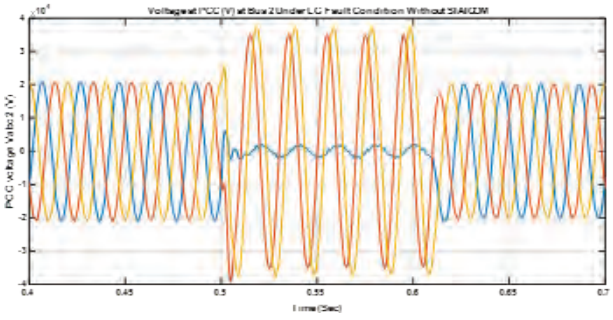

Fig. 4 Three-phase voltage at wind farm bus under L-G fault without STATCOM.

The LG fault (0.5–0.6 s) causes a phase-A voltage drop and a slight rise in other phases. Recovery (~0.1–0.15 s) shows oscillations; without STATCOM, stability is weak with poor LVRT.

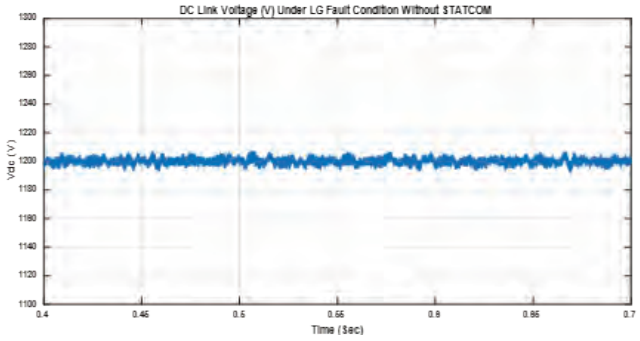

Fig. 5. DC bus voltage under L-G fault condition without STATCOM.

The DC link voltage remains constant even during LG fault due to less severity of the fault type.

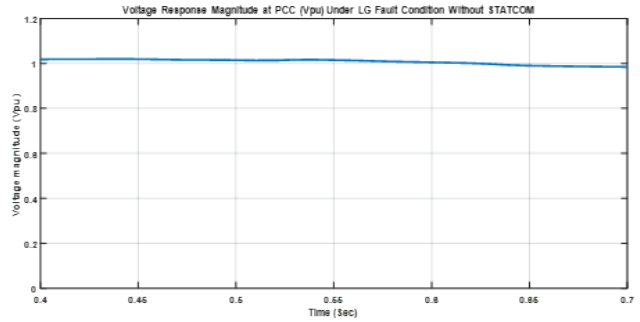

Fig. 6 Magnitude of voltage response (pu) at PCC under L-G fault without STATCOM.

PCC voltage remains steady even during the LG fault period (0.5–0.6 s).

b) With STATCOM & GOA–PSO Tuned PI Controller

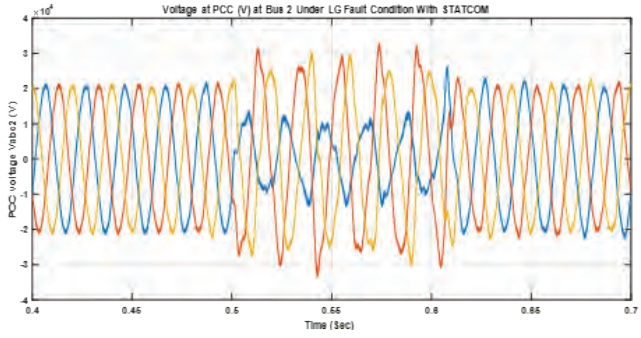

Fig. 7 Three phase voltage at wind farm bus under L-G fault with STATCOM.

With STATCOM, voltage dip during LG fault improves. STATCOM injects reactive power during fault duration (0.5-0.6 s), improving LVRT capability and reducing oscillations.

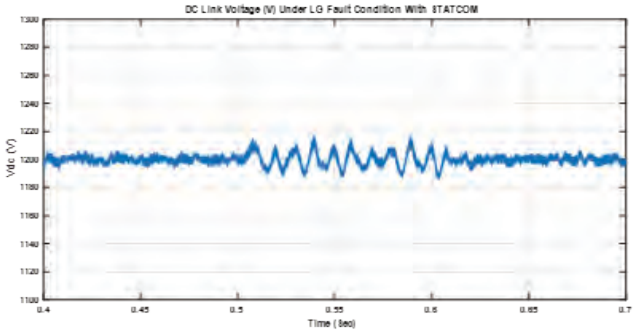

Fig. 8 DC link voltage under L-G fault with STATCOM

DC link voltage oscillations are ~2% and stabilize quickly after fault clearance; STATCOM reduces Converter stress.

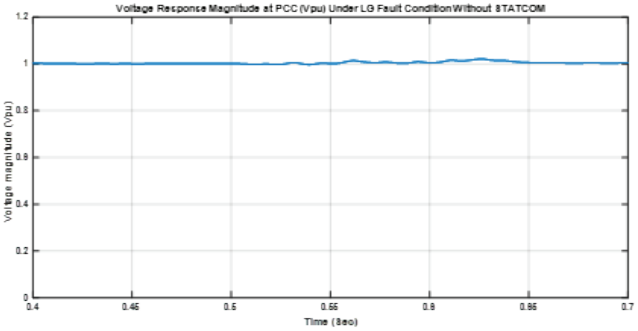

Fig.9 Magnitude of voltage response (pu) at PCC under L-G fault with STATCOM.

PCC voltage stays above 0.995 pu and recovers in ~0.05 s; STATCOM improves voltage profile and grid compliance.

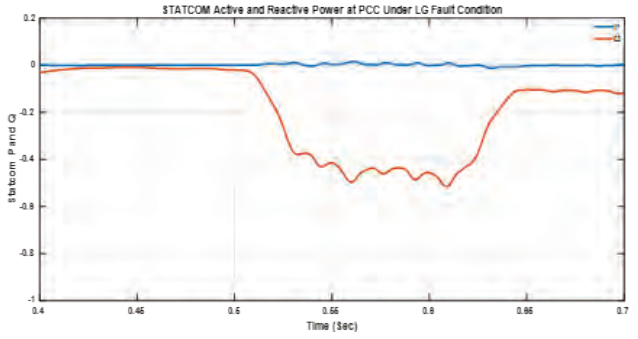

Fig. 10 Active and reactive power injected at PCC under L-G fault with STATCOM

During LG fault, reactive support stabilizes voltage and helps power recovery after 0.6 s.

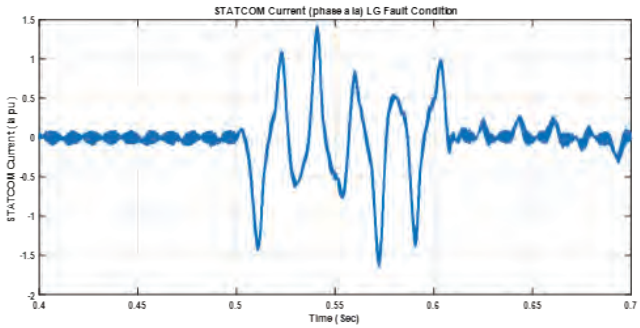

Fig.11 STATCOM current for a phase (pu)under

L-G fault with STATCOM

STATCOM injects reactive current during the fault and quickly returns to nominal after clearance.

L-L-G Fault Condition

a) Without STATCOM & GOA–PSO Tuned PI Controller

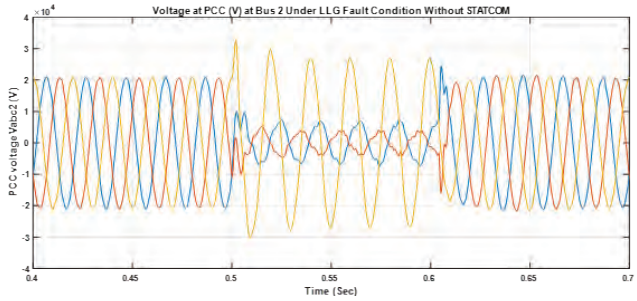

Fig. 12 Three phase voltage at wind farm bus under L-L-G fault without STATCOM

Without control, PCC voltage drops to ~0.57 pu with strong oscillations during LLG fault; recovery is slow, indicating poor LVRT.

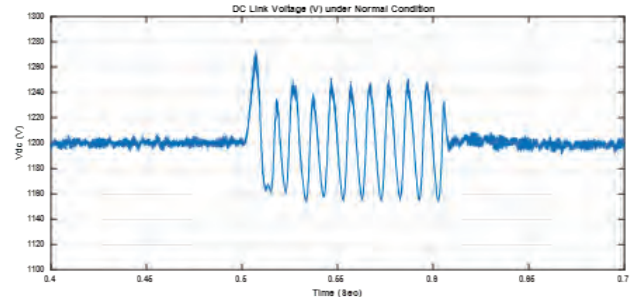

Fig. 13 DC bus voltage under L-L-G fault condition without STATCOM

DC link voltage oscillations persist during fault. Converter stress increases significantly.

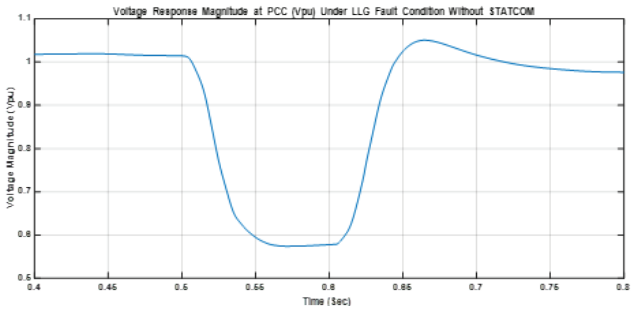

Fig. 14 Magnitude of voltage response (pu) at PCC under L-L-G fault without STATCOM.

PCC voltage drops to ~0.58 pu with post-fault oscillations; lack of reactive support causes instability.

b) **With STATCOM & GOA–PSO Tuned PI Controller**

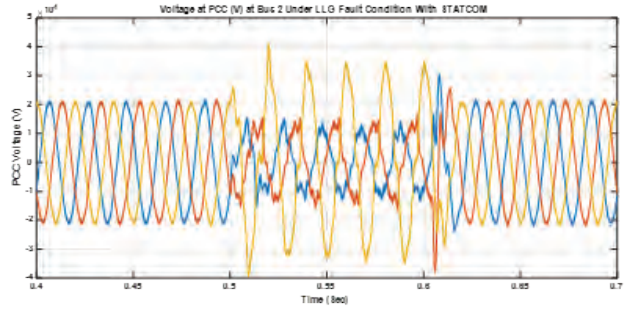

Fig. 15 Three phase voltage at wind farm bus under L-L-G fault with STATCOM.

Voltage improves to about 0.875 pu during fault with STATCOM. Recovery occurs within 0.05–0.08 s after fault clearance.

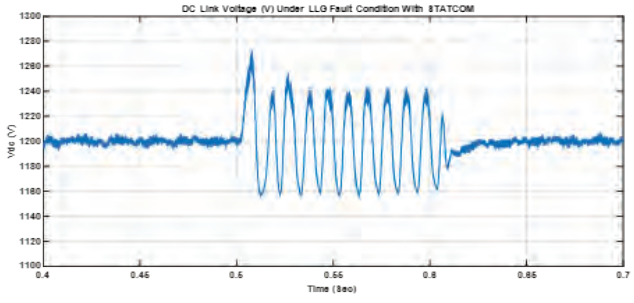

Fig. 16 DC link voltage under L-L-G fault with STATCOM.

Faster stabilization of DC link voltage occurs due to reactive power support.

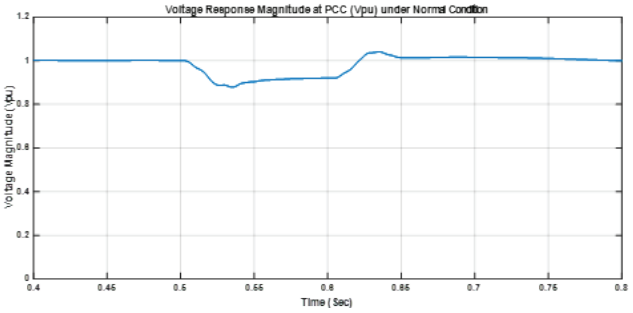

Fig. 17 Magnitude of voltage response (pu) at PCC under L-L-G fault with STATCOM.

PCC voltage remains above 0.875 pu during fault (improved from 0.58 pu without STATCOM). Voltage recovery is faster and oscillations reduce significantly.

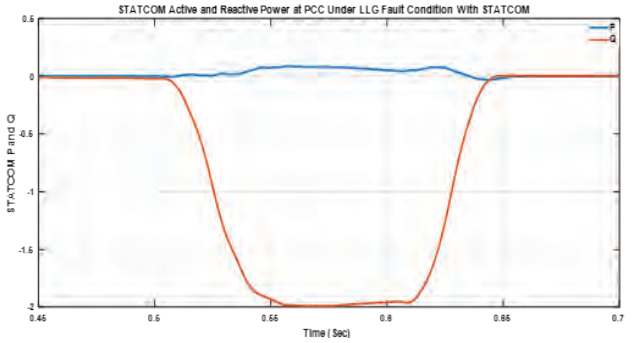

Fig. 18 Active and reactive power injected at PCC under L-L-G fault with STATCOM.

Reactive power injection increases during fault, helping voltage stabilization and faster active power recovery.

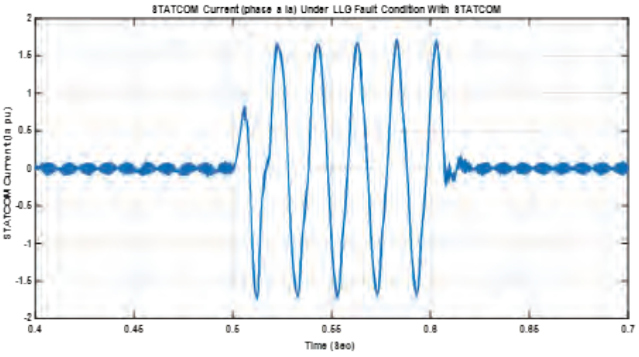

Fig. 19 STATCOM current for a phase (pu) under L-L-G fault with STATCOM.

L-L-L-G Fault Condition

a) Without STATCOM & GOA–PSO Tuned PI Controller

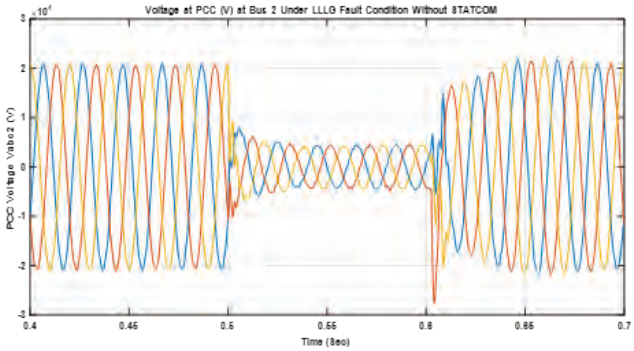

Fig. 20 Three phase voltage at wind farm bus under L-L-L-G fault without STATCOM.

Voltage collapses to nearly 0.2 pu during fault. Recovery is slow and unstable after 0.6 s.

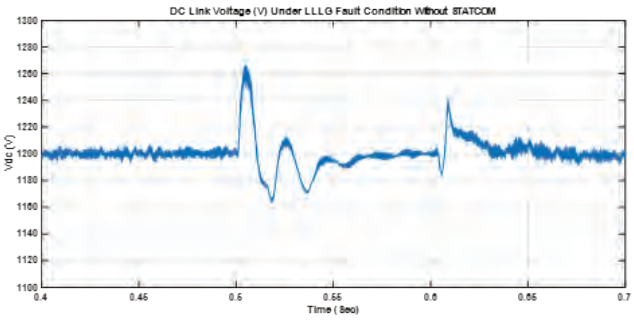

Fig. 21 DC bus voltage under L-L-L-G fault condition without STATCOM.

DC voltage severe oscillations occur due to sudden power loss.

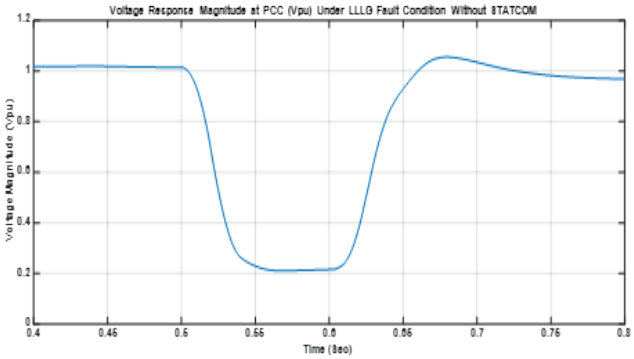

Fig. 22 Magnitude of voltage response (pu) at PCC under L-L-L-G fault without STATCOM.

PCC voltage drops to 0.2 pu which is close to 0.15 pu limit for LVRT as per Grid Code in India during fault and recovers slowly with oscillations lasting for more than 2 s.

b) With STATCOM & GOA–PSO Tuned PI Controller

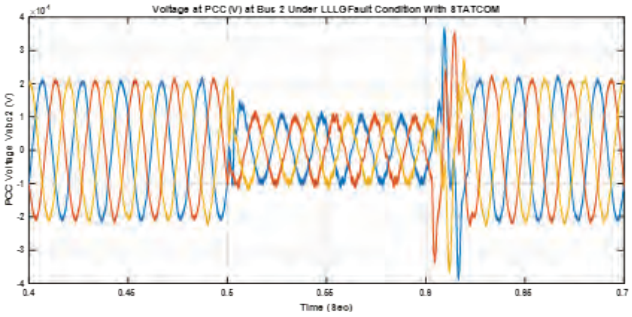

Fig. 23 Three phase voltage at wind farm bus under L-L-L-G fault with STATCOM.

With STATCOM, voltage dip improves to 0.43 pu (from 0.2 pu without STATCOM) instead of complete collapse. Faster recovery occurs after fault clearance with transients.

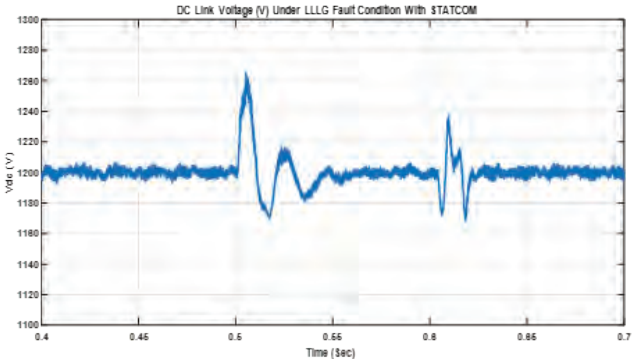

Fig. 24 DC link voltage under L-L-L-G fault with STATCOM.

DC voltage oscillations damp quickly due to reactive support.

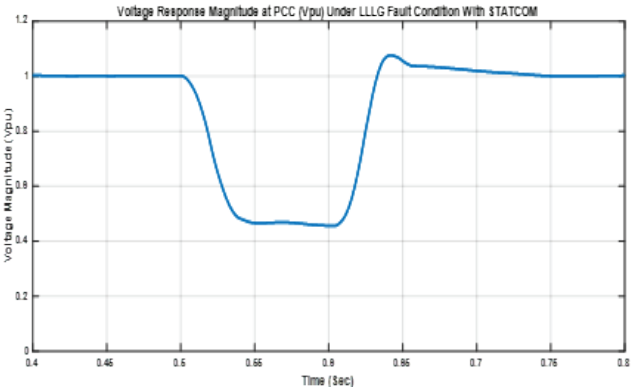

Fig. 25 Magnitude of voltage response (pu) at PCC under L-L-L-G fault with STATCOM.

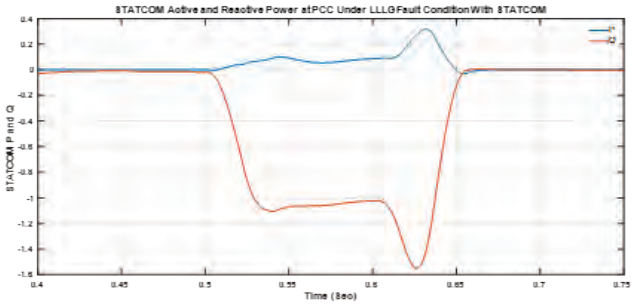

Fig. 26 Active and reactive power injected at PCC under L-L-L-G fault with STATCOM.

Reactive power injection peaks during and after the fault. Active power swells temporarily but recovers quickly around 0.65 s.

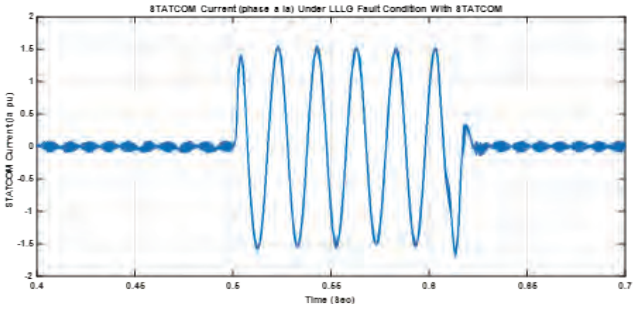

Fig. 27 STATCOM current for a phase (pu) under L-L-L-G fault with STATCOM.

Injecting of reactive current supports voltage.It returns to nominal after fault clearance.

CONCLUSION

This paper introduced a successful LVRT improvement approach for DFIG-based microgrids based on the STATCOM with PI controllers optimally tuned by hybrid GOA-PSO algorithm. The proposed approach is able to address the limitations of conventional tuning and standalone optimization methods in a successful manner. Simulation results show enhanced voltage recovery, less oscillations and compliance with modern grid code requirements under severe fault conditions. Future work will be focused on real-time implementation, and extension of the proposed method to hybrid renewable microgrids.

REFERENCES

1. Hassan, Q., Viktor, P., Al-Musawi, T.J., Ali, B.M., Algburi, S., Alzoubi, H.M., Al-Jiboory, A.K., Sameen, A.Z., Salman, H.M., Jaszczur, M.: The renewable energy role the global energy transition. Renew. Energy

Focus48, 100545 (2024). https://doi.org/10.1016/j.ref.2024.100545

2. McKenna, R., Pfenninger, S., Heinrichs, H., Schmidt, J., Staffell, I., Bauer, C., Gruber, K., Hahmann, A.N., Jansen, M., Klingler, M., et al.: Highresolution large-scale onshore wind energy assessments: a review of potential definitions, methodologies and future research needs. Renewable Energy 182, 659–684 (2022)
3. Naveed, I., Zhao, G., Yamin, Z., Gul,W.: Steady state performance analysis of DFIG with different magnetizing strategies in a pitch-regulated variable speed wind turbine. In: 2020 4th International Conference on Power and Energy Engineering (ICPEE), pp. 174–179. IEEE, Piscataway, NJ (2020)
4. Zhu, D., Zou, X., Dong, W., Jiang, C., Kang, Y.: Disturbance feedforward control for type-3 wind turbines to achieve accurate implementation of transient control targets during LVRT. Int. J. Electr. Power Energy Syst.119, 105954 (2020)
5. Yameen, M.Z., Lu, Z., Rao, M.A.A., Mohammad, A., Nasimullah, Younis, W., "Improvement of LVRT capability of grid-connected wind-based microgrid using a hybrid GOA-PSO- tuned STATCOM for adherence to grid standards," IET Renew. Power Gener. 18, pp. 3218-3238, June 2024. https://doi.org/10.1049/rpg2.13036
6. Kamel, O.M., Diab, A.A.Z., Do, T.D., Mossa, M.A.: A novel hybrid ant colony-particle swarm optimization techniques based tuning STATCOM for grid code compliance. IEEE Access 8, 41566–41587 (2020)
7. Noureldeen, O.: Behavior of dfig wind turbines with crowbar protection under short circuit. International Journal of Electrical & Computer Sciences IJECS-IJENS 12(3), 32–37 (2012)
8. Benbouhenni, H., Yessef, M., Colak, I., Bizon, N., Kotb, H., AboRas, K.M., ELrashidi, A.: Dynamic performance of rotor-side nonlinear control technique for doubly-fed multi-rotor wind energy based on improved super-twisting algorithms under variable wind speed. Sci. Rep. 14(1), 5664 (2024)
9. Salyani, P., Zare, K., Abapour, M., Safari, A., Shafie-khah, M.: An analytical framework for evaluating the impact of distribution-level LVRT response on transmission system security. IEEE Trans. Power Syst. 38(3), 1995–2006 (2023). https://doi.org/10.1109/TPWRS.2022.3179333
10. Zhang, D., Xu, H., Qiao, L., Chen, L.: Lvrt capability enhancement of DFIG based wind turbine with coordination control of dynamic voltage restorer and inductive fault current limiter. PloS One 14(8), e0221410 (2019)
11. Naderi, S.B., Negnevitsky, M., Jalilian, A., Hagh, M.T., Muttaqi, K.M.: Low voltage ride-through enhancement of DFIG-based wind turbine using DC link switchable resistive type fault current limiter. Int. J. Electr. Power Energy Syst. 86, 104–119 (2017)
12. Falehi, A.D., Rafiee, M.: Maximum efficiency of wind energy using novel dynamic voltage restorer for DFIG based wind turbine. Energy Rep. 4, 308–322 (2018)
13. Huang, J., Zhang, L., Sang, S., Xue, X., Zhang, X., Sun, T., Wu, W., Gao, N.: Optimized series dynamic braking resistor for LVRT of doubly-fed induction generator with uncertain fault scenarios. IEEE Access 10, 22 533–22 546 (2022)
14. Ye, Y., Yang, Z., Hu, J., Yi, H., Zhang, L.: Control strategy of doubly-fed induction generator under zero voltage fault of power grid. Sustainability 14(23), 15835 (2022)
15. Rafiee, Z., Heydari, R., Rafiee, M., Aghamohammadi, M.R., Blaabjerg, F.: Enhancement of the LVRT capability for DFIG-based wind farms based on short-circuit capacity. IEEE Syst. J. 16(2), 3237–3248 (2022)
16. Hete, R., Mishra, S.K., Dash, R., Ballaji, A., Subburaj, V., Reddy, K.J.: Analysis of DFIG-STATCOM P2P control action using simulated annealing techniques. Heliyon 8(3), e09008 (2022)
17. Dö¸so˘glu, M.K.: Enhancement of LVRT capability in DFIG-based wind turbines with STATCOM and supercapacitor. Sustainability 15(3), 2529 (2023)
18. Muisyo, I.N., Muriithi, C.M., Kamau, S.I.: Enhancing low voltage ride through capability of grid connected DFIG based WECS using WCA-PSO tuned STATCOM controller. Heliyon 8(8), e09999 (2022)
19. Gad, A.G.: Particle swarm optimization algorithm and its applications: a systematic review. Arch. Comput. Methods Eng. 29(5), 2531–2561 (2022)
20. Wu, L., Wu, J., Wang, T.: Enhancing grasshopper optimization algorithm (GOA) with levy flight for engineering applications. Sci. Rep. 13(1), 124 (2023)
21. Badr, A.A., Saafan, M.M., Abdelsalam, M.M., Haikal, A.Y.: Novel variants of grasshopper optimization algorithm to solve numerical problems and demand side management in smart grids. Artif. Intell. Rev. 56(10), 10 679–10 732 (2023).

A Hybrid Renewable Charging Station for Electric Vehicles with Thermal-Aware Battery Management and IoT-Based Dual Interface Monitoring

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ABSTRACT

The carbon footprint of electric-vehicle (EV) charging is shaped by the upstream energy mix, not by the vehicle itself. This paper reports a roadside EV charging station built around three on-site renewable sources: a distributed photovoltaic array (one 20 W and four 5 W panels), a Favonius vertical-axis wind turbine sited to capture ambient and traffic-induced airflow, and a piezoelectric speed-breaker module that recovers part of the mechanical work done by passing vehicles. A 4S2P 18650 lithium-ion bank stores the harvested energy, with a discrete BMS PCB and an ESP32-driven thermal loop that toggles a 12 V cooling fan on a 40 °C / 35 °C hysteresis. The bus drives two outputs: a buck-boost CC/CV port for an EV under test, and a 230 V / 50 Hz pure-sine inverter that exports surplus to the grid through a PZEM-022 smart meter. Operators see twelve live parameters either through a Blynk dashboard or through a local SSD1306 OLED panel navigated by two TTP223 capacitive pads.

Seven days of field testing in Durg, India returned a daily mean of 284.5 W/h, distributed as 75.6

% solar, 24.2 % wind, and 0.2 % piezoelectric. The cooling loop produced no false triggers across five trials, the inverter held

3.8 % THD at 49.85 Hz, and the IoT path completed 99.2 % of telemetry transmissions over 8500 attempts. The work argues that a three-source roadside microgrid can be assembled from off-the-shelf components at a cost compatible with academic prototyping.

KEYWORDS: *Battery management system, electric vehicle charging, energy harvesting, ESP32, hybrid renewable energy, IoT, MPPT, piezoelectric transducer, vertical-axis wind turbine.*

INTRODUCTION

Global EV adoption has grown faster than the supporting charging infrastructure can keep up. The IEA reports that the worldwide stock of electric cars passed 40 million by the end of 2023, with forecasts placing it well above 250 million by 2030 [1]. India, through the FAME-II programmed and the National Electric Mobility Mission, has aligned its own roadmap with that trend [2]. The environmental case for EVs nevertheless remains tied to the cleanliness of the electricity that charges them. In a grid still dominated by coal, plugging a vehicle into the wall socket relocates emissions rather than removing them.

On-site renewable harvesting at the charging point is one practical answer. A solar canopy is the obvious starting point, and recent prototypes have shown that

a sized PV array with maximum-power-point tracking (MPPT) can supply a substantial fraction of slow-charge demand [3], [4]. Solar intermittency motivates hybridization; wind, biomass, fuel cell, and second-life battery storage have all been examined as companions to PV in EV-charging contexts [5]–[8]. Most of the architectural novelty in roadside microgrids comes not from the choice of any single source but from how those sources are sized, coupled, and orchestrated for a use case where both supply and demand are irregular.

Two harvesting modes have received less attention than they deserve in the EV-charging literature. The first is recovery of vehicular wake by a vertical-axis turbine sited at the verge of the carriageway [9]–[13]. Favonius rotors are drag-driven, self-start at low wind speeds, accept omnidirectional flow, and are mechanically simple, all of which suit a roadside enclosure that is rarely visited. The second is piezoelectric capture from speed-breakers, in which the compressive load of an axle crossing produces a brief voltage pulse that, after rectification, can trickle charge a storage bank [14]–[18]. Neither mode is energy-dense in absolute terms; both, however, generate power in correlation with traffic, that is, in correlation with charging demand.

Storage and thermal management matter equally. A lithium-ion bank exposed to a roadside enclosure regularly sees ambient temperatures above 35 °C in tropical climates, and electrochemical degradation accelerates noticeably once cell temperature passes about 40 to 45 °C [19]–[22]. Air cooling, even in its simplest forced-convection form, slows ageing without the complexity of liquid loops [21], and that is the approach we adopted: one DS18B20 probe, one relay, one 12 V fan, gated by hysteretic firmware logic on the ESP32.

Off-board DC fast chargers based on isolated and non-isolated DC-DC converter topologies have been surveyed extensively [23], [24]. At the prototype scale relevant here, a buck-boost module running a CC/CV profile is sufficient to demonstrate the operational envelope without industrial-grade silicon. Grid feed-in then completes the picture: surplus generation is inverted, sold back, and metered through a low-cost smart meter, with anti-islanding behavior broadly conforming to the IEEE 1547 framework [25].

On the visibility side, low-cost Wi-Fi-enabled microcontrollers (the ESP32 in particular) have made cloud connected energy monitoring almost trivial to implement [26]–[28]. What is less common is the pairing of a remote dashboard with a deliberately local interface, namely an OLED panel mounted on the cabinet itself. The two interfaces serve different audiences: the dashboard is for the operator at a desk; the OLED is for a technician with a multimeter standing in front of the panel.

The contributions of this paper are: (i) the design and construction of an EV charging station that integrates three on-site renewables (PV, roadside Favonius VAWT, piezoelectric speed-breaker) with thermal-aware lithium ion storage, CC/CV DC fast charging, and a metered grid feed-in path; (ii) a dual-interface monitoring scheme combining a Blynk cloud dashboard and a local OLED with capacitive-touch navigation, all driven by a single ESP32; and (iii) a seven-day field characterization in Durg, India that gives a daily mean harvested energy of 284.5 W/h with detailed breakdown by source, alongside thermal-loop response, inverter quality, and IoT telemetry reliability. The combination of all three harvesting modes with thermal-aware BMS, dual-interface monitoring, and grid feed-in inside a single integrated control panel does not appear, to our knowledge, to have been reported as a unified prototype.

Section II surveys the relevant literature. Section III sets out the system architecture. Sections IV through VII cover the harvesting subsystems, storage and BMS, power delivery, and embedded control. Section VIII reports experimental results, Section IX discusses limitations, and Section X concludes.

RELATED WORK

Hybrid renewable EV charging stations have moved from simulation to laboratory prototype over the last five years. Singla and colleagues simulated a 4 kW solar-plus-storage hybrid station with three-stage charging and surplus export [3]. He and colleagues coupled solar with wind through Monte-Carlo simulation of EV demand and a queueing model for chargers, then optimized the dispatch with a hybrid metaheuristic [4]. Mandal and colleagues built a MATLAB/Simulink solar-wind microgrid prototype with grid coupling and surplus export [6]. Wider reviews of the topology space [23], [24] note that converter choice scales

with power level: neutral-point clamped converters dominate above 100 kW, while half-bridge and buck-boost variants populate the prototype range we work in. Techno-economic analyses of Indian highway sites [5] suggest payback periods compatible with public/private deployment, though the assumed tariffs vary widely between studies.

On the wind side, prototypes have validated that traffic-induced airflow on highways is a real if modest energy resource. Alsahli and colleagues simulated a thirty-turbine grid-connected Favonius array fed by vehicle-induced airflow, with capacitive compensation and bidirectional grid interaction [9]. Lee and colleagues used CFD to optimize blade geometry for a Banki-style turbine sited in the highway central reservation [10]. Ulus and colleagues showed that adding three guide vanes around a VAWT raises power output by up to 242 % under passenger-vehicle wake conditions [11]. Talese [12] and Uddin [13] reported median-mounted Favonius rotors driving alternators for street lighting, both at scales similar to ours. The 5 to 500 W range that those papers describe matches what we see at our test bench.

Piezoelectric road harvesting has matured along two distinct lines. Cantilever-based circuits focus on reducing standing power loss during the idle interval between vehicles. Pavement-embedded transducer arrays pursue volumetric energy density at the cost of installation complexity. Wang and colleagues [15], [17] published systematic size-effect studies of stacked piezoelectric units under random traffic, reporting peak voltages above 80 V for SUV-class vehicles and 21.4 % energy output efficiency for an optimized disc geometry. Cao and colleagues built a power-intensive harvester with a 23 to 138 % power-density gain over comparable designs and demonstrated 500 000 cycles with only 2.6 % open-circuit voltage drop [16]. Peng and colleagues introduced a piezoelectric electromagnetic hybrid for low-frequency speed-bump excitation, reaching 31.2 V at 10 Hz [14]. Our use of speed breaker mounted PZT discs places us in the low-yield, low-cost regime that those papers bookend.

Thermal management of lithium-ion banks has been the subject of a steady stream of reviews [19]–[22]. The consensus is that even passive forced-air convection slows cycle ageing, and active liquid cooling becomes attractive only above continuous discharge rates well beyond what stationary buffer storage sees. Hwang and colleagues [19] consolidate this view across air, liquid, PCM, and thermo-electric methods, concluding that air cooling fits shortdistance EVs and small banks, the regime that includes our prototype. Our 40 °C activation / 35 °C deactivation hysteresis comes directly from these findings.

On the IoT side, ESP32-centred energy monitoring has become a near-standard reference design [26]–[28]. He and colleagues built an open-source SCADA architecture combining ESP32, Banana Pi, Node-RED, and MQTT

[26]; Khalid and colleagues reported sub-2 s latency over Wi-Fi and sub-5 s over GSM with a similar Blynk/ESP32 stack at a CAD 35 implementation cost [27]. What remains underexplored is the integration of cloud-side telemetry with a robust local interface that does not depend on internet connectivity for diagnostic visibility. The dual interface approach in this work is an attempt to fill that gap.

To position the proposed prototype against the wider literature, Table I sets it alongside eight recent hybrid-renewable EV charging prototypes that match it most closely on architecture, scale, or instrumentation. The comparison axes were chosen to reflect what an academic reviewer would actually look for: which renewable sources are integrated, whether the work is a numerical study or a built prototype, whether thermal protection of the storage layer is described, what monitoring path the operator sees, whether grid export is included, and what scale or yield was actually reported.

Table 1. Comparative Summary of Recent Hybrid-Renewable Ev Charging Prototypes

Ref.	Energy sources	Implementation	Thermal-awa re BMS	Monitoring interface	Grid export	Reported scale / yield
[3]	Solar (4 kW) + grid	MATLAB simulation	Not described	Not described	Yes (modeled)	4 kW rated, three-stage charging strategy

[5]	Solar + wind	HOMER techno-economic study	Not described	Not described	Yes (on-grid)	$0.072/kWh, 17 EVs/day across five Indian sites
[6]	Solar + wind	MATLAB/Simulink microgrid	Not described	Not described	Yes (modeled)	Solar primary, wind secondary; surplus to grid
[29]	Solar (350 W) + wind (100 W)	Hardware prototype	Not described	None reported	None	425 W office load; PV 98 % share, wind 2 %
[30]	Solar + wind	Arduino + Blynk + GSM	Not described	Cloud only (Blynk + GSM)	Not reported	INC vs P&O MPPT compared on hybrid bench
[31]	Solar + battery (ATS)	ESP32 + IoThingsHub	Not described	Cloud only	None	300 Wp PV, 100 Ah battery, 50 W lamp load
[32]	Solar + wind + piezo	Portable wearable prototype	Not described	Wi-Fi	web dashboard None	Sub-watt USB output for portable military gear
[33]	Solar + wind tower	Simulink + Opal-RT validation	Not described	Not described	Yes (modeled)	15 to 20 kWh/day per highway tower
This work	Solar + wind + piezo	Hardware, 7-day field test	Yes, 40 / 35 °C hysteresis on DS18B20 + relay-driven fan	Dual: Blynk dashboard + local OLED with TTP223 touch	Yes, PZEM-0 22 metered	284.5 Wh/day measured (75.6 % solar / 24.2 % wind / 0.2 % piezo)

Two patterns stand out across the surveyed works. First, the majority remain at the simulation or technoeconomic stage [3], [5], [6], [33], and where hardware does exist [29], [30], [31] the storage layer is typically left without any reported thermal management strategy. Second, three-source integration of solar, wind, and piezoelectric harvesting is rare, and the only nearby work that includes all three operates at a portable, subwatt scale [32]. The present prototype occupies a position that none of the surveyed designs covers simultaneously: a built and field-tested three-source station, with a hysteretic thermal loop on the lithium-ion bank, a dual-interface monitoring path that survives an internet outage, and a metered grid feed-in branch.

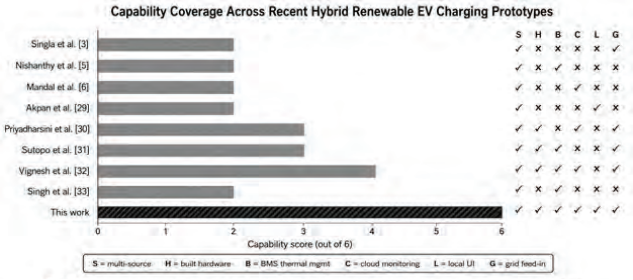

Fig. 1. Capability coverage of recent hybrid renewable EV charging prototypes scored against six common axes

SYSTEM ARCHITECTURE

The station is organized as five functional blocks coupled by a single 12 V DC bus and a single AC export branch. The harvesting block comprises the PV array, the VAWT, and the piezoelectric module. The storage block is the 4S2P Li-ion bank with its BMS PCB, temperature probe, and cooling fan. The load and grid interface combines the DC fast-charge port with the DC-AC inverter and smart meter. The embedded control block is the ESP32 with its peripheral I/O. The monitoring block consists of the Blynk cloud dashboard and the local OLED with capacitivetouch navigation. All five sit inside an IP54-rated steel cabinet of approximately 300 × 70 × 300 mm internal dimensions, with the harvesting structures (panels, turbine, speed-breaker) external to the cabinet but cabled in through weatherproof glands.

Each harvesting source presents a DC interface to the bus after appropriate conditioning. The PV array uses a CN3791 fixed-voltage MPPT module (300 kHz buck) for the small panels and a separate PWM charge controller for the larger one. The VAWT output passes through a single-phase bridge rectifier, capacitor filter,

DC-DC regulator, and a 1N5822 blocking diode. The piezoelectric stack output passes through a bridge rectifier, DC-DC boost converter, and a Schottky output diode. The bus sits at the battery-pack voltage (about 14.8 V nominal). Two loads tap the bus: a buck-boost EV fast-charger module operating in CC/CV, and a 300 W (600 W peak) pure-sine inverter feeding the grid through a PZEM-022 smart meter and an SSR. Fig. 2 summarizes the topology.

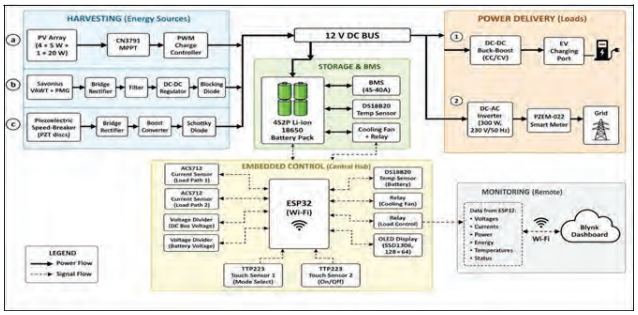

Fig. 2. Block diagram of the proposed multi-source hybrid charging station.

The choice of a single common DC bus rather than separate buses for harvesting and load keeps the converter count low and the cabinet wiring tractable, at the cost of marginally higher conduction losses when several sources feed simultaneously. For the prototype scale considered here, that trade-off is acceptable; for a 10 kW deployment, separate buses with active power-flow management would likely be the better choice [4].

ENERGY HARVESTING SUBSYSTEMS

Distributed Solar PV with MPPT

Five photovoltaic panels with a combined nameplate capacity of 40 W are partitioned into a centralized module (one 20 W panel, Voc = 21.6 V, Isc = 1.2 A) installed at the latitude tilt angle (about 21° south-facing) and four small distributed modules (4 × 5 W each, Voc = 16 V) mounted around the canopy and on auxiliary supports. The split is deliberate. A single large module experiences shading as a step loss, whereas a distributed cluster degrades more gradually under partial occlusion. The four small modules are connected in parallel into the CN3791 MPPT input, and the large module feeds an independent PWM charge controller.

MPPT on the small-panel cluster is implemented through the controller's internal fixed-voltage tracking with a 300 kHz buck stage. The classical perturb-and-observe (P&O) technique dominates the cost-sensitive prototype space because of its small computational footprint and tolerable steady-state oscillation. We did not try to outperform commercial controllers; we relied on them, and we validated only that the array operating point under load stayed near the panel datasheet Vmpp of 18 V across the test window.

Roadside Favonius VAWT

The wind turbine is a four-bladed Favonius rotor of approximately 30 cm diameter and 50 cm height, fabricated from polymer blades on steel end-discs. The Favonius topology was preferred here over Darious or H-rotor variants because it self-starts at wind speeds below 2 m/s, accepts omnidirectional and turbulent inflow, and demands almost no upkeep [10], [13]. A 24 V / 0.8 A permanent-magnet generator is direct-coupled to the rotor shaft. The PMG output is variable-frequency single-phase AC; we rectify it with a 4 × 1N5408 bridge, filter with an electrolytic capacitor, and regulate the result through a buck stage to the bus. A 1N5822 Schottky in series at the output blocks reverse current when wind drops below cut-in.

At this scale, siting matters more than rotor specification. The turbine is placed alongside the carriageway approximately 1.5 m above road level, where bypass flow from passing vehicles overlays the prevailing ambient wind. Vehicle-induced wake is intermittent and decays quickly. CFD studies and field tests by Lee and colleagues [10] and Ulus and colleagues [11] both find that traffic-induced contributions are small in absolute terms but consistently positive, and that geometry tweaks (guide vanes, blade thickness, curvature angle) can lift output by tens of percent. We did not pursue any of those optimizations in the present prototype.

Piezoelectric Speed-Breaker

Eight PZT (lead-zirconate-titanate) disc transducers, each rated to about 30 Vpp under design loading, are embedded in parallel beneath a rigid speed-breaker pad at the station entrance. The pad spreads vehicle wheel load across the array. Each axle crossing produces a short bipolar pulse: a primary positive peak followed by a damped ring-down. Pulse amplitude scales with vehicle mass and approach speed [16], [17]. The

aggregate AC pulse train is rectified by a bridge, filtered through a capacitor bank, boosted to bus voltage by a DC-DC stage, and isolated from reverse current by a Schottky output diode.

The piezoelectric branch is the smallest contributor in absolute terms, by some margin. We included it not for its raw output but for two qualitative properties. First, it generates only when traffic is present, producing a useful, if weak, correlation between supply and the demand for charging. Second, it adds essentially no recurring cost or moving parts beyond the speed-breaker pad itself, which would be installed at the station entrance regardless.

STORAGE AND THERMAL-AWARE BATTERY MANAGEMENT

Energy is buffered in a 4S2P assembly of eight 18650 Li-ion cells (about 3000 mAh each), with two spares retained for replacement. The pack delivers about 14.8 V nominal and 6 Ah, for an effective energy of roughly 88 Wh. $LiFePO_4$ chemistry would be preferable for stationary use on safety and cycle-life grounds [22]; we used standard NMC 18650 cells in this prototype to keep cost and procurement simple, while accepting that the thermal management discipline becomes correspondingly more important.

The battery's discrete BMS PCB (rated 4S, 40 A) handles cell-level overcharge (above 4.25 V/cell), overdischarge (below 2.8 V/cell), overcurrent (above 40 A), and short-circuit protection in hardware. Active balancing equalizes cells during the upper SoC region. Pack current is measured by an ACS712 Hall sensor (±20 A range, about 1.5 % full-scale accuracy when verified against a calibrated clamp meter). Pack-surface temperature is sampled by a single DS18B20 1-Wire probe (±0.5 °C). Both feeds are read by the ESP32 every 5 s.

Thermal control is deliberately simple. When the DS18B20 sample exceeds 40 °C, the ESP32 raises GPIO 33, latching a 5 V relay that energizes a 12 V / 3 W axial fan inside the cabinet. The fan stays on until temperature drops below 35 °C, at which point the GPIO returns LOW. The 5 °C hysteresis band prevents short-cycle wear of the relay contacts. The threshold pair was chosen with reference to the cell-ageing literature [19], [20]: 40 °C is just below the regime where degradation rates begin to climb noticeably for NMC cells, and 35 °C provides a comfortable return margin without forcing the fan to run continuously.

POWER DELIVERY: DC FAST CHARGING AND GRID FEED-IN

CC/CV DC Fast Charging

The EV-side output is provided by a 200 W buck-boost module accepting 12 to 18 V at the input and delivering a regulated charging voltage to the prototype EV battery, which is a 2S 18650 pack inside the test vehicle. The module enforces a Constant-Current/Constant-Voltage profile. During the bulk phase, current is held at the configured set-point until the EV pack reaches its upper voltage limit; during the absorption phase, voltage is held while current tapers naturally. This profile is the de facto standard for Li-ion charging and balances charge speed against ageing [23], [24].

Protection on the EV port includes output overvoltage clamping, output short-circuit detection, on-board thermistor-based over-temperature shutdown of the converter, and a reverse-polarity diode at the connector. None of these features are exotic; the design intent was simply that no single misuse, whether wrong polarity, dead-short on the charging cable, or an EV pack already full, should propagate back to the bus.

Grid Feed-In and Smart Metering

Surplus energy is exported through a 300 W (600 W peak) pure-sine inverter producing 230 V_RMS at 50 Hz. Pure-sine output is required for compliance with utility-side power-quality expectations and to avoid harmonic injection into neighboring loads [25]. The inverter incorporates passive over/under-frequency and over/undervoltage anti-islanding: if grid voltage falls outside ±10 % of nominal or frequency outside ±0.5 Hz, the output stage gates off and remains so for at least the IEEE 1547-suggested two-second window [25].

Export is gated by the ESP32 on a slow control loop. Every 10 s, the firmware compares pack SoC against generation-minus-local-load. Export is enabled when SoC exceeds 90 % and surplus exceeds 50 W for at least 30 s; export is disabled when SoC falls below 80 % or surplus falls below 10 W. The hysteresis prevents

relay chatter at the threshold. A PZEM-022 single-phase smart meter is wired in series at the export point. It exposes voltage, current, power, energy, and power factor over a UART interface; the ESP32 polls it every 30 s and writes accumulated W/h into NVS so that the counter survives power cycles.

EMBEDDED CONTROL AND DUAL-INTERFACE MONITORING

All control logic, sensor sampling, display rendering, and cloud telemetry runs on a single ESP32-WROOM32 (Espressif). FreeRTOS lets the firmware split into cooperatively scheduled tasks: a 5 s sensor-acquisition task; a 5 s BMS task that evaluates the temperature threshold and asserts the fan relay; a display task that updates the OLED on touch events or every 10 s in auto-cycle; a 10 s telemetry task that publishes to Blynk; and a 10 s control logic task for the export relay. The Arduino-ESP32 v2.x toolchain is used, with the standard Wire, Adafruit_SSD1306/SH110X, One Wire/ Dallas Temperature, INA219, WiFi, and Blynk libraries.

The local interface is an SSD1306 128 × 64 monochrome OLED module addressed at I²C 0x3C and rendered through Adafruit_GFX. The menu is structured as a circular list of eight screens (home, solar, wind, piezoelectric, battery, temperature, EV charging, and grid export), each summarizing the most recent values for its subsystem. Two TTP223 capacitive pads, one wired to GPIO 14 (forward) and one to GPIO 27 (back), increment or decrement the screen index with a 50 ms debounce. After 30 s of inactivity, the menu auto-returns to the home screen. The capacitive choice was made specifical figure ly to allow operation through a polycarbonate cabinet door, which would defeat membrane buttons.

The remote interface is a Blynk dashboard configured with twelve virtual pins covering instantaneous solar/ wind/piezo power, battery V/I/SoC, battery temperature, fan state, EV charging power, exported energy, and an estimated revenue counter. The estimated-revenue widget is a simple multiply-and-display of accumulated kWh against the local feed-in tariff (the can be updated at runtime through a Blynk widget). Telemetry is published every 10 s. We deliberately avoided MQTT broker setup in this iteration; the latency overhead of Blynk's HTTP interface was acceptable for the deployment, and minimizing firmware moving parts reduced field debug effort.

EXPERIMENTAL RESULTS

Test Site and Methodology

The prototype was deployed and operated continuously for seven days on the campus of the Bhilai Institute of Technology, Durg (21.19° N, 81.28° E, altitude 297 m). The seven-day window deliberately spanned a mix of weather: three clear days, two partly cloudy days, one fully overcast day, and one rainy day with reduced solar input. Vehicle traffic past the speed-breaker varied between roughly 80 and 180 vehicles per hour during daylight, and dropped to under 20 per hour overnight. The IoT dashboard logged every parameter at 10 s intervals; selected channels were cross-checked at intervals against a calibrated digital multimeter, a UNI-T clamp meter, and a benchtop oscilloscope.

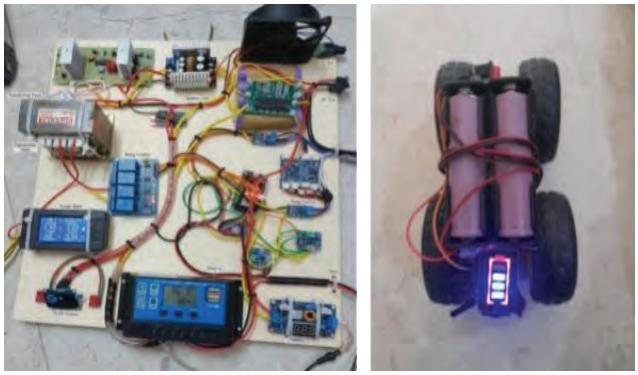

Fig. 3. Annotated hardware prototype of the integrated control panel and the test EV.

Solar PV Generation

The combined PV array reached a peak instantaneous output of 36.4 W on the brightest test day (measured around 12:15 local time, with pyranometer-equivalent irradiance estimated at about 970 W/m² from a calibrated solar reference cell), corresponding to a system efficiency of roughly 91 % relative to nameplate. Daily yield averaged 214.2 W/h on clear days and 156.8 W/h on partly cloudy days. On the fully overcast day, output dropped to about 55 % of clear-day peak, which suggests that diffuse irradiance, though far less productive, still contributes meaningfully under a thick monsoon-style overcast. The MPPT controller pulled the array operating voltage down from open-circuit

(about 17.0 V observed) to roughly 13.5 V under load, consistent with the small panels' rated V_mpp.

The distributed-versus-centralized split delivered the partial-shading benefit we expected. On one afternoon, an overhanging tree shadow swept across the canopy and occluded roughly two of the four small panels for about 25 minutes. Aggregate output dropped by about 22 %, rather than the roughly 50 % that a single same-area module would have shown; the unshaded small panels and the large, separately-controlled module continued at full capacity throughout the event.

VAWT Performance

VAWT output was measured against rotor RPM, sampled by a Hall-effect pickup on GPIO 18. During the morning peak-traffic window (08:00 to 11:00), the rotor averaged about 350 RPM with mean output 4.5 W. The largest single-event peak observed during the test, 12.8 W, was logged when a heavy goods vehicle (estimated 15 t) passed at roughly 55 km/h. Outside peak hours, ambient wind alone sustained an average of 1.2 W. Aggregated over the day, VAWT yield averaged 68.4 Wh on a typical weekday with about 120 vehicles/h.

The cubic dependence of available wind power on velocity (P ρAv³C_p) explains why heavy fast-moving vehicles dominate the energy harvest while passenger cars contribute much less per crossing. We did not attempt a full aerodynamic characterization of the bypass-flow profile. The operational measurements are reported here as observed, and we treat the VAWT contribution as an empirical figure rather than a model-predicted one.

Piezoelectric Yield

The piezoelectric branch was characterized by class of vehicle. Mean rectified peak voltages were 12.4 V (two wheeler, about 150 kg), 45.2 V (passenger car, about 1200 kg), and 82.6 V (light goods vehicle, about 3500 kg). Energies per axle, integrated across the rectifier output, were correspondingly 8.5 mJ, 115.0 mJ, and 340.0 mJ. At a peak traffic rate of 150 vehicles/h, aggregate piezoelectric output was 0.052 Wh/h. Over a daily traffic count of about 1800 mixed-class vehicles, the daily yield reached 0.624 Wh: small in absolute terms but, as already noted, useful for its strong correlation with charging demand.

Storage and Thermal Loop

From a 20 % SoC starting point and a typical generation profile averaging 15 W aggregated across the three sources, the bank reached 100 % SoC in approximately 4.5 h. Hardware-level overcharge protection on the BMS asserted within about 80 ms of any cell crossing 4.25 V; over-discharge protection asserted within about 120 ms at 2.8 V/cell. Cell-to-cell voltage imbalance, measured at full charge after 20 cycles, was 45 mV with active balancing disabled and 8 mV with balancing enabled. Active balancing was therefore effective even on a low-cost module.

The cooling loop was characterized by deliberately heating the cabinet to about 45 °C and observing the response. Across five trials, the fan asserted at 40.0 ± 0.5 °C and de-asserted at 35.0 ± 0.5 °C, with no false triggers. With the fan running, pack temperature fell at an average rate of about 0.8 °C/min; the round-trip from 42 °C down to 35 °C took 8.75 min. The 5 °C hysteresis band was sufficient to prevent the fan from cycling more than twice in any one-hour window during normal operation.

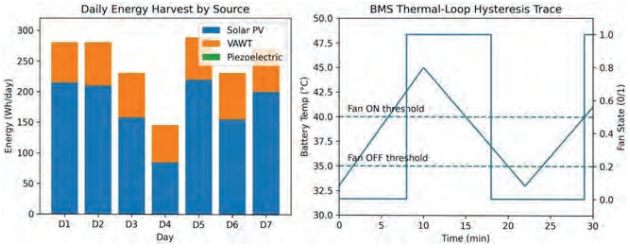

Fig. 4. Aggregate experimental results: (a) seven-day energy harvest by source; (b) thermal hysteresis trace.

F. DC Fast Charging

The CC/CV charging algorithm held output current within ±1.2 % of the bulk-phase set-point and output voltage within ±0.5 % during the absorption phase, validated against a Hantak 1008C oscilloscope and a calibrated bench multimeter. Conversion efficiency, measured at full rated load, came out to 92.4 %, within typical ranges for no isolated buck-boost converters at this power class [24]. The fast-charge port reduced the 0 to 80 % charging time of the test EV pack by approximately 65 % relative to a Level-1 AC charge through the same vehicle's onboard charger; in the prototype's context this is a practically meaningful

improvement, even though absolute charge time is dominated by the small EV pack capacity.

Grid Feed-In and Energy Metering

The inverter delivered 227.4 V RMS (target 230 V; deviation about 1.1 %) at 49.85 Hz (target 50 Hz; deviation 0.3 %). Total harmonic distortion on the output current was 3.8 %, comfortably under the conventional 5 % threshold for distributed-resource interconnection [25]. Inverter efficiency was 89.5 % at 50 % of rated load and 93.2 % at full load, which is reasonable for the cost class. Anti-islanding behaviors was tested by deliberately tripping the AC supply to the export branch; the inverter de-energized within about 600 mms in all five trials, well inside the IEEE 1547 two-second envelope.

The PZEM-022 smart meter recorded an average daily export of 195 W/h across the seven-day window, with a peak of 281 W/h on the brightest day. Cross-checking against a calibrated Yokogawa reference revealed agreement within ±0.85 % over a cumulative 2500 W/h sample. At an indicative feed-in tariff of ₹7.5/ unit (a realistic figure for distributed solar export in central India in 2024), the projected monthly revenue is approximately ₹1,460. That is a modest sum in isolation, but the order of magnitude begins to matter when scaled across multiple stations.

Monitoring System Reliability

Fig. 5. IoT monitoring interfaces: Blynk mobile dashboard

On the local side, the OLED menu accumulated zero false touches and zero missed touches over a session of more than 250 deliberate transitions across the eight screens, evaluated under both fluorescent indoor lighting and direct sunlight on the cabinet door. The auto-return timer behaved correctly in every test.

DISCUSSION

A few observations from the seven-day campaign deserve flagging beyond the headline numbers. Solar dominated the harvest, as expected at this latitude, contributing 75.6 % of total energy on a weekly basis. The VAWT's 24.2 % share is more nuanced: it bundles ambient wind and traffic-induced contributions together, and disentangling the two would require either an upstream anemometer or an off-traffic baseline test, neither of which we conducted in this prototype. The piezoelectric share of 0.2 % is, on its own, almost negligible. We retain it in the system not as a meaningful generator but as a demand-correlated indicator and a low-cost speed-management feature.

The thermal-loop hysteresis worked as designed and was, in practice, the simplest subsystem to commission. We observed no ageing-related capacity fade across the seven-day window. A much longer test would be needed to actually evaluate the cooling system's effect on cycle life, but the fact that the fan never cycled more than twice in an hour during normal operation suggests that the hysteresis is well sized.

Three limitations deserve explicit acknowledgement. First, the absolute capacity of the prototype (40 Wp solar, about 10 W rated VAWT) is not representative of a deployable highway station; scaling to a kW-class system would alter the converter topology choices, the BMS class, and almost certainly the inverter supplier. Second, the PZEM022 smart meter, while convenient, does not meet the metrological accuracy class typically required for revenue grade billing under Indian regulations; a class-1.0 utility-grade meter would be needed for a real feed-in arrangement. Third, the 99.2 % telemetry reliability figure is conditioned on Wi-Fi signal strength at the test site; deployment at locations without reliable Wi-Fi would require migration to an LPWAN or cellular link, with corresponding firmware and cost implications.

On the methodological side, we note that the seven-day window is short relative to seasonal variation. Solar yields in December at this latitude are typically 25 to 35 % below those measured in the test week, while the southwest monsoon would compress yields further. A multi-month study would be required to project annualized performance, and we did not attempt that here.

CONCLUSION AND FUTURE WORK

This paper has shown that a three-source hybrid renewable EV charging station, coupling distributed solar PV, a roadside Favonius VAWT, and a piezoelectric speed-breaker, is realizable as an integrated single-cabinet prototype using widely available components. Field measurements over seven days returned a daily mean of 284.5 W/h, a thermal-loop response with no false triggers across five test cycles, an inverter THD of 3.8 % at near-nominal 50 Hz, and an IoT telemetry success rate of 99.2 % over thousands of transmissions. The dualinterface monitoring scheme, pairing a cloud dashboard with a local OLED menu navigated through capacitive pads, was more robust than either interface alone.

Several extensions follow naturally. The most immediate is a longer-duration deployment that captures seasonal variation, especially the monsoon period. Beyond that, the storage layer is the natural target for a second iteration: replacing the NMC 18650 pack with $LiFePO_4$ cells would extend cycle life and improve thermal margins, and integrating second-life EV cells would address the capital-cost question that any commercial deployment will eventually face. A V2G-capable bidirectional charger would convert the EV from a pure load into a dispatchable resource. On the prediction side, a small embedded learned model trained on the dashboard's own historical telemetry could shift the export-decision logic from a reactive threshold to a proactive schedule. Each of these is a self-contained piece of follow-up work, and the architectural foundation reported here accommodates them without redesign.

REFERENCES

1. International Energy Agency, "Global EV Outlook 2024," IEA, Paris, France, 2024. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2024
2. Ministry of Heavy Industries, Government of India, "FAME-II Scheme Guidelines (Revised)," New Delhi, India, 2024.
3. P. Singla, S. Boora, P. Singhal, N. Mittal, V. Mittal, and F. Gared, "Design and simulation of 4 kW solar power-based hybrid EV charging station," Sci. Rep., vol. 14, art. 7307, 2024, doi: 10.1038/s41598-024-56833-5.
4. L. He, Y. Lu, J. Li, L. Wang, and X. Yan, "Advancing sustainable EV charging infrastructure: A hybrid solar-wind fast charging station with demand response," Renewable Energy, vol. 232, art. 121049, 2024.
5. J. Nishanthy, S. C. Raja, T. Praveen, J. P. Roselyn, and D. P. Devaraj, "Techno-economic analysis of a hybrid solar wind electric vehicle charging station in highway roads," Int. J. Energy Res., vol. 46, no. 6, pp. 7883–7903, 2022, doi: 10.1002/er.7688.
6. S. Mandal, A. K. Mishra, and S. K. Sahoo, "Design and development of a solar-wind hybrid electric vehicle charging station," in Proc. 2024 IEEE 7th Int. Conf. on Condition Assessment Techniques in Electrical Systems (CATCON), 2024, pp. 1–6.
7. A. A. K. Al-Sahlawi, S. Ayob, M. M. Tan, M. Tanveer, and H. M. Hasanien, "Optimal design of grid-connected hybrid renewable energy system considering electric vehicle station using improved multi-objective optimization: technoeconomic perspectives," Sustainability, vol. 16, no. 6, art. 2491, 2024, doi: 10.3390/su16062491.
8. S. Rajesh, M. Kavitha, S. Ravichandran, and A. Karthikeyan, "EV charging station using renewable systems (solar and wind)," in Proc. 2022 6th Int. Conf. on Computing Methodologies and Communication (ICCMC), 2022, pp. 1–6.
9. A. Alsahli, A. Al-Awami, and M. A. Abido, "Design and simulation of grid-connected vertical axis wind turbines for roadside energy harvesting from vehicle-induced airflow," in Proc. 2025 IEEE PES Conf. on Innovative Smart Grid Technologies - Middle East (ISGT Middle East), 2025, pp. 1–6.

10. O. M. Lee, T. Bartzanas, and N. Katsoulas, "Optimising highway energy harvesting: A numerical simulation study on factors influencing the performance of vertical-axis wind turbines," Energies, vol. 16, no. 17, art. 6234, 2023, doi: a.10.3390/en16176234.

11. A. Ulus, S. Aslan, and B. Yıldız, "Optimization of vertical axis wind turbine systems to capture vehicle-induced highway winds," Energies, vol. 18, no. 4, art. 932, 2025, doi: 10.3390/en18040932.

12. A. K. Talele, R. K. Yadav, and S. P. Patil, "Vertical axis wind turbine for highway applications," in Proc. 2023 IEEE Bombay Section Signature Conf. (IBSSC), 2023, pp. 1–5.

13. R. Uddin, M. Hasan, and M. K. Hossain, "Smart vertical axis highway wind turbine," Int. J. Eng. Adv. Technol. Stud., vol. 10, no. 2, pp. 25–34, 2022.

14. L. Peng, J. Li, S. Liu, and Y. Zhao, "A hybrid piezoelectric-electromagnetic energy harvester used for harvesting and detecting on the road," J. Cleaner Production, vol. 414, art. 137624, 2023, doi: 10.1016/j.jclepro.2023.137624.

15. S. Wang, H. Li, and J. Yang, "Size effect of piezoelectric energy harvester for road with high efficiency electrical properties," Applied Energy, vol. 330, art. 120422, 2023, doi: 10.1016/j.apenergy.2022.120422.

16. Y. Cao, J. Sha, Y. Xiao, and S. Wang, "A power-intensive piezoelectric energy harvester with efficient load utilization for road energy collection: Design, testing, and application," J. Cleaner Production, vol. 369, art. 133447, 2022, doi: a.10.1016/j.jclepro.2022.133447.

17. J. Wang, S. Wang, Y. Cao, and H. Li, "Experimental field study on a full-scale road piezoelectric energy harvester," Smart Mater. Struct., vol. 31, no. 9, art. 095037, 2022, doi: 10.1088/1361-665X/ac86bc.

18. A. A. Girde, S. R. Wankhede, and P. P. Deshmukh, "Harnessing piezoelectric sensors for electricity generation from speed breaker," IOP Conf. Series: Earth and Environmental Science, vol. 1409, art. 012036, 2024, doi: a.10.1088/17551315/1409/1/012036.

19. F. S. Hwang, T. Confrey, C. Reidy, D. Picovici, D. Callaghan, D. Culliton, and C. Nolan, "Review of battery thermal management systems in electric vehicles," Renew. Sustain. Energy Rev., vol. 192, art. 114171, 2024, doi: a.10.1016/j.rser.2013.11. 4171.

20. R. Kumar, K. Goel, A. Saxena, and N. Kumar, "A study on thermal management system of lithium-ion batteries for electrical vehicles: A critical review," J. Energy Storage, vol. 71, art. 108025, 2023, doi: 10.1016/j.est.2023.108025.

21. S. Chavan, B. Venkateswarlu, R. Prabakaran, M. Salman, S. C. Kim, and Y. K. Joo, "Thermal management strategies for lithium-ion batteries in electric vehicles: Fundamentals, recent advances, thermal models, and cooling techniques," Int. J.

a. Heat Mass Transfer, vol. 232, art. 125918, 2024, doi: 10.1016/j.ijheatmasstransfer.2024.125918.

22. L. He, Y. Wang, X. Wei, M. Liu, X. Hu, and H. Shi, "Review on thermal management of lithium-ion batteries for electric vehicles: Advances, challenges, and outlook," Energy Fuels, vol. 37, no. 7, pp. 4835–4857, 2023, doi: a. 10.1021/acs.energyfuels.2c04243.

23. M. Safayatullah, M. T. Elrais, S. Ghosh, R. Rezaii, and I. Batarseh, "A comprehensive review of power converter topologies and control methods for electric vehicle fast charging applications," IEEE Access, vol. 10, pp. 40753–40793, 2022, doi: 10.1109/ACCESS.2022.3166935.

24. M. C. Annamalai and N. Amutha Prabha, "A comprehensive review on isolated and non-isolated converter configuration and fast-charging technology for battery and plug-in hybrid electric vehicles," Heliyon, vol. 9, no. 8, art. e18808, 2023, doi: 10.1016/j.heliyon.2023.e18808.

25. IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE Std 1547-2018 (Rev. of IEEE Std 1547-2003), 2018.

26. W. He, P. Dong, S. Wang, and Z. Zhang, "An open-source supervisory control and data acquisition architecture for photovoltaic system monitoring using ESP32, Banana Pi M4, and Node-RED," Energies, vol. 17, no. 11, art. 2511, 2024, doi: 10.3390/en17112511.

27. W. Khalid, S. Ali, R. Khan, and A. Ahmad, "Open-source Internet of Things-based supervisory control and data acquisition system for photovoltaic monitoring and control using HTTP and TCP/IP protocols," Energies, vol. 17, no. 18, art. 4628, 2024, doi: 10.3390/en17184628.

28. N. Iksan, A. Sutrisno, and B. Setiawan, "Real-time monitoring of photovoltaic systems and control of electricity supply for smart micro grid-PV using IoT," TEM Journal, vol. 13, no. 2, pp. 1142–1150, 2024, doi: 10.18421/TEM132-32.

29. U. V. Akpan, B. O. Anyaka, and N. M. Eyenubo, "Design, sizing and optimization of a solar-wind hybrid power system," Journal of Energy Research and Reviews, vol. 11, no. 4, pp. 1–16, 2022.

30. R. Priyadharsini, P. Subhashini, and B. Geethalakshmi, "A hybrid solar photovoltaic and wind turbine power generation for stand-alone system with IoT-based monitoring and MPPT control," Electric Power Components and Systems, vol. 51, no. 11, pp. 1142–1159, 2023, doi: 10.1080/15325008.2023.2179461.

31. A. M. Sutopo, F. F. Faqih, and S. Aripriharta, "IoT-based automatic transfer switch system design on solar home system," International Journal of Integrated Engineering, vol. 16, no. 5, pp. 168–179, 2024.

32. K. Vignesh, S. Karthikeyan, and R. Anand, "Integration of piezoelectric, solar and wind energy sources for portable military power generation," in Proc. 2025 4th Int. Conf. on Automation, Computing and Renewable Systems (ICACRS), 2025, pp. 1–6.

33. S. P. Singh, V. K. Tayal, and H. Tyagi, "Estimation of hybrid energy generation of solar-wind tower for electric vehicle charging: A case study of Indian highway," Energy Storage, vol. 6, no. 4, art. e641, 2024, doi: 10.1002/est2.641.

Reduction of Electromagnetic Torque Ripples in SRM using PI Controller for Electric Vehicle Applications

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ABSTRACT

Switched Reluctance Motors (SRMs) have advanced quickly and are utilized frequently. Currently, SRM has demonstrated excellent competitiveness in the traction, electric vehicle, and other industries. Unfortunately, the torque ripple, distortion, and vibrations of SRM are severe due to its nonlinear and high coupling system features, which restricts its practical application range. In this research, SRM is controlled with PI, and its effectiveness is examined in a stable setting. Simulation assessment is performed with MATLAB/Simulink. Findings were obtained utilizing various performance indicators. With this control, torque ripples are greatly decreased and current and speed are treated properly.

KEYWORDS: *Electric Vehicle (EV), Switched Reluctance Motor (SRM), Torque Ripples Reduction, PI Controller.*

INTRODUCTION

SRMs are a specialized form of DC stepper motor that runs on reluctance torque. The stator's windings, not the rotors, receive the energy. SRM incorporates wrapped field windings for the stator. The coils for the rotor are not attached, unfortunately. It includes a salient pole rotor comprised of laminate steel, a soft magnetic element. On the rotor, poles were also projected. The rotor's magnetic reluctance creates a power, which attempts to coordinate the rotor poles with the adjacent stator-poles whenever electricity is applied to the stator winding. To keep the rotor rotating, Electronic Control System (ECS) controls are fitted. As a result, the magnetic fields of the stator and rotor are always behind one another. Furthermore, an "Electronic Position Sensor" is used for measuring the inclination of the rotor's central component (or shaft) rather than a largely mechanical commutator that needs regular inspection. Stator winding switching is accomplished using solid-state devices. As a result, dynamic control over wave duration and shaping is possible [1]. The design of machines that are very efficient and economical, easy to build, have simpler cooling mechanisms, and properly complete software functions even in severe environments, is an existing research concern.

Along with its performance and reliability, which have already been demonstrated in diverse fields like full-featured drive systems, airplane systems, the food industry, condensers, fans, pumping systems, compressors, and electric cars, a future success of this machine could well revolutionize washing machines and the private industry of laundries will operate 24hours with no disruptions. Also, the battery charger is increasingly being integrated into SRM driving circuits, which has the potential to enhance energy capacity and performance [31].

By reducing the torque ripple, two phases' direct torque could be regulated. The self-adaptive phase torque abides by the rule of linear transmission while both commutating phases seem to be in respective excitation phases. Torque-sensing applies and turns off the incoming phase. Due to an SRM's fundamental non-linear and phase commutation torque generation features, the newly regulated method may efficiently smooth out the torque fluctuations that are induced by these factors. In an experimental setting, the Based

Drive System has used the torque approach. The torque ripple minimization controller's sensitivity is unaffected by on- and off-angle configurations. As contrasted to the torque ripple minimization control approach, the traditional flat-topped current's noise is decreased through "hysteresis controlling". To operate with minimal torque ripple during the low-to-moderate range of speed and also at top speed, a "mixture of the turn-on angle, turn-off angle, and phase torque distribution coefficient-k" is required [2]. They are both made of laminations and have a single stack. The simplest configuration is created diametrically by the opposing stator holding coils' poles (which are series-coupled) to create a 2-pole field pattern [3]. From the point of view of increasing the machine's efficiency, it's indeed crucial how "Mutual Inductance" might be removed, according to investigations of stepping motors. It is a characteristic of the concept [4] that the mutual inductance caused by the primary (air gap) flux will become negligible.

A few of the control mechanisms are "feedback control using a starting-torque loop, speed loop, torque loop, position-matched angle control, and sequencing control". The fundamental need for timing supports the implementation of the digital circuitry by angle regulation. As from the fifteen-degree pulse-orientation modulator throughout the greater speeds, the indication of feedback speed is created. In the reduced speed range, a sensor of the Teledyne class is employed [5].

A converter is employed in the SRM design of current power semiconductors to enable power factor correction. A sine input current that is in phase with the voltage source could be obtained with the proper filtration. With less utilization of power electronic devices and more complicated regulation, the classical drive is necessary. Phases wouldn't operate entirely independently of one another. Fast recovery rectifier diodes must be used in at minimum two phases. The drive's power factor is sufficient for the restricted output range. Extremely low-power passive filtration represents the most economical solution. For greater powers, a further active rectification or active filtering step is necessary [6].

The feed-forward compensation is used to train the motor how to operate under stable conditions. The actual current that passes through the circuit at the stator is unique, and the learning activities for the current controller and feed-forward compensator have absolutely nothing to do with one another. Every time a torque need is indicated, the required current waveform is enabled. The required rotor locations for this learning have no connection to the exact motor speed, as torque could be predicted by employing the non-linear approach for the specified phase angle [7].

SRMs are a powerful challenger to Induction Motors (IMs) [32] due to their pattern of speed/torque profile. But on the other end, the existence of a position detector and torque ripples represent the disadvantages of SRMs. The fundamental idea behind its design and operation is the cause of these problems [8]. Two phases are simultaneously activated when it comes to the SRM's construction. Both four- and five-phase phase types of machinery can use phase excitation. Its total performance improves as an outcome. Mutual coupling is used to create windings that are fully and partially tuned. When contrasted to SRMs with single-tooth winding, such winding designs enhance torque density as well as time increasing the number of wasteful end-turns [9]. Numerous electrical devices analyze the dynamic characteristics (torque and speed) to reduce cost, and torque fluctuations and improve the SRM's reliability and performance [10, 11].

The evaluation of current waveforms aims to reduce torque ripples. The torque of SRM must have an impact on the rotor positions as well as the current within every phase. As a result, the "Fuzzy Iterative (FI)" approach was suggested, then FI-based rules are used to produce current waveforms [12, 13]. As per the requirements for power semiconductor devices, easier assembly, and little price, SRM had many benefits. Electrically, physically, and magnetically, the stator and the rotor—are completely separate from one another. This is caused by the SRM's rotor being devoid of any coils or magnets, which allows for great speed to be attained. The maximum speed is 1×10^5 rpm.

SRM's salient structure produces extremely potent nonlinear magnetization. Consequently, it is challenging to evaluate and govern. The main objective of the machine is to provide sensitive and simple control without sacrificing precision [14]. Both "2-phase SRM

with a 2-switch driven split supply converter and 1-phase SRM with a 2-switch driven asymmetric converter" has been demonstrated to be effective for low-price, flexible speed purposes [15].

To figure out the frequency for the normal state, a vibration assessment is carried out using the rotor at a fixed position. The motor's first phase gets switched on by a pulse of short voltage, resulting in a triangle pulse of current. A particular amount of time is allowed for the vibrations to stop between pulses when the pulse-recurrence frequency is 30 Hz and the pulse width is 5 milliseconds [16]. The highest and lowest inductances of "1-phase and 2-phase SRMs" can be determined analytically. With the use of field tests and finite analysis of data, a significant connection is demonstrated. A calculation about an equivalent circuit of a motor's inductance was also provided. To enhance the precision of findings from simulation and observational results, the end of every iteration effects must be taken into account. The SRM is equipped with a variable reluctance stepping motor to transfer energy effectively. The SRM is double salient and contains a potential in the creation of torque when stator poles≠ rotor poles. Power circuits by unipolar current flow only need a primary switching device per phase. Additionally, the SRM has a brushless rotor and negligible winding of any type [17, 18].

By using mean scores for the comprehensive model, the SRM is sorely tested in a real-world scenario. The amount of electrical formulas employed in the SRM designs is equivalent to the standard amount of machine phases. This latest design simply employs electrical formulas. Two stages have been involved in the creation of this design. Reducing the amount of system dynamic formulas was the initial step [19].

SRMs were noted for their reduced cost and improved efficiency, which gives companies the most promising cost/benefit proportion. SRM has a very significant driving circuit and design. As a result, it functions effectively under some challenging contexts, such as when it is applied to Electric Vehicle (EV) purposes. SRM is the ideal alternative to traditional motors in applications that require robust variable-speed drives and hazardous environments. SRM windings with the above 2 phases can generate a self-starting torque. However, both "1-phase and 2-phase SRMs" seem to be more intelligent, mechanically robust, lightweight, and tiny as a result of lower price drive circuits, they typically experience dead-zone problems [20]. The development of simulator software is adaptable whenever the "Finite Element Analysis" is considered as a different scheme because of coupling parameters that operate with the circuit analysis procedures [21].

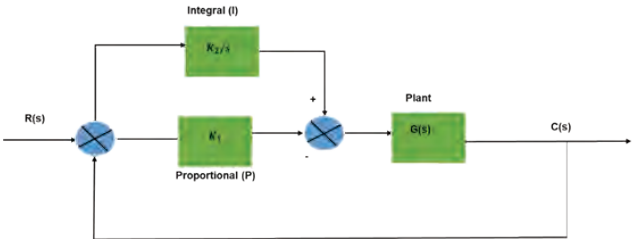
A novel experimental and direct way for SRM design is depending upon the premise of phase-inductance characteristics of the SRM have triangular forms. Because of magnetic saturation, maximum values in this method rely on the current that flows through the phase windings. In this study, the proposed PI controller-based SRM is simulated using MATLAB/Simulink toolbox.

Paper's organization: The modelings of the PI controller and 8S/6R SRM are demonstrated in section 2. Section 3 produces the simulated outcomes while section 4 concludes the overall research.

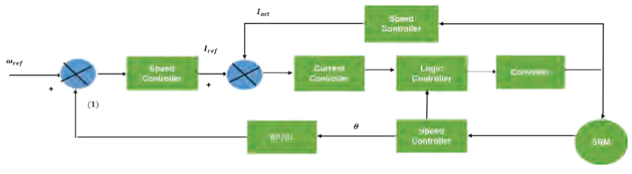
METHODOLOGY

PI Controller

The mixture of both proportional and integral components is required to lower steady-state errors while also increase response time. By providing feedback to the converter and overcoming the interruption, the PI controller's effectiveness can be improved. The steady-state imperfections and caused oscillations can be removed using proportional controllers and ON-OFF controllers, accordingly. Figure 1 depicts the generalized and closed-loop PI-controller models.



(a)



(b)

Fig. 1. Configurations of (a) generalized and (b) closed-loop PI controller models for SRM

The PI controller's operations are described here. With the aid of the speed controller, I_ref is produced in the PI controller. A current comparator compares the actual and benchmark currents using a sensor that is built into an SRM to detect the motor's actual current. Following evaluation, the required signal is sent to the active controller. An excited pole's location is sensed by a position sensor, which then sends the derived outcome to a "speed comparator" that regulates speed. This is accomplished by using distinct kinds of logic switches [22].

Therefore, using a PI controller, it is possible to monitor the SRM's current and speed. When constant fluctuation in values is desired, this method is not suitable. Because changing their variables requires a lot of time, this might be the issue.

The speed controller should first be subjected to the reference speed. To reduce the error signal, the speed controller contrasts the switched reluctance motor's exact speed with the desired speed. Comparably, "Current Controller (CC)" is employed to reduce the imperfection in the values of current—which also arises from the SRM—between "reference and actual" currents. Similar to SRM, the rotor has almost no winding meanwhile the stator has to wind. To match the rotor and stator poles and detect the generated current, the rotor incorporates a position sensor [24].

Torque ripple reduction

The torque swelling is influenced by several variables, including the design of the rotor or stator, the length of the air, the correspondence mechanism, the control scheme, and the crucial element of regulating current. Various methods to lower torque ripple for SRM are presented in this research. (1) Using the combination of internal torque and current synchronization with practical goals, a method is developed to regulate the torque. The reference/benchmark current from the link is acquired using the electromagnetic torque that the motor produces.

The second approach modifies the fragment design for the rotor pole roundabout. The torque ripple is diminished in this manner. Since the inductance is often high whenever the 2 poles are parallel, the rotor shaft and stator shaft lines are equal. In such settings, it's important to prevent the current before it completely changes the location of the rotor pole. Due to the absence of a zero slope inductance zone, SRM transmits negative torque if the current keeps moving in the direction of positive inclination [25–28]. This is due to the corresponding rotation of the stator and rotor poles.

SIMULATED RESULTS

The primary control challenge in SRM is typically the generation of ripple-free torque. When there is a torque ripple, it causes undesired vibrating and loudness to be produced while the machine is operating. Because of this, this study uses a PI controller in SRM to address the problem. To assess the efficiency of the PI controller-based SRM in e-vehicle applications, this experiment is modeled using the Matlab/Simulink toolset. The model of PI controller-based SRM is shown in Figure 3.

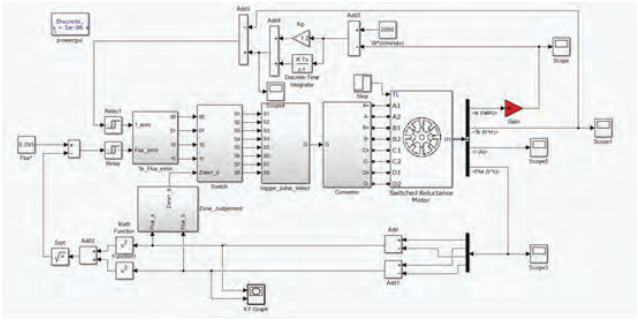


Fig. 3. SRM's Simulink diagram

Figure 4 depicts the waveforms of switching gate pulses. Typically, the firing angle component specifies the degrees for control turn-on and turn-off, and the switch pulse component creates the control pulses for the switching devices of the SRM power converter. The x-axis of figure 4 indicates the time within the range from 0 to 1 while the y-axis indicates the magnitude of the switching pulse within the range from 0 to 1. During the energizing or conducting state, switches are kept locked. Installation of the PI controller for the 8S/6R SRM results in the expected result. The on/off and switching phases of the motor windings are controlled by the position sensor. The torque oscillations are controlled by the phase windings' on/off switching angles. When switching between driving and braking operations, the turn-on and turn-off angle measurements are dramatically altered.

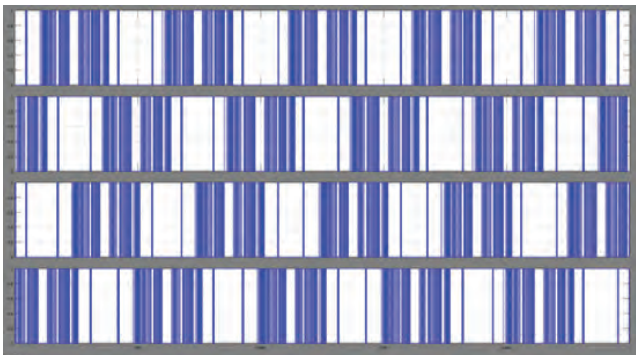


Fig. 4. Switching gate pulses

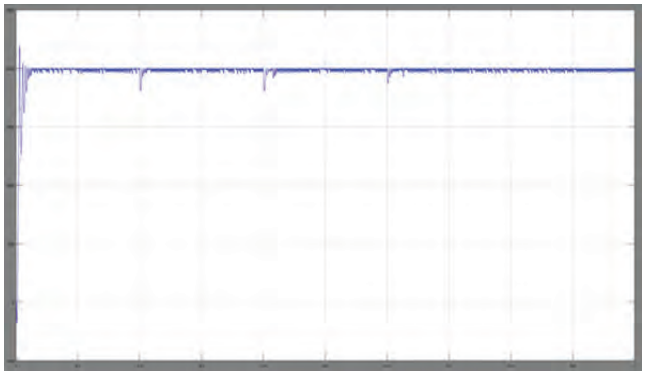


Fig. 5. Speed analysis of PI-controlled SRM

Figure 5 depicts the speed analysis of SRM based on the PI controller. Figure 5's x-axis represents the time between 0 and 1, while the y-axis represents the speed value between 0 and 2500 (rpm). Depending on the load, the motor will accelerate. Hence, it can be stated that the dynamical and mechanical characteristics only determine the motor's ability to accelerate. To achieve the desired speed with the PI concept, the speed controller incorporates a comparative circuit between the observed and reference values. Comparing the observed and reference values is another way that the current controller applies the PI concept to obtain the desired result. As a result, the speed of the SRM can be regulated by altering the current or by a speed controller developed using the PI concept. When starting the e-vehicle, the speed can be accelerated initially. Before reaching 0.4s, the speed is varied between 1260rpm and 2240rpm, and reduced gradually. After 0.5s, there is a minimum variation ±40 to ±50rpm to attain the speed of 2000rpm in SRM-driven e-vehicle. Followed by, the speed 2000rpm is reached with PI-controlled SRM with very few oscillations during full load.

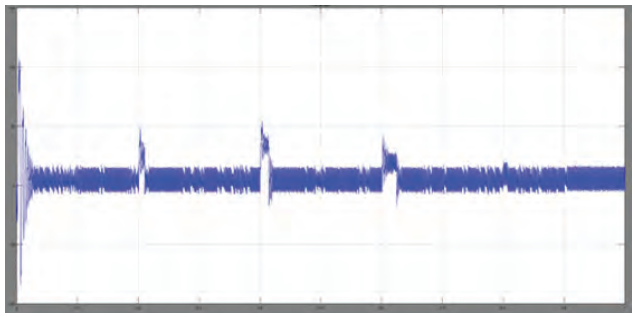


Fig. 6. Torque analysis of PI-controlled SRM

Figure 6 depicts the torque waveform of PI controller-based SRM. As output speed increases, the available output torque decreases proportionately. The x-axis in figure 6 displays time between 0 and 1, as well as the y-axis the torque (Nm) ranging from -80 to 120 Nm. According to figure 5, the torque oscillates since the inverse proportion concerning speed. The PI-controlled SRM's torque reaches a maximum of 20 Nm in 0.2s. In the same way, our suggested controller-based SRM achieves 30Nm, 15Nm, 10Nm, and 5Nm torque values in turn, respectively, in 0.4s, 0.6s, 0.8s, and 0.9s. It is obvious that the PI-controlled SRM achieves the desired torque value with a range of +22 Nm to -10 Nm.

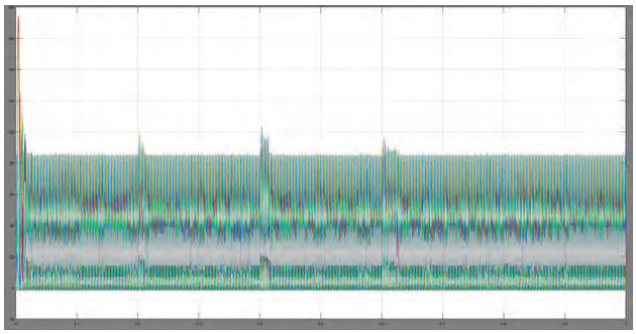


Fig. 7. Current analysis PI-controlled SRM

Figure 7 depicts the current waveform of PI controller-based SRM. While torque is typically exactly related to the square of current in ordinary motors, it is directly related to the current in SRMs. By managing the current and choosing the proper turn-on and turn-off angles, torque oscillations can be reduced. The torque's ripple component causes the SRM performance to be loud. Because of the higher level of the load current, the torque distortion has increased. From figure 7, it can be seen that the current is increased to nearly 86A during 0-0.5s which leads to an increase in the torque

ripples, as well as after 0.5s, the current is furtherly increased to 90A. Figure 8 depicts the output of flux in SRM. As speed increases, flux starts to decline and achieves saturation when speed is steady. We draw the conclusion from this research that since the torque of SRMs depends on the value of current, while torque gradually increases (to almost 50Nm), the current also increases (to almost 100A).

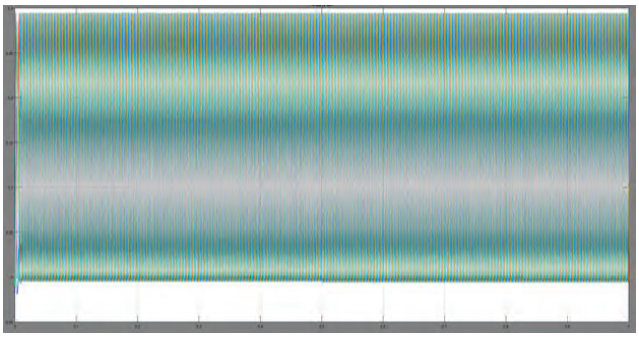


Fig. 8. Flux analysis PI-controlled SRM

The figures mentioned above show that the torque inaccuracy increases with increasing load, which is caused by a change in load current. And it can be seen that the torque oscillations become greater as the load torque gets larger. Lastly, torque ripples are affected by the load current.

Table 1: Comparative assessment of the proposed and existing controllers

Controllers Metrics	P controller [30]	PI controller [proposed]
Settling time (s)	0.108	0.0125
Reduction rate of torque ripples (%)	96.12	98.97

Table 1 displays the comparative assessment of the proposed and existing controllers. In terms of settling time and torque ripple reduction rate, the effectiveness of the PI controller is enhanced when compared with the P controller [30]. The assessments of the settling time and reduction rate for both controllers are shown in figures 9 and 10, correspondingly. These evaluations lead us to the conclusion that the suggested PI controller achieves the minimum settling time (0.0125s) and the highest reduction rate (98.97%) compared to the P controller.

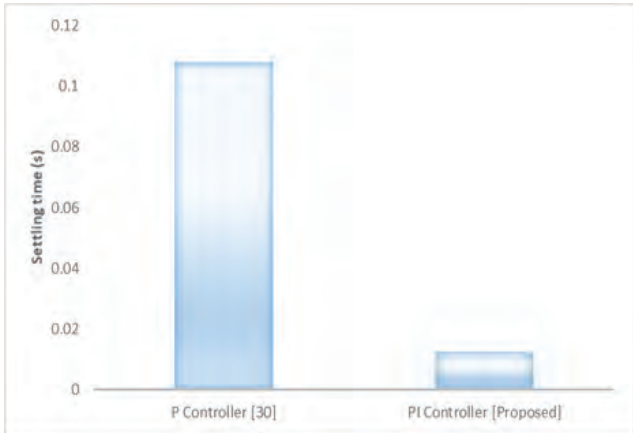


Fig. 9. Settling time analysis

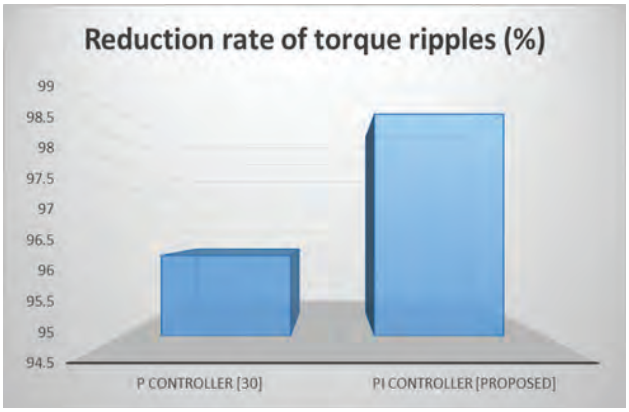


Fig. 10: Reduction rate analysis

CONCLUSION

In this work, the effectiveness of SRM's PI controller for minimizing torque ripples was examined. The modeling of the SRM and the PI controller was shown. The Matlab/Simulink toolkit was utilized to model this investigation. Analysis and comparison of the suggested PI controller's performance with the P controller were conducted. The PI controller achieved the intended results in terms of speed control, torque ripple reduction, and settling time metrics based on the findings of the simulation. The proposed PI controller outperformed the P controller in terms of the greatest reduction rate (98.97%) and minimum settling time (0.0125s). Our study is limited by the fact that the PI controller only reduces torque ripples with the maximal variation. So, the future electromagnetic torque ripples will be further reduced if we integrate the PI controller with a fuzzy logic controller or an adaptive controller.

REFERENCE

1. Zhang, M., Xie, H., Hu, W., Li, J., Huang, Q. and Zhou, R., 2022. A vibration reduction method based on smooth voltage PWM control of switched reluctance machines. Energy Reports, 8, pp.1398-1405.
2. Deng, X., Mecrow, B., Wu, H., Martin, R. and Gai, Y., 2018. Cost-effective and high-efficiency variable-speed switched reluctance drives with ring-connected winding configuration. IEEE Transactions on Energy Conversion, 34(1), pp.120-129.
3. Bin, W., 2021, December. Research and implementation of a new controller for Switched Reluctance Motor. In 2021 3rd International Conference on Electrical Engineering and Control Technologies (CEECT) (pp. 222-227). IEEE.
4. Seshadri, A. and Lenin, N.C., 2020. Review based on losses, torque ripple, vibration and noise in switched reluctance motor. IET Electric Power Applications, 14(8), pp.1311-1326.
5. Jing, J., 2020. A power factor correction buck converter-fed switched reluctance motor with torque ripple suppression. Mathematical Problems in Engineering, 2020.
6. Mahalakshmi, G. and Kanthalakshmi, S., 2022, March. Design of Iterative Learning Controller for Switched Reluctance Motor with Least Torque Ripple. In 2022 8th International Conference on Advanced Computing and Communication Systems (ICACCS) (Vol. 1, pp. 299-304). IEEE.
7. Omaç, Z., Polat, M., Öksüztepe, E., Yıldırım, M., Yakut, O., Eren, H., Kaya, M. and Kürüm, H., 2018. Design, analysis, and control of in-wheel switched reluctance motor for electric vehicles. Electrical Engineering, 100(2), pp.865-876.
8. Azer, P., Bilgin, B. and Emadi, A., 2020. Comprehensive analysis and optimized control of torque ripple and power factor in a three-phase mutually coupled switched reluctance motor with sinusoidal current excitation. IEEE Transactions on Power Electronics, 36(6), pp.7150-7164.
9. Abdel-Fadil, R.M. and Számel, L., 2019. Direct Instantaneous Torque Control of the Switched Reluctance Motor for Electric Vehicles Applications Using Fuzzy Logic Control. Acta Technica Jaurinensis, 12(2), pp.101-116.
10. Sial, M.R. and Sahoo, N.C., 2020, December. Comparative Performance Analysis of Hysteresis and PI Current Controller for Torque Control of Switched Reluctance Motor. In 2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES) (pp. 1-6). IEEE.
11. Gan, C., Wu, J., Sun, Q., Kong, W., Li, H. and Hu, Y., 2018. A review on machine topologies and control techniques for low-noise switched reluctance motors in electric vehicle applications. IEEE Access, 6, pp.31430-31443.
12. Tursini, M., Villani, M., Fabri, G. and Di Leonardo, L., 2017. A switched-reluctance motor for aerospace application: Design, analysis and results. Electric Power Systems Research, 142, pp.74-83.
13. Omac, Z., 2019. Fuzzy-logic-based robust speed control of switched reluctance motor for low and high speeds. Turkish Journal of Electrical Engineering and Computer Sciences, 27(1), pp.316-329.
14. Jackson, L.S., Crook, J.A. and Forster, P.M., 2016. An intensified hydrological cycle in the simulation of geoengineering by cirrus cloud thinning using ice crystal fall speed changes. Journal of Geophysical Research: Atmospheres, 121(12), pp.6822-6840.
15. Zhang, Z., Yaman, S., Salameh, M., Singh, S., Chen, C. and Krishnamurthy, M., 2021. Effectiveness of Power Electronic Controllers in Mitigating Acoustic Noise and Vibration in High-Rotor Pole SRMs. Energies, 14(3), p.702.
16. Kim, J.H. and Kim, R.Y., 2018. Sensorless direct torque control using the inductance inflection point for a switched reluctance motor. IEEE Transactions on Industrial Electronics, 65(12), pp.9336-9345.d
17. Li, C., Wang, G., Li, Y. and Xu, A., 2018. An improved finite-state predictive torque control for switched reluctance motor drive. IET Electric Power Applications, 12(1), pp.144-151.
18. Zhang, M., Ali, N. and Gao, Q., 2021. Winding inductance and performance prediction of a switched reluctance motor with an exterior-rotor considering the magnetic saturation. CES Transactions on Electrical Machines and Systems, 5(3), pp.212-223.
19. Golatgaonkar, P., Chaudhari, B. and Ugale, R., 2019. Torque ripple reduction in homopolar poly-phase transverse flux machine. The Journal of Engineering, 2019(17), pp.3553-3558.

20. Sun, Y., Zhang, B., Yuan, Y. and Yang, F., 2018. Thermal characteristics of switched reluctance motor under different working conditions. Progress In Electromagnetics Research M, 74, pp.11-23.

21. Mishra, A.K. and Singh, B., 2017. Control of SRM drive for photovoltaic powered water pumping system. IET Electric Power Applications, 11(6), pp.1055-1066.

22. Rajendran, A. and Karthik, B., 2021. Design and analysis of fuzzy and PI controllers for switched reluctance motor drive. Materials Today: Proceedings, 37, pp.1608-1612.

23. Sajid, O., 2018, October. Performance analysis of switched reluctance motor for 24/7 working environment. In 2018 15th International Conference on Smart Cities: Improving Quality of Life Using ICT & IoT (HONET-ICT) (pp. 56-60). IEEE.

24. Bian, H., Chen, H. and Wang, R., 2020, November. Modeling and simulation of three-phase 6/4 switched reluctance motor speed control system. In Journal of Physics: Conference Series (Vol. 1684, No. 1, p. 012139). IOP Publishing.

25. Ferková, Ž., Suchý, Ľ. and Bober, P., 2020. Comparison of 6/4 and 12/8 switched reluctance motor models using direct torque control with torque lookup table. Electrical Engineering, 102(1), pp.75-83.

26. Ferková, Ž. and Suchý, L.U., 2018, May. Simulation of 6/4 and 12/8 switched reluctance motor using direct torque control. In 2018 ELEKTRO (pp. 1-5). IEEE.

27. Xiao, L., Sun, H., Gao, F., Hou, S. and Li, L., 2018. A new diagnostic method for winding short-circuit fault for SRM based on symmetrical component analysis. Chinese Journal of Electrical Engineering, 4(1), pp.74-82.

28. Ali, N., Gao, Q., Xu, C., Makys, P. and Stulrajter, M., 2018. Fault diagnosis and tolerant control for power converter in SRM drives. The Journal of Engineering, 2018(13), pp.546-551.

29. Zhu, Y., Jia, Y. and Wu, H., 2020. Modeling, Simulation and Experimental Verification of Four-Phase 8/6 Switched Reluctance Motor Considering Interactive Excitation. IEEE Access, 8, pp.70411-70419.

30. Anyalebechi, A.E., 2018. SIMULATION OF SPEED CONTROL TECHNIQUES OF SWITCHED RELUCTANCE MOTORS (SRM). SIMULATION, 5(12).

31. Deebiga, R., Thamil alagan, M. and Suresh Padmanabhan, T., 2015. Modified SEPIC Converter Based Electric Vehicle Battery Charger. IJAREEIE International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, ISSN (Print) : 2320 – 3765, ISSN (Online): 2278 – 8875, pp.1-8.

32. Mohan, V., Stalin, N. and Jeevananthan, S., A Double Random Pulse Width Modulation based on Discrete Carrier Frequencies and Random Pulse Position for Induction Motor. International Journal of Applied Engineering Research 10(51), 479-484.

An IoT Based Electric Vehicle with Wireless Charging Technology

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ABSTRACT

Electric vehicles (EVs) are widely adopted as a sustainable transportation solution to reduce environmental pollution and dependence on fossil fuels. However, conventional wired charging systems have several limitations, including cable wear, safety hazards, and user inconvenience. This paper presents the design and implementation of an Internet of Things (IoT) based wireless charging system for electric vehicles using inductive coupling technology. The proposed system consists of a transmitter unit, a receiver unit, a Battery Management System (BMS), and an IoT monitoring module. Electrical energy is transferred wirelessly from the transmitter coil to the receiver coil through electromagnetic induction. The received energy is rectified, boosted, and regulated before charging the battery. A microcontroller monitors system parameters such as battery voltage and charging status, while a Wi-Fi module sends the data to an IoT platform for remote monitoring. Experimental testing demonstrates that the system successfully wirelessly transfers power to the EV and enables real-time monitoring of the EV battery conditions. The proposed system improves safety and user convenience compared to traditional wired charging systems.

KEYWORDS: *Electric Vehicle, Wireless Power Transfer, IoT Monitoring, Inductive Coupling, Battery Management System.*

INTRODUCTION

The need for eco-friendly transport has been responsible for the advancement of electric vehicles (EVs). It helps to reduce the amount of greenhouse gases and make less dependence on fossil fuel and thus contribute towards sustainable transport. However, the traditional charging system of EV, which is based on cable connection can leads to wear and tear of the connecting plug, besides making the process inconvenient for users. The technique called wireless power transmission (WPT) provides a good solution for this because it transfers electrical energy from the transmitter to the receiver coil without requiring any physical contact. This is a safer procedure and makes less maintenance as well as more convenient for users. Another advantage is that the integration of Internet of things (IoT) technology can further improve the performance of the wireless charging system. It monitors the parameters such as voltage of the battery, charging status and others through cloud computing. This paper describes a wireless charging system for EV using IoT technology.

LITERATURE REVIEW

Inductive wireless power transfer is widely used in EV charging systems due to its simplicity and effectiveness [1]. However, power transfer efficiency is affected by factors such as coil misalignment and increased air gap. To solve these problems, monitoring and control using the IoT technology have been implemented in the charging system. [2].

Maintaining stable and efficient power transfer remains

a major challenge in wireless charging systems. Proper system design and optimization techniques are essential to ensure reliable operation under varying conditions [3]. Studies show that efficiency can be improved by minimizing transmission losses and enhancing coupling between transmitter and receiver coils [4], [5].

To further improve performance, hybrid systems integrating renewable energy sources are adopted, which enhance efficiency and sustainability [6]. Modeling and analysis of wireless power transfer systems help to evaluate performance under both steady-state and dynamic conditions, enabling better system optimization [7]. The integration of IoT significantly enhances monitoring and control capabilities by enabling real-time data acquisition, remote access, and smart system management [8]. Optimized circuit design and IoT-based strategies also improve the system's power transfer efficiency and adaptability [9], [10]. Advanced control strategies ensure efficient energy transfer and improved system responsiveness under varying load conditions [11]. High-efficiency wireless power transfer techniques are essential for practical EV applications, though challenges such as infrastructure requirements, cost, and efficiency optimization [12], [13].

IoT-controlled systems further improve safety and reliability through continuous monitoring and fault detection [14]. The use of electromagnetic induction and power electronic converters confirms the feasibility of wireless EV charging systems for future applications [15]. Overall, these technologies enhance efficiency, reliability, and convenience, while challenges such as misalignment and power losses remain important areas for future discussion.

WIRELESS POWER TRANSFER (WPT) AND CHARGING TECHNIQUES

WPT an innovative technology whereby electricity can be transferred from a power source to a load without any physical connection between them. In EV charging systems, WPT ensures increased efficiency, safety and ease of use by removing the requirement for cables. In this proposed method, power is transmitted wirelessly using the principle of electromagnetic induction between the transmitter and the receiver coil. When an alternating current flows through the transmitter coil, it generates a time-varying magnetic field that induces an electromotive force in the nearby receiver coil, according to Faraday's Law of Electromagnetic Induction. The induced voltage in the receiver coil is then converted into usable electrical energy through a rectifier circuit and power conditioning stage. The wireless charging system consists of several important components, including the power supply unit, high-frequency inverter circuit, transmitter & receiver coil, rectifier circuit, boost converter, and battery charging unit. On the transmitter side, DC power is converted to high-frequency AC using a switching inverter circuit driven by a PWM controller and MOSFET switches. This high-frequency AC energizes the transmitter coil, generating a magnetic field. The receiver coil, placed near the transmitter, captures this magnetic flux and generates an induced AC voltage. The induced AC voltage is rectified and filtered to obtain DC power, which is then further regulated and used to charge the electric vehicle battery. Wireless power transfer offers several advantages, including eliminating physical connectors, improving user convenience, reducing maintenance due to the absence of cables, and enhancing safety in charging systems. Different wireless charging techniques are used in electric vehicle charging systems depending on the distance, efficiency, and power requirements.

Inductive Coupling

Inductive coupling is the most widely used wireless charging technique for electric vehicles. It works on the theory of electromagnetic induction by means of two windings. When AC current is supplied to the transmitting winding, a magnetic field is created, and the receiving winding receives this magnetic field to generate electricity. This method is suitable for short-distance power transfer and offers high efficiency when the coils are properly aligned. In the proposed system, inductive coupling is used as the primary charging technique.

Resonant Inductive Coupling

Resonant induction coupling enhances efficiency through the operation of both coils at a resonant frequency. In this case, energy transfer is achieved efficiently even if the separation between the coils is slightly higher.

Capacitive Wireless Charging

Capacitive wireless charging uses electric fields between metal plates to transfer energy, rather than magnetic fields. Although this method can transfer energy wirelessly, it is less commonly used for electric vehicle charging because it requires large plates and high voltages.

Microwave or Radio Frequency Charging

This technique uses electromagnetic waves to transmit power over longer distances. However, it is mainly used in low-power applications, such as sensors and IoT devices, because it is less efficient in high-power applications, such as EV charging.

WPT - ARCHITECTURE

WPT architecture describes the overall structure for wirelessly transmitting electrical energy from the charging station to the EV battery. In the proposed IoT-based EV wireless charging system, the architecture consists of two main sections: the transmitter side and the receiver side, along with monitoring and control units.

Transmitter Side Architecture

The transmitter side is responsible for generating the electromagnetic field required for wireless energy transfer and is located at the charging station. The transmitter side architecture is shown in Figure 1. The system receives electrical power from a 230 V AC grid supply. A step-down transformer reduces high AC voltage to a lower level, typically 12-0-12 V AC, suitable for electronic circuits. The reduced AC voltage is then converted to DC using a bridge rectifier, and capacitors are used to smooth the output and reduce ripple.

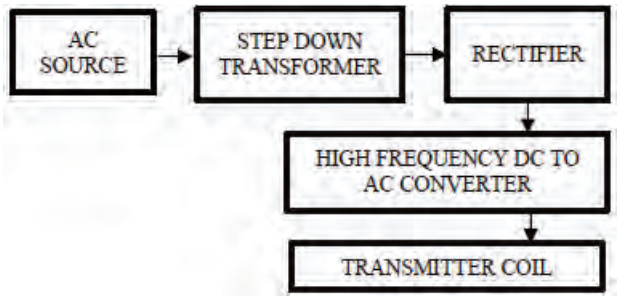

Fig. 1. Transmitter side architecture

The DC voltage is then changed into high frequency AC through the high frequency inverter circuit that uses PWM control and MOSFET switching technique. High frequency AC voltage is used to supply the transmitter coil that produces a varying magnetic field in its surroundings. This magnetic field becomes the wireless power transmission medium from the transmitter to the receiving coil.

Receiver Side Architecture

The receiver side is placed on the EV and is responsible for capturing the transmitted energy and converting it into usable electrical power. The receiver side architecture is shown in Figure 2. The main component is the receiver coil, which is positioned close to the transmitter coil. It captures the magnetic field produced by the transmitter and generates an induced AC voltage through electromagnetic induction.

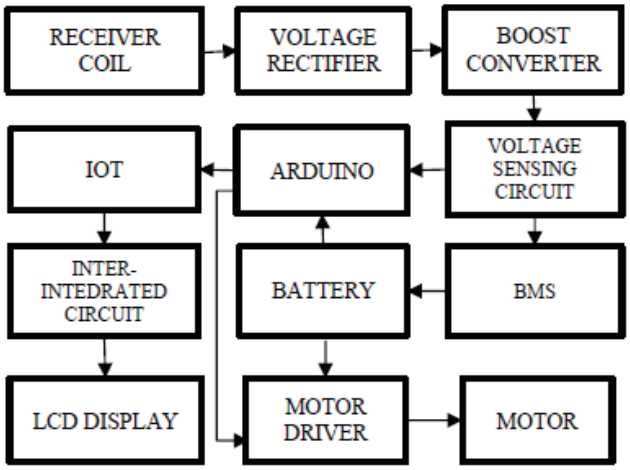

Fig. 2. Receiver side architecture

The received voltage may be low due to transmission losses, so a boost converter is used to increase the DC voltage to the required level for charging the battery. A voltage regulator also provides a stable output voltage, protecting electronic components and ensuring proper system operation.

High Frequency DC to AC Converter

It is an electronic circuit that converts DC into high Frequency AC. The use of high frequency DC-to-AC converters is common in wireless energy transfer systems, induction heating, and switching power supply circuits. It is being proposed to be used in the

EV wireless charging station circuitry to produce high frequency AC for energizing the transmitter coil. In WPT systems, energy is transferred via electromagnetic induction, and for efficient induction, the current supplied to the transmitter coil must be high-frequency AC rather than DC. Therefore, the DC output from the rectifier is converted into high-frequency AC using a DC–AC converter, also known as an inverter. The converter consists of several components, including a PWM controller, MOSFET switching devices (IRF540), gate resistors (100 Ω), a timing resistor, a capacitor (4700 μF), and the transmitter coil. The microcontroller generates high-frequency PWM signals to control the MOSFETs' switching. The MOSFET switches rapidly turn the DC supply on and off, producing a high-frequency AC output. Gate resistors protect the MOSFET gates and control switching speed, while the timing resistor and capacitor determine the circuit's operating frequency. The high-frequency AC output is then supplied to the transmitter coil, which generates the alternating magnetic field required for wireless power transfer.

Battery Management System (BMS)

A BMS is an electronic system that monitors and protects rechargeable batteries in electric vehicles. It ensures safe charging and discharging of the battery pack by controlling voltage and current. The BMS protects the battery from overcharging and discharging, short circuits, which can damage lithium-ion batteries. It continuously monitors each battery cell's voltage and controls charging and discharging using MOSFET switches.

In the proposed system, a 3S lithium-ion battery pack (11.1 V nominal, 12.6 V fully charged) is used. The BMS monitors the battery condition and disconnects the charging circuit if the voltage exceeds the safe limit. Similarly, it disconnects the load when the battery voltage drops below the minimum level to prevent deep discharge. Thus, the BMS improves battery safety, performance, and lifespan in the IoT-based EV wireless charging system.

Motor Driver

A motor drive is an electronic circuit that allows a microcontroller to control a DC motor. In this work, the motor driver receives control signals from the Arduino and uses the battery power (12 V) to drive the DC geared motors connected to the wheels of the electric vehicle prototype. The driver circuit increases the current from the battery to allow the motors to rotate properly. When the Arduino sends a control signal, the motor driver activates the motor and allows it to rotate. This enables the vehicle to move forward. The motor driver also protects the microcontroller from the high current produced by the motor. Thus, the motor driver helps in efficient control and safe operation of the motors in the IoT-based electric vehicle system.

IOT Controller

The IoT controller is the unit that enables the system to communicate with the internet and monitor data remotely. In this work, the Wi-Fi module serves as the IoT controller, sending system information to an online platform. The IoT controller receives data, such as battery voltage and charging status, from the Arduino microcontroller via serial communication. It then transmits this data to a cloud server using a Wi-Fi network. This allows users to monitor the charging condition of electric vehicles in real time on a mobile phone or computer. By integrating the IoT controller, the system provides remote monitoring, improved control, and better management of the EV wireless charging process. An IoT platform with a WiFi module provides remote monitoring of battery voltage and charging status.

METHODOLOGY

The methodology of the proposed system is based on WPT using inductive coupling and IoT-based monitoring. The system is divided into transmitter, receiver, control, and monitoring modules.

An Arduino microcontroller continuously monitors the battery voltage and system parameters using voltage-sensing circuits. The measured values are displayed on an LCD. An IoT module sends battery and charging data to a cloud platform using Wi-Fi, allowing remote monitoring of the charging system. The overall methodology ensures efficient wireless energy transfer, safe battery charging, and real time monitoring of the EV system.

Experimental Setup

The hardware implementation of the proposed system comprises several components integrated to perform wireless charging and system monitoring for the electric vehicle prototype, as shown in Figure 3. The system receives electrical power from a 230 V AC grid supply, which serves as the charging station Thus, the voltage is stepped down, and the reduced AC voltage is then converted to DC using a rectifier circuit. The DC output from the rectifier is then converted into high-frequency AC using a high-frequency DC–AC converter. This converter is built using the SG3525 PWM controller and MOSFET switching devices. SG3525 generates high-frequency PWM signals to control the MOSFET switching. These MOSFETs rapidly switch the DC voltage, producing a high-frequency AC output. This high-frequency AC signal is supplied to the transmitter coil, which generates a time-varying magnetic field around it. This magnetic field acts as the medium for wireless power transfer. On the receiver side, a receiver coil is placed close to the transmitter coil. When the transmitter coil generates a magnetic field, the receiver coil captures this magnetic flux and induces an AC voltage through electromagnetic induction. The induced voltage is then processed to make it suitable for charging the battery. Since the received voltage may be low due to transmission losses and coil misalignment, a boost converter is used to increase the DC voltage to the required level for efficient battery charging. Misalignment can be reduced by proper coil alignment, maintaining a fixed air gap, using ferrite coils for better coupling. The Arduino UNO microcontroller monitors important system parameters, such as battery voltage and charging status, using voltage-sensing circuits. The microcontroller processes the measured values and controls the operation of different components in the system. The system status and voltage readings are displayed on an LCD, allowing users to easily monitor charging conditions and battery status. To enable remote monitoring, an ESP32 Wi-Fi module is integrated into the system. The ESP32 receives data from the Arduino and sends system information to the ThingSpeak server for remote monitoring through a mobile phone or computer. The system uses a 3S lithium-ion battery pack as the energy storage unit.

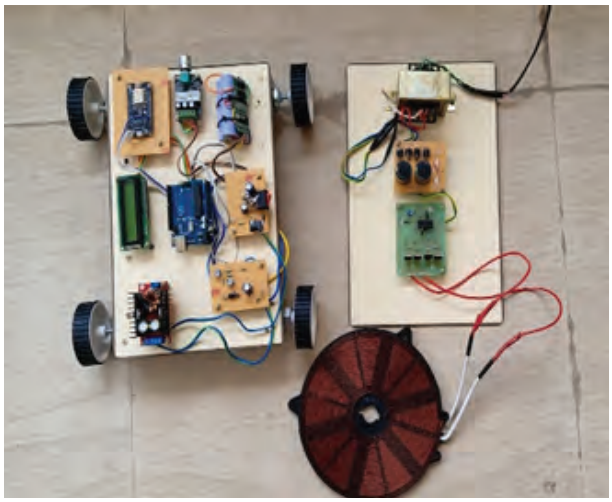

Fig. 3. Prototype Hardware Setup of IoT-Based Wireless Charging System for Electric Vehicle

In this configuration, three lithium-ion cells are connected in series, providing a nominal voltage of 11.1 V and a fully charged voltage of approximately 12.6 V. The battery stores the energy received from the wireless charging system and supplies power to the vehicle components. In addition, a motor driver circuit controls the vehicle's DC geared motors. The motor driver acts as an interface between the Arduino microcontroller and the motors. Since the microcontroller cannot supply enough current to drive the motors directly, the motor driver receives control signals from the Arduino and provides sufficient current from the battery to operate the motors. The DC geared motors convert electrical energy into mechanical motion, allowing the electric vehicle prototype to move. Overall, integrating these hardware components enables efficient wireless power transfer, safe battery charging, real-time monitoring, and proper control of the electric vehicle system.

Sequence of operation of wireless charging of EV

The complete operation of wireless charging of an Electric Vehicle is given in eight stages as follows.

Stage 1: 230V ac source voltage is stepped down to 12V and rectified

Stage 2: The rectified DC voltage is converted into high-frequency AC

Stage 3: The transmitter coil generates the time-varying magnetic field

Stage 4: The receiver coil captures the transmitted electrical energy

Stage 5: The receiver side rectified voltage is boosted to charge the battery using a boost converter

Stage 6: The microcontroller displays the battery voltage and status of the battery on the LCD display

Stage 7: WiFi module is integrated with the microcontroller to send data to the Thingspeak server to monitor battery voltage and battery status

Stage 8: The microcontroller sends PWM signals to the driver circuit to drive the EV motor.

Design details

Input power	: 60W
Output power	: 30-50W
Transmitter coil input voltage	:12V
Receiver coil output voltage	: 18mV
Inductance of transmitter coil	: 100µH
Air gap	: 15mm
Coil type	: inductance coil with 27 turns

Software Implementation

The software implementation controls and monitors the system using Arduino UNO. The Arduino is programmed in the Arduino IDE to read the battery voltage and charging status using the voltage-sensing circuit. The system parameters are displayed on the LCD via Inter-Integrated Circuit. The Wi-Fi module sends the collected data to an IoT cloud platform for real-time monitoring. This allows users to check the battery and charging status online.

ThingSpeak

ThingSpeak is an IoT cloud platform for storing, analyzing, and visualizing sensor data in real time. In this research, the Wi-Fi module sends battery voltage and charging data to the ThingSpeak server over the internet. The data is displayed in graphs on the ThingSpeak dashboard, allowing users to monitor the EV battery condition on a mobile phone or computer. The real time IoT dashboard for the Thingspeak server is shown in Fig 4.

Fig. 4. Dashboard of Thingspeak IoT platform

Embedded C Program

The system is programmed using Embedded C in the Arduino IDE. The program reads the battery voltage through the analog pin, processes the data, and sends it to the IoT platform through the ESP32 module. The Arduino also controls the LCD to show battery voltage and system status. The embedded program enables communication between sensors, the microcontroller, the LCD, and the IoT platform for real-time monitoring.

RESULTS AND DISCUSSION

The proposed IoT-based EV wireless charging system was successfully implemented and evaluated under practical conditions. The transmitter circuit generated high-frequency AC at approximately 20 kHz using the PWM controller and MOSFET switching devices, energizing the transmitter coil and producing a varying magnetic field. The receiver coil, placed near the transmitter coil, captured this magnetic field and induced an AC voltage through electromagnetic induction. The received voltage ranged from approximately 6 to 18 V.

The AC voltage depends on the coil alignment in the 15 mm air gap. This induced AC voltage was rectified and

boosted using the boost converter to obtain a stable DC output suitable for charging the 3S lithium-ion battery pack. The battery charging voltage was maintained at 12–14 V DC, enabling safe charging of the 11.1 V nominal battery (12.6 V fully charged). The integrated Battery Management System ensured battery safety by protecting against over-voltage, under-voltage, and unstable charging conditions.

The Arduino microcontroller continuously monitored the battery voltage via a sensing circuit and displayed

the charging status on the LCD. In addition, the Wi-Fi module transmitted battery voltage and system data to the ThingSpeak cloud platform, enabling real-time remote monitoring of the charging process.

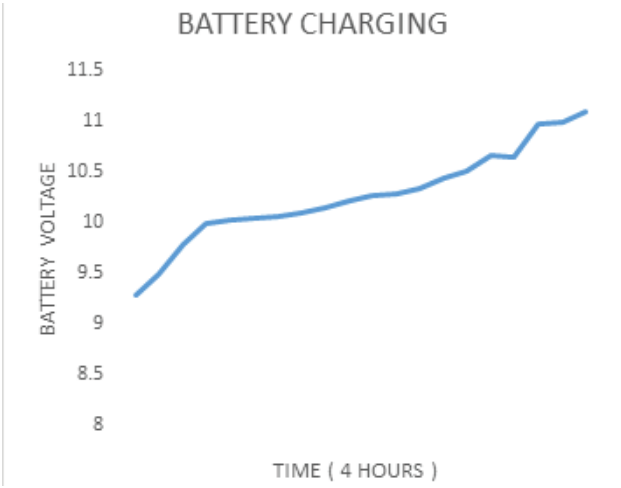

Fig. 5. Battery charging

The experimental results demonstrate that the developed system successfully performs wireless power transfer of approximately 30–50 W from an AC source to the EV battery, while providing stable battery charging, IoT-based monitoring, and reliable system operation.

Figure 5 shows the battery charging characteristics, where the voltage increases from 9.3 V to 11.1 V over 228 minutes. The gradual, smooth rise indicates a stable, efficient charging process with minimal fluctuations.

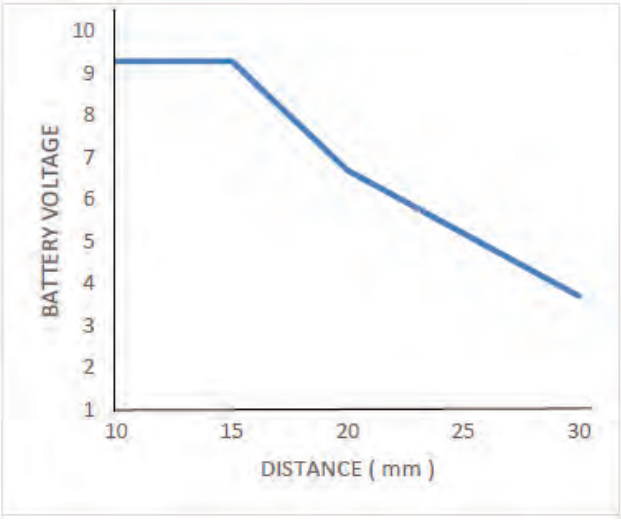

Fig. 6. Battery charging with distances

Figure 6 shows the variation in battery voltage with distance. It is observed that the voltage decreases significantly as the distance between the transmitter coil and receiver coil increases from 10 mm to 30 mm. Initially, the voltage remains nearly constant up to 15 mm, after which a sharp decline is observed. This reduction is mainly due to decreased coupling efficiency between the transmitter and receiver coils at larger distances. The results indicate that maintaining a smaller distance is essential for achieving higher efficiency in wireless power transfer systems.

Table 1 illustrates the variation in battery voltage over time during discharge. It is observed that the voltage decreases steadily from 10.51 V at the initial stage to 9.28 V at 228 minutes. The discharge curve shows a gradual reduction with a slightly faster drop in mid-duration, followed by a more stable decline towards the end. This indicates a controlled and uniform energy release throughout the operation.

Table 1 Battery Discharging with time

S.No.	Time (min)	Volts (V)
1.	0	10.51
2.	12	10.45
3.	24	10.40
4.	36	10.35
5.	48	10.33
6.	60	10.28
7.	72	10.22
8.	84	10.17
9.	96	10.07
10.	108	10.02
11.	120	9.99
12.	132	9.83
13.	144	9.74
14.	156	9.62
15.	168	9.55
16.	180	9.49
17.	192	9.44
18.	204	9.39
19.	216	9.33
20.	228	9.28

Charging Efficiency

The battery takes 228min to change its state of charge

from 10% to 80% and corresponding battery voltage change from 9.3V to 11.1V. The usuable capacity of the Lithium ion battery used in the proposed module is 45.6Wh. The energy required to charge the battery to 70% of its capacity is 31.92Wh, but the battery actually takes 36.6 Wh from the source. The charging efficiency of battery is calculated as follows.

$$The\ charging\ efficiency = \frac{Energy\ stpred\ in\ the\ battery}{Energy\ taken\ from\ the\ source}$$

$$The\ charging\ efficiency = \frac{31.92}{36.6}\ x\ 100\% = 87.2\%$$

CONCLUSION

This paper presented an IoT-based EV wireless charging system using inductive coupling technology. The system successfully transfers electrical energy wirelessly from the transmitter to the receiver coil. The received power is converted and used to charge the battery safely through the BMS. The Arduino microcontroller monitors system parameters, and the ESP32 IoT module enables real-time monitoring of battery voltage and charging status through the internet. The proposed system improves charging convenience and safety compared to conventional wired charging methods. This research also demonstrates that as the distance between the transmitter and receiver coils decreases, power transfer increases.

REFERENCES

1. O. Abuajawa, S. P. Thiagarajah, and A. P. David, "Comprehensive Review of Wireless Power Transfer Systems for Electric Vehicle Charging Applications," Discover Applied Sciences, vol. 7, 2025.
2. S. I. Tadaval and D. S. Waghmode, "Wireless Power Transfer for EV Charging," International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering, 2025.
3. V. K. B. Veeresha and M. G. Manjula, "Wireless Charging System for Electric Vehicles Using Inductive Coupling," International Journal of Recent Engineering Science (IJRES), 2025.
4. Z. Xue, W. Liu, and C. Liu, "Critical Review of Wireless Charging Technologies for Electric Vehicles," World Electric Vehicle Journal, vol. 16, no. 2, 2025.
5. B. D. S. Veni, G. Snehith, and K. V. S. Niharika, "Design of IoT-Based Smart Wireless Charging System for Electric Vehicles," International Journal of Scientific Research in Engineering and Management, 2024.
6. S. Iqbal and N. F. Alshammari, "Smart and Sustainable Wireless Electric Vehicle Charging Strategy with IoT Integration," Sustainability, vol. 16, no. 6, 2024.
7. S. Sandeep, H. V. Monika, S. Chacko, and S. Kulal, "Wireless Power Transmission for Electric Vehicle Charging Using Solar Energy," International Journal of Engineering Research & Technology (IJERT), 2024.
8. A. Bharadwaj K. K., "Real-Time Wireless Charging for Electric Vehicles," International Journal of Engineering Research & Technology (IJERT), vol. 12, no. 11, 2023.
9. S. Gayathri Priya, M. Lokesh, P. Tejesh, P. Baluchandu, and P. Sravan, "IoT-Based Wireless Charging System for Electric Vehicles," International Journal of Engineering a. Research & Technology (IJERT), 2023.
10. S. G. Karneswaran, E. Elizabeth, and M. Muraligharan, "Efficient Wireless Charging System for Electric Vehicles Using Inductive Power Transfer,"International Journal of Advanced Research in Electrical Engineering, 2023.
11. X. Ma and Y. Zhou, "Analysis of Wireless Power Transfer System for Electric Vehicle Charging,"IEEE Conference on Transportation Electrification, 2022.
12. R. Thankam, S. R., and S. Farheen,"IoT Controlled Wireless Power Transfer System for Electric Vehicles,"International Journal of Engineering Research & Technology (IJERT), 2022
13. A. M. Ahmed and O. O. Khalifa,"Wireless Power Transfer for Electric Vehicle Charging Systems,"International Journal of Power Electronics and Drive Systems, 2019.
14. M. Amjad and M. Farooq-i-Azam,"Wireless Power Transfer Technologies for Electric Vehicle Applications: A Review,"Renewable and Sustainable Energy Reviews, 2018.
15. S. Li and C. C. Mi, "Wireless Power Transfer for Electric Vehicle Applications", IEEE Journal of Emerging and Selected Topics in Power Electronics, 2015.

Intent-to-Execution Manufacturing: A Generative AI Framework for Autonomous Robotic Toolpath Synthesis from Semantic Prompts and Sketch-Based Inputs

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ABSTRACT

The translation of conceptual design intent into executable robotic manufacturing trajectories remains a major challenge in digital fabrication workflows. Conventional Computer-Aided Manufacturing (CAM) systems require explicit geometric modelling and manual toolpath programming, creating a significant barrier between creative design and physical production. This paper presents an Intent-to-Execution manufacturing framework that autonomously synthesizes industrial robotic toolpaths directly from unstructured human inputs, including natural language prompts and hand-drawn sketches. The proposed web-based system integrates generative artificial intelligence, digital image processing, and robotic trajectory planning into a unified pipeline for automated toolpath generation. A constrained text-to-image generative model first converts semantic prompts into simplified morphological images, which are subsequently processed using an OpenCV-based Digital Image Processing pipeline to extract contours and transform raster features into ordered coordinate sequences. To ensure safe and smooth robotic motion across disconnected contours, a Fly-Arc trajectory strategy is introduced, generating sinusoidal Z-axis lift transitions that minimize kinematic jerk and prevent tool dragging during robotic incremental sheet forming operations. The synthesized trajectories are automatically compiled into executable ABB RAPID programs, enabling direct deployment on industrial robotic systems. Experimental validation on an ABB robotic forming cell demonstrates that the proposed framework converts conceptual inputs into robot-ready toolpaths, while preserving geometric fidelity and ensuring workspace safety through real-time boundary validation. The results demonstrate a new paradigm for intent-driven, software-defined manufacturing, bridging artistic creativity with autonomous robotic production.

KEYWORDS: *Generative AI, Robotic Path Planning, Image-Based Toolpath Extraction, ABB Industrial Robot Programming.*

INTRODUCTION

Industrial robots are increasingly being integrated into modern manufacturing environments due to their flexibility, large workspaces, and capability to perform complex multi-axis motions. Unlike traditional CNC machines, robotic manipulators can execute complex trajectories across large work envelopes, making them suitable for applications such as forming, surface processing, additive manufacturing, and artistic fabrication. A critical component of such robotic operations is the generation of accurate and smooth toolpaths, which define the spatial trajectory followed by the robot's end effector during manufacturing tasks. In current industrial workflows, toolpath generation

is typically performed using Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) systems. These platforms generate robot trajectories based on predefined geometric models and user-defined machining parameters. While CAD/CAM systems are widely used in industrial production, they rely heavily on structured parametric geometry and often require extensive manual intervention to generate valid trajectories. This dependency creates a significant barrier when translating conceptual designs, sketches, or creative ideas into executable robot motions. Another challenge arises from the complexity of robotic trajectory programming. Industrial robots possess multiple degrees of freedom and complex kinematic structures, which require carefully planned motion paths to ensure smooth operation and avoid sudden changes in velocity or acceleration. Generating these trajectories often requires specialized knowledge of robot programming languages, controller-specific post-processing, and motion optimization techniques. As a result, converting a conceptual design into an executable robot program remains a time-consuming and expertise-intensive process. These limitations highlight the need for automated systems capable of transforming high-level human design intent into valid robotic toolpaths without relying entirely on traditional CAD/CAM workflows.

In recent years, artificial intelligence has been increasingly explored within manufacturing research to enhance automation and decision-making processes. Numerous studies have applied machine learning and deep learning techniques to predict manufacturing outcomes, including process parameters, tool wear, production quality, and system performance. These approaches have demonstrated significant potential for improving efficiency and predictive capabilities within industrial systems. However, the application of artificial intelligence in manufacturing remains largely focused on predictive modeling rather than generative trajectory synthesis. Existing AI-based solutions typically analyze data generated from pre-existing toolpaths rather than generating the toolpaths themselves. Consequently, the creation of robotic trajectories still depends heavily on traditional CAD/CAM systems and manual programming workflows. Furthermore, many real-world design inputs originate from unstructured sources, such as hand-drawn sketches, raster images, or natural language descriptions. These forms of input cannot be directly interpreted by conventional CAD/CAM software because they exist as unorganized pixel grids rather than structured geometric entities. Converting such unstructured data into an ordered sequence of coordinates suitable for robotic execution remains a significant technical challenge. The lack of automated systems capable of transforming conceptual or artistic inputs into executable robot trajectories represents an important gap in current manufacturing technologies.

To address these limitations, this research proposes a novel Intent-to-Execution framework for automated robotic toolpath generation. The objective of the proposed system is to bridge the gap between human design intent and industrial robot execution by enabling the direct conversion of conceptual inputs into robot-ready trajectories. The framework integrates generative artificial intelligence, digital image processing, and robotic path planning within a unified web-based platform. Users can generate toolpaths either through natural language prompts or by uploading raster sketches. A generative AI model first produces simplified morphological representations of the desired geometry. These images are subsequently processed using an automated Digital Image Processing pipeline to extract contours and convert pixel-based features into ordered coordinate sequences. To ensure smooth robotic motion, the system incorporates a Fly-Arc transition strategy, which generates sinusoidal vertical lift motions when the robot moves between disconnected contour segments. This approach minimizes abrupt motion changes and improves trajectory continuity during execution. The generated toolpaths are then automatically compiled into ABB RAPID programs, allowing the trajectories to be executed directly on industrial robotic systems. Through this approach, the proposed framework aims to significantly reduce the complexity and time required for robotic trajectory programming, enabling a more intuitive workflow that translates human creativity and conceptual design directly into executable robot motion.

LITERATURE REVIEW

Toolpath generation is a critical component of automated manufacturing systems because it determines the spatial trajectory followed by a machine tool or

robotic end effector during task execution. In modern industrial workflows, toolpaths are typically generated using Computer-Aided Manufacturing (CAM) systems that convert geometric models created in Computer-Aided Design (CAD) environments into machine instructions such as G-code or robot-specific programs. These systems integrate machining parameters, tool geometries, and process constraints to generate feasible trajectories for manufacturing operations [1]. Despite their widespread use, conventional CAD/CAM systems remain heavily dependent on structured geometric models and predefined feature definitions. As a result, the generation of manufacturing trajectories often requires significant manual configuration and iterative adjustments to ensure compatibility with machine kinematics and process constraints [2]. This limitation becomes particularly evident when dealing with freeform geometries or creative design inputs that do not originate from parametric CAD models.

Several researchers have proposed algorithmic methods to improve toolpath efficiency and machining performance. For example, region-based toolpath generation approaches have been developed for robotic machining of freeform surfaces to improve system stiffness and machining accuracy [3]. Similarly, continuous toolpath strategies based on offset contours have been investigated in robotic manufacturing applications to improve geometric consistency and reduce motion discontinuities during tool traversal [4]. While these methods enhance the efficiency of toolpath planning, they still rely on structured CAD inputs and conventional design workflows.

Artificial intelligence has emerged as an important technology in modern manufacturing systems, particularly in the context of Industry 4.0 and digital manufacturing. Machine learning algorithms have been widely applied to manufacturing tasks such as predictive maintenance, process monitoring, and quality control. In machining environments, neural network models have been used to predict machining cycle times and process parameters based on toolpath characteristics and machine conditions [6]. Recent studies on intelligent CAD–CAM integration have highlighted the growing role of AI in automating design and manufacturing processes. These approaches focus on tasks such as feature recognition, machining parameter optimization, and production planning [2]. However, the majority of these applications remain focused on predictive analysis and process optimization rather than generative trajectory synthesis. Consequently, the generation of robot trajectories still relies heavily on traditional CAD/CAM software and manual programming. AI systems are primarily used to analyze or optimize existing toolpaths rather than generate new manufacturing trajectories from conceptual design inputs.

METHODOLOGY

The proposed "Intent-to-Execution" framework requires a highly synchronized integration of web-based user interfaces, cloud-based artificial intelligence, digital image processing, and industrial robotic kinematics. To achieve this, a full-stack, software-defined architecture was developed. The core of the system is architected using a modular Python-Flask backend, serving as the computational bridge between the user interface and the robotic hardware.

- Generative AI Integration: The Google Imagen 3 API (models/imagen-3.0-generate-001) is utilized as the Latent Diffusion engine, tasked with synthesizing raster arrays directly from semantic text prompts.
- Data Abstraction and Morphological Processing: Digital image processing is executed using OpenCV (cv2), converting AI-generated pixel data into discrete Euclidean vectors. Data abstraction and manipulation are handled via high-performance Pandas Data Frames and NumPy matrix operations, ensuring sub-millimetre mathematical precision.
- Visualization Engine: To provide users with immediate spatial feedback, the frontend utilizes Three.js and WebGL. This renders a dynamic, fully interactive 3D simulation of the generated toolpath, plotting Move L (Linear) and Move C (Circular) interpolations within a virtual coordinate space.

Ultimately, the conclusion of this software stack is the autonomous generation of a native ABB RAPID .mod file, serving as the direct digital-to-physical bridge for hardware execution.

PROPOSED FRAMEWORK

To successfully translate human creativity into deterministic machine code, the framework employs a

sequential, four-phase pipeline. This modular approach ensures that the stochastic nature of Generative AI is strictly constrained and normalized before reaching the physical hardware.

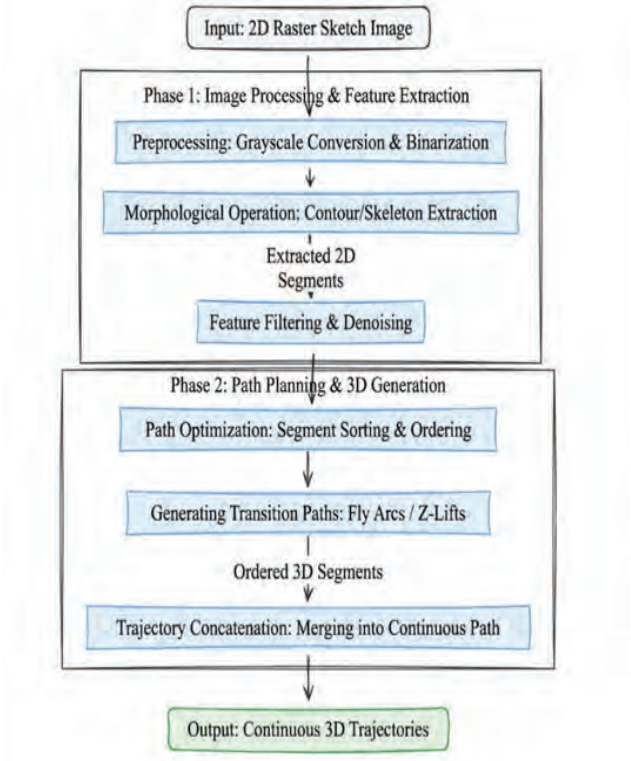

Fig. 1: Proposed Framework

Phase 1: Semantic Intent & AI Generation

The pipeline begins by capturing the user's design intent via a natural language prompt. To prevent the diffusion model from generating realistic shading or 3D effects that would corrupt the Z-depth pathing, the backend employs programmatic constraint injection. User-selected UI parameters (Complexity, Line Weight, and Art Style) are dynamically mapped into a strict system prompt overlay. The system explicitly requests "pure black and white vector line art, stencil style, absolute white background, pure 2D flat contours." This constrained prompt is executed, returning a 2D raster image representing the geometric topology.

Phase 2: Morphological Image Processing

The synthesized raster image is held in temporary memory and immediately processed using an automated extraction engine (ImageProcessor class).

- Preprocessing: The RGB image is converted to grayscale, and binary thresholding is applied to eliminate anti-aliasing artifacts.
- Contour Extraction: The framework utilizes the Douglas-Peucker algorithm (cv2.findContours) to approximate and extract contiguous geometric boundaries from the binary pixel clusters.
- Feature Filtering: To remove noise, microscopic artifacts (contours consisting of fewer than 5 coordinate pairs) are automatically filtered out.

Phase 3: Kinematic Path Planning & C2 "Fly-Arc" Synthesis

The isolated 2D vector segments are transformed into a continuous 3D spatial trajectory. A critical challenge in multi-feature robotic system is transitioning the tool between disconnected contours without introducing infinite mechanical jerk. To resolve this, the framework implements a C2 continuous "Fly-Arc" strategy.

Phase 4: Industrial Execution and Transformation

In the final phase, the user can apply manual affine transformations (Translation, Rotation, and Scaling) to position the 3D path precisely within the robot's physical workspace. The backend recalculates the coordinate matrix using NumPy dot products and verifies it against the predefined safe bounding box. Once validated, the Rapid Exporter class compiles the trajectory into executable ABB RAPID code (.mod). The compiler automatically maps points to standard Move L commands and applies Move C commands for curves, appending standard base frames and tool orientations.

RESULTS AND DISCUSSION

The system was tested using an unstructured hand-drawn car sketch. The OpenCV-based Image Processor successfully filtered environmental noise from the purple paper background using adaptive thresholding.

Image-to-Path Synthesis and CSV Validation, the system was tested using an unstructured car sketch. The image processor successfully filtered background noise and extracted the primary contours Coordinate Accuracy.

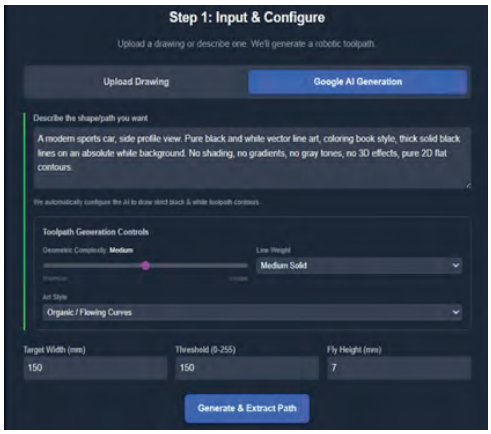

Fig. 2: User interface of the proposed framework

Fig. 3: Tool path and 3D visualization

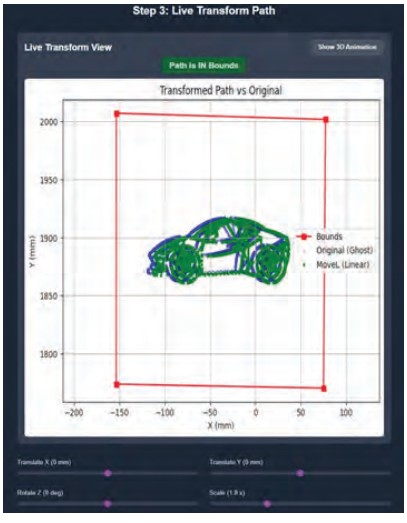

Fig. 4: Transformation of path

Fig. 5: Toolpath direct deployment to ABB robot

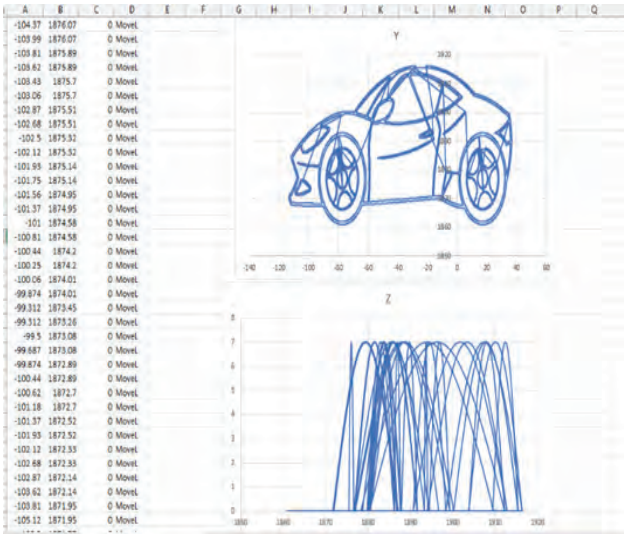

Fig. 6: Validation of generated tool path using Excel

CONCLUSION

The image-based toolpath generation module was successfully implemented using OpenCV-based contour extraction and morphological processing techniques. The system converts raster images into structured coordinate datasets and integrates optimized path sequencing with safe Z-axis linkage arcs for robotic execution. This approach effectively transforms visual sketches into manufacturable toolpaths, expanding geometric flexibility and accessibility.

ACKNOWLEDGEMENT

The author acknowledges the support and laboratory facilities provided by the Department of Mechanical Engineering, CSMSS, Chh. Shahu College of Engineering, Chhatrapati Sambhajinagar, for conducting the physical robotic validation.

REFERENCES

1. J. Jeswiet, et al., "Early CAM-assisted ISF implementations and limitations," Journal of Materials Processing Technology, vol. 162, pp. 1-9, 2005.
2. J. R. Duflou, et al., "Systematic assessment of commercial CAM systems applied to ISF," CIRP Annals - Manufacturing Technology, vol. 57, pp. 1-4, 2008.
3. M. Yang, et al., "Evaluation of commercial CAM tools for autonomous incremental forming systems," International Journal of Advanced Manufacturing Technology, vol. 112, pp. 1-15, 2021.
4. H. Huang, et al., "Feasibility of commercial CAM platforms for robot-assisted ISF in automotive applications," Journal of Manufacturing Systems, vol. 56, pp. 112-124, 2020.
5. H. Meier, B. Buff, and R. Laurischkat, "Kinematic limitations of robotic incremental sheet forming," Key Engineering Materials, vol. 549, pp. 248-255, 2013.
6. J. Belchior, et al., "Analysis of the robot structural stiffness and its influence on the incremental sheet forming process accuracy," International Journal of Advanced Manufacturing Technology, vol. 74, pp. 1-12, 2014.
7. S. Bharti, "Factors Contributing to Inaccuracy in Roboforming (IISc)," Scientific Reports, vol. 14, no. 1, p. 70746, 2024.
8. R. Malhotra, "Automatic 3D spiral toolpath generation for single-point incremental forming," Journal of Manufacturing Science and Engineering, vol. 132, no. 6, 2010.
9. S. Nagargoje, "Application of artificial intelligence techniques in incremental forming: a state-of-the-art review," Journal of Intelligent Manufacturing, vol. 34, pp. 1-28, 2023.
10. A. Alsamhan, "Prediction of formation force during single-point incremental sheet metal forming using artificial intelligence techniques," PLoS ONE, vol. 14, no. 10, e0221341, 2019.
11. D. Möllensiep, "Prediction of forming accuracy in SPIF using ANNs on local surface representations," International Journal of Advanced Manufacturing Technology, vol. 120, pp. 1-14, 2024.
12. S. Thiery, "Failure prediction by using a recurrent neural network in incremental sheet forming with active medium," International Journal of Material Forming, vol. 18, 2025.
13. D. Mourtzis, J. Angelopoulos, and N. Panopoulos, "Integrating Large Language Models into Digital Manufacturing: A Systematic Review and Research Agenda," Computers, vol. 14, no. 8, p. 318, 2024.
14. T. Hart-Rawung, et al., "Deep Reinforcement Learning Based Toolpath Generation for Minimizing Springback in Incremental Forming," Journal of Manufacturing Processes, vol. 58, pp. 1-12, 2020.

Casting Simulation Technique for Prediction and Removal of Casting Shrinkage in Ductile Iron Casting

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ABSTRACT

To reduce the lead times in development of a component, the number of trials in foundry shop floor is to be eliminated. The current paper uses finite volume method for simulating Flange casting. The flange holds the ring gear, which is spun by the pinion gear, and together these equal a vehicles final drive axel ratio. The purpose of Flange is to provide power transfer from the drive train to wheels. In current research of Flange, the modelling of casting and feeding system is done using the CAD software. This model is imported in the simulation environment for solidification simulation. Initially freezing naked of the casting is done to identify the location of the feeders. Then after attaching the feeding system, the casting model simulation runs are conducted. The simulation runs for defect prediction and removal of defects are conducted to achieve the feeding system which will assure sound casting.

KEYWORDS: *Ductile Iron; Casting Simulation; Defect prediction; Shrinkage.*

INTRODUCTION

Since the mid-1980s, foundries have effectively employed casting process simulation to anticipate casting issues and resolve them prior to the production of a real casting. Although many foundries have benefited from this technology, many more have not. To be successful in fierce global competition, and satisfy customer expectations in terms of quality assurance, shorter lead time and lower pricing computer modelling and simulation has become inevitable [1]. From sketch to final product, a typical, medium-complex design component typically takes 10 to eleven weeks to complete. This is because, the component needs to undergo repeated pilot run and trial and error modifications before fit for actual production [2].

Ductile iron is not a single material; rather, it belongs to a class of materials whose microstructure may be controlled to provide a variety of characteristics. Ductile Iron is a family of engineering materials offering a range of tensile strength [3]. In many automobile components, when strength requirements exceed those of aluminum but steel is not always necessary, ductile iron is very helpful. Thin-wall ductile iron is being used by the truck and automobile sectors to lower vehicle weight [4]. Although ductile cast iron has outstanding mechanical qualities, reducing the castings' wall thicknesses is required to make them lighter. Castings with varying thicknesses allow for varying cooling speeds during the casting's solidification. A casting's cooling rate, expressed in degrees Celsius per minute, is determined at each stage of the casting. In addition to thickness, the cooling rate also depends on the size of nearby portions and the mold's design, which affects how much metal flows through the thin area of interest [5]. The solidification cooling rate decides the final microstructure in cast components. With the help of Image analyzer for metallographical evaluation and spectrometer for chemical analysis, it has become possible to predict the microstructure of Ductile Iron quantitatively [6]. Chemical composition, cooling pace, liquid treatment, and heat treatment are the primary variables that affect the microstructure. Rapidly cooling portions of the casting often have a better grain structure

and less partly soluble chemical deposition at the grain borders. As a result, these regions often have superior material qualities including hardness, elongation, and strength. Poorer material qualities are typically seen in the parts of the casting that cool more slowly. It is possible to correlate cooling rates with material properties. As the section size increases, the intercellular pearlite/ carbide network becomes more extended and caused an increase in yield strength, which is mainly controlled by the structure of the matrix. As the cooling rate decreases, the pearlite/carbide zones are less uniformly dispersed in the structure, resulting in a softening of the matrix [2]. As the section size increases, the average spheroids diameter decreases. The chemical makeup of melts and nodulizers determined the section size influence on the pearlite content in the ductile iron castings' matrix. The thinner section contains more pearlite than thicker [7]. Thin-section ductile iron loses mechanical qualities, particularly ductility and toughness, as a result of the high cooling rate, which increases the number of carbides [3]. The quantity and distribution of ferrite in the microstructure have a significant impact on the mechanical characteristics of as-cast ductile iron. Elements like chromium, nickel, and copper improve the hardness of cast iron, whereas silicon decreases it [8].

METHODOLOGY

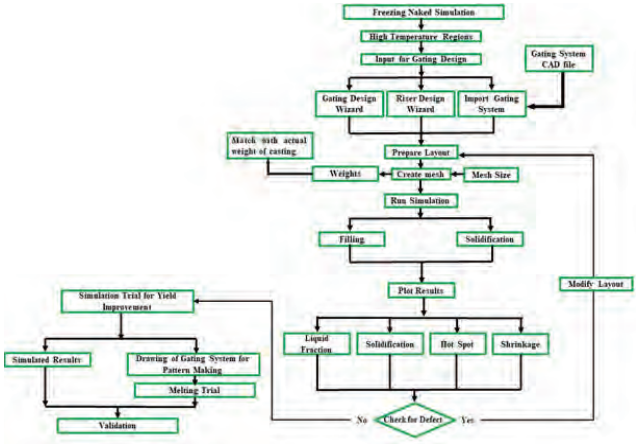


Fig. 1. Methodology Flowchart

For solidification simulation, the casting's CAD model is introduced into the virtual system. The solidification simulation is performed using the finite volume method-based software. To confirm adequate feeding for producing quality components, simulations are run [9]. The melting tests are conducted in a casting foundry. Correlation analysis is done on the defect and yield of both simulated and actual castings. Shrinkage and yield in the investigational castings are obtained by analysing the different parameters during the process [10]. The results are based on simulation and experimental results. The methodology used to perform the work is mentioned in Figure 1.

Calculations:

Gating system for ductile iron [11], Ac:Ar:Ag=1:3:3

Total cross section of ingate =Ag =3*Ac

$=3*8.06906*10^4\ m^2$

$=2.42071*10^3\ m^2$

Where,

No. of ingates = 1

Cross section of each ingate $= 2.42071*10^3\ m^2/1$

$=2.42071*10^3\ m^2$

Let,

Height of ingate = a

Width of ingate $=2a^2$

$2a^2 = 2.42071*10^4\ m^2$

$a^2 = 1.21035*10^4$

$a = 0.01102$ m

$a = 11.02$ mm

Height of ingate = 11.02 mm = 11

Width of ingate = 22 mm

D] Feeder Design:

Height =340.00 mm

Size = 390 mm

Volume = 1442.55 cm^3

$=1442.55*10^6$ mm

Mass = Volume *Density

$=1442.55*10^6*7300$

=10.53 kg

SIMULATION TECHNIQUE

Gathering the necessary component's data and sketching is the initial stage in the casting simulation process [12]. The material of the casting is ductile iron having tensile strength 500 N/mm2 with 7 % elongation. Shell molds of cope and drag must be prepared for the casting process. Sand covered with resin is utilized as the molding material. The medium frequency induction furnace used for melting has a 300-kilogram capacity and a temperature range of 1490 to 1500 degrees Celsius. Melted metal should be poured between 1380 and 1390 degrees Celsius. The chemical composition is checked by the spectrometer. The mold coats are given for achieving surface finish in the final castings. The gating system consists of multi-gates connected to common riser [10]. The pouring is done through the common feeder which is also acting as down sprue in this case. The 3D CAD model as per above layout of the part, gating system and riser are modelled using solid modelling program CATIA V5R16. All these models are saved in STL formats and then imported into the simulation environment [13].

Processing

The ASCII STL files are converted to binary STL formats. The binary STL model of casting, gating and feeding system are imported and assembled as per the existing layout [14]. Material properties are applied to the casting as ductile iron and shell mold respectively. The CAD model of existing layout of the casting is meshed with 1 mm node size and meshed model is then simulated for fast processing. This meshing and simulation are carried out using AutoCAST simulation software [15]. The meshing and simulations are carried out with 1 mm to arrive at final simulation results which are matching with actual casting layout.

Post Processing

The results are plotted by using in built criteria's like solidification time, liquid fraction, temperature gradient and material quality. The material quality criterion uses 0-1 scale for predicting density [16]. The value of density above 0.975 is treated as sound casting [17]. The isolated temperature regions above solidus temperatures indicates probable hotspots which may not be fed properly, ultimately will turn into local hotspots. It is possible to correlate cooling rates with material properties. The regions in castings which cool more slowly generally tend to have poorer material properties [18].

Existing Layout

The CAD model of existing layout is created using CATIA as shown in Figure 2.

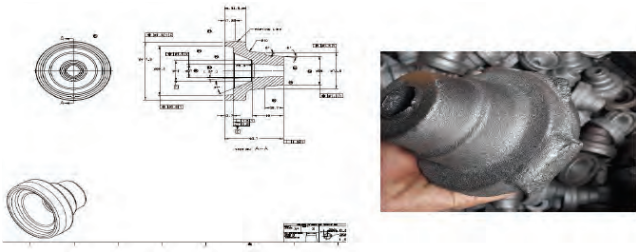


Fig. 2. The 3D CAD model and casting image

Simulation Trials

The trials are performed for different method designs are per the calculations [19]. Total three trials performed. Initial layout is prepared with the sprue, runners and ingates as per the calculations. The layout 2 is prepared with addition of feeders and the layout 3 is prepared with addition of sleeves on the feeders.

Layout 1

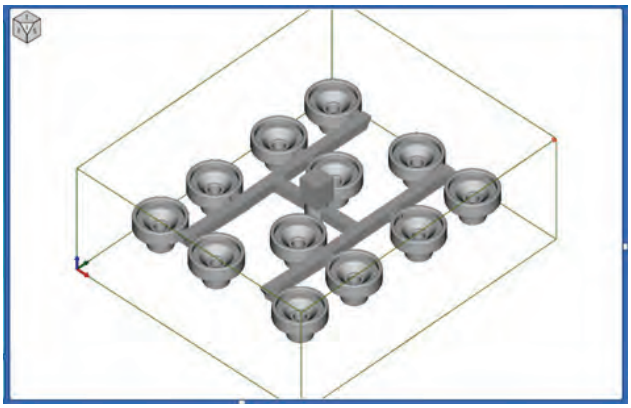


Fig. 3: Layout 1

In one box there are twelve differential casings as per the company layout shown in Figure 3.

The gating system with sprue, runner and ingates are designed as per the calculations and created in the simulation environment. The material and chemical composition are updated as per the standard [20]. All

the boundary conditions are applied like pouring time, pouting temperature and location of pouring.

Hotspot criteria before the simulation -

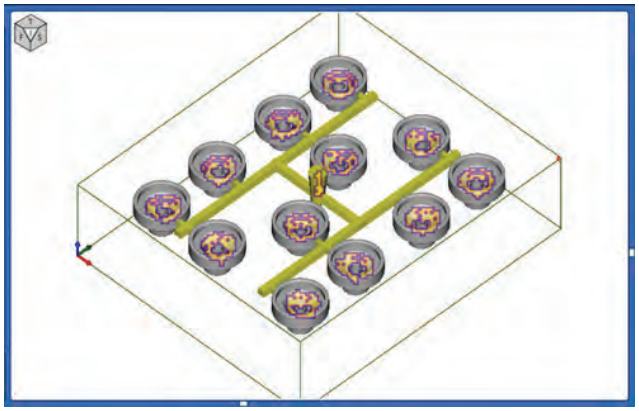


Fig. 4: Hotspot criteria before the simulation

The hotspot in the layout and castings are checked using hotspot criterion. The hotspot is checked before performing the simulation trial. The hotspots are the indication of high temperature regions. With the help of this criterion the feeding and gating system can be decided [21]. The Figure 4 shows the hotspots in the layout 1.

Solidification view of casting bunch -

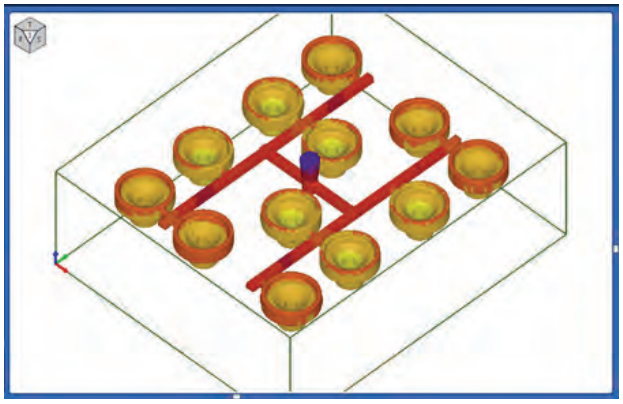


Fig. 5: Solidified view of Casting bunch for layout 1

Figure 5 displays the solidification view of the casting bunch following the simulation in the aforementioned photos. This has a low temperature (700°C) in the hollow portion and a high temperature at the bottom. Surfaces that readily come into contact with the outside world harden rapidly [22].

Color is a flaw in the temperature. Thus, following simulation, the real solidification in the casting lot may be effectively seen [23].

Liquid fraction view of casting bunch -

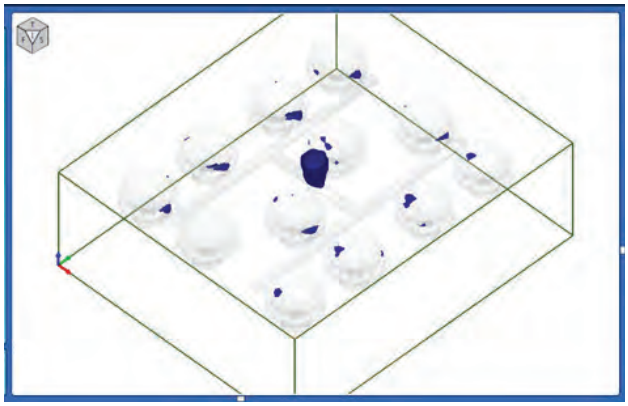


Fig. 6: Liquid Fraction plot for layout 1

Figure 6 above illustrates the need for a lower liquid percentage in the arrangement to ensure consistent casting quality. As seen in Figure 6, the liquid fraction plot on the differential flange's boss displays the final solidified portions. In actuality, basin runners are not included in differential cases. Therefore, they are not interfering with the casting's quality.

Shrinkage Plot

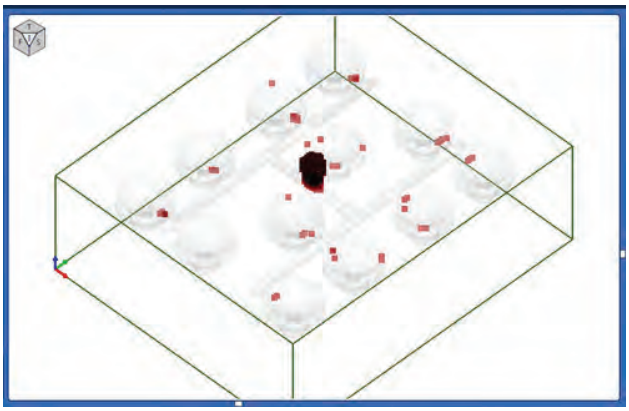


Fig. 7: Shrinkage Plot for layout 1

A portion of the metal shrinks once the solidification process is finished. The casting's shrinkage-prone sections are indicated by the dark pink spots in the figure above [24]. Figure 7 illustrates the shrinkage in the casting in the existing arrangement. The shrinkage is observed at the top boss of the casting to reduce the shrinkage and improve the yield. A new layout

is constructed by reducing the size of the runner and ingates in the existing configuration.

Layout 2

The simulation for layout number 2 is performed with the same procedure which is used for simulation of layout number 1. The steps in the simulation consist of:

1. Pre-processing

2. Processing

3. Post-Processing

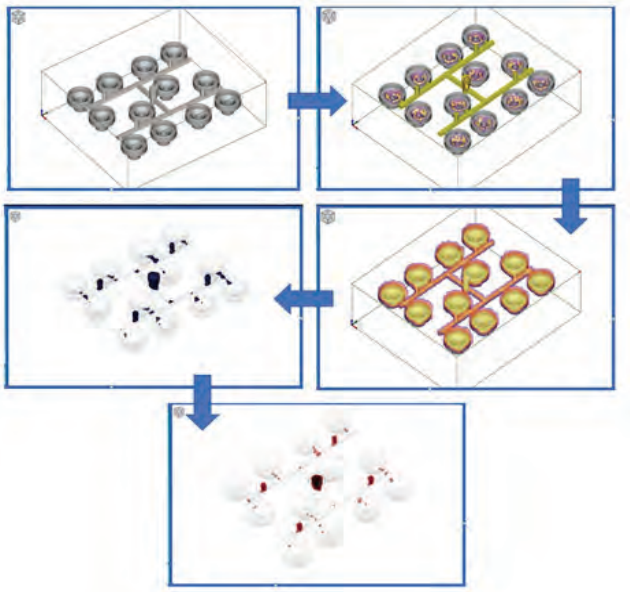


Fig. 8: Layout 2-Steps

All the steps for layout 2 are shown in Figure 8 including layout, hotspot, solidification, liquid fraction and shrinkage plots.

New layout size-

Mold Box volume - 469mm*459mm *438 mm

Mold volume - 894653.53 cm^3

Mold Weight - 138.67 kg

In the above image we can see the gating system arrangement of differential.

Mold size/mould length = 0.75

After adding feeders, the hotspot is still observed. The layout's hotspot is shown in the image above. Here, we adjust the feeder's size and volume to decrease the hotspot. Only their hotspot remains at the sprue, meaning that the metal is correctly solidified in the sprue's center. [25].

The solidification view of the casting is displayed prior to the simulation in the image above, and the maximum temperature (1540°C) and low temperature (1360°C) are delicate. It takes 1176 minutes to solidify. The temperature at different portions is displayed here. Different coolers code the temperature.

Figure 7 displays the solidification view of the casting bunch following the simulation in the aforementioned photos. This has a low temperature (700°C) in the hollow portion and a high temperature at the bottom. Surfaces that readily come into contact with the outside world harden fast.

The components' quality is demonstrated by shrinkage criterion [26]. The components' quality is higher when there is less shrinking. Shrinkage is shown in the hollow area in the picture above. Compared to the prior arrangement, there is less shrinkage in the casting. Therefore, this layout is superior than the old one. The final areas of the casting to harden are the dark blue areas. Compared to the prior arrangement, there was less shrinkage in the casting.

Layout 3:

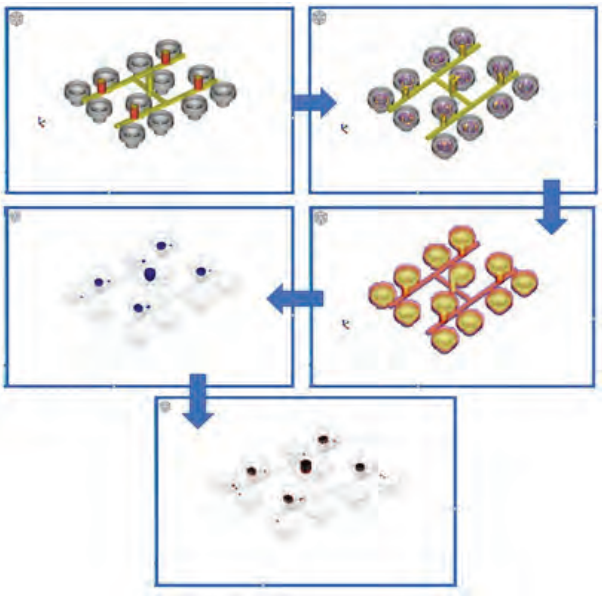


Fig. 9: Layout 3-Steps

There is casting shrinkage in the existing configuration. The top boss of the casting exhibits the shrinking. The existing arrangement is changed to decrease shrinkage and increase yield [27]. A new layout is created and the runner and ingate are made smaller. The different steps are shown in Figure 9.

The feeders are now equipped with sleeves to further minimize shrinkage from the casting. Feeders with sleeves are cast in layout number three.

We provide both feeders in this arrangement exothermic sleeves. The exterior size is 420 mm, meaning the feeder is 6 mm thick, and the sleeves are 110 mm tall. Exothermic sleeves lower the feeder's temperature losses. Because feeders do not cool quickly, molten metal in the feeders is supplied to the component for an extended period of time, reducing liquid fraction and shrinkage and ensuring correct component filling.

Solidification perspective It is preferable since, following simulation, we can see that the temperature in most of the regions of the above image is the same [28].

Liquid fraction view: Since the liquid fraction rate in the previous two configurations was unsuitable for quality, we used the sleeve in this arrangement, which led to a significant reduction in the liquid fraction [29]. They own a very little portion of the liquid fraction. So, this layout is better to our component. This decreased liquid percentage is visible in the figure above.

Shrinking plot: We need to minimize component shrinking; thus, we included a sleeve in this arrangement. As we can see in the figure above, the shrinkage is largely minimized, and the quality is higher than in other layouts [30]. With this arrangement, casting shrinkage is minimized.

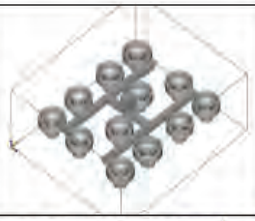
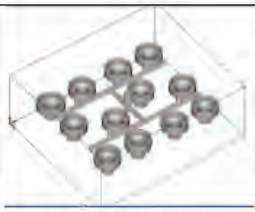
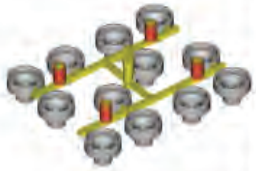
RESULTS AND DISCUSSION

The following conclusions were drawn from the current research work undertaken:

Simulation Analysis

The comparison of different parameters of existing casting layout and new suggested layout are tabulated in Table 1.

Table 1: Details of old and new casting layout

Sr. No.	Details	Layout 1	Layout 2	Layout 3
1	Layout Sketch			
2	Feeder and Gating	one sprue runner and ingates	Gating with reduced dimensions and feeders	Same gating with sleeves on feeder
3	Weight of Casting	2.82	2.82	2.82
4	Weight of Casting Bunch of 12	33.84	33.84	33.84
5	Weight of gating	7.72	4.49	4.49
5	Weight of Layout	40.56	38.33	38.33
6	Yield	**83.43 %**	**88.29 %**	**88.29 %**
7	Defect	Shrinkage	Shrinkage	No Shrinkage

CONCLUSIONS

1. The simulation results and experimental castings show that the location of feeding system plays a vital role in the casting solidification. The use of casting simulation process can be able to predict the exact matching of shrinkage porosity locations and its areas in the casting.
2. The new suggested layout is able to remove the defect from the casting. The shrinkage is removed from the casting after changing the gating system. In the new layout, the Gating weight is increased which is needed to assure defect free castings. This will increase the yield of the new casting layout.

Conflict of Interest and declaration

On behalf of all authors, the corresponding author attests that there has been no involvement that may give rise to concerns about bias in the work presented or in the findings, inferences, or opinions expressed in this manuscript.

FUNDING

For the work carried out and mentioned in this paper, no funding is received.

REFERENCES

1. Tavakoli, R., & Saeed, H. (2022). Simulation of solidification and shrinkage porosity in ductile iron castings using the thermal criterion function. Journal of Materials Processing Technology,287,116679. DOI: 10.1016/j.jmatprotec.2020.116679
2. Zhao, G., Zhang, W., & Wu, C. (2020). Prediction of shrinkage defects in ductile iron castings based on solidification simulation and experimental validation. Metals, 10(9), 1177. DOI: 10.3390/met10091177
3. Xie, Z., & Luo, Z. (2021). Solidification and shrinkage prediction for ductile iron castings using a novel simulation approach. Materials Science and Engineering: A, 823, 141764. DOI: 10.1016/j.msea.2021.141764
4. Pavlík, M., & Svoboda, J. (2021). Simulation of solidification and shrinkage in ductile cast iron with simultaneous porosity formation prediction. Journal of Alloys and Compounds, 877, 160387. DOI: 10.1016/j.jallcom.2021.160387
5. Xia, J., & Zhang, W. (2020). Advanced solidification simulation of ductile iron castings for shrinkage prediction and removal techniques. Casting, 33, 283–289. DOI: 10.1007/s00339-020-03614-0
6. Mikhaylov, A., & Petrov, E. (2022). Simulation of shrinkage porosity formation in ductile cast iron using solidification modeling. Metallurgical Research & Technology, 119(3), 307–312. DOI: 10.1051/metal/2022003
7. Zhu, C., & Zhou, C. (2021). Improved method for shrinkage cavity prediction in ductile iron castings. Journal of Materials Engineering and Performance, 30(7), 4860–4869. DOI: 10.1007/s11665-021-05896-6
8. Banda, D., & Kumar, P. (2021). Numerical simulation of shrinkage and porosity formation in ductile iron castings. Foundry Journal, 19(4), 237–245. DOI: 10.1177/10653670211007179
9. Chandrasekaran, M., & Ramakrishnan, R. (2022). Solidification simulation techniques for improving the mechanical properties of ductile iron castings. Journal of Manufacturing Processes, 67, 203–216. DOI: 10.1016/j.jmapro.2021.12.021
10. Wang, X., & Li, L. (2020). Shrinkage cavity prediction and its elimination for ductile iron castings using thermal analysis and simulation techniques. Computational Materials Science, 179,109676. DOI: 10.1016/j.commatsci.2020.109676
11. Li, X., & Zhang, J. (2021). Development of a simulation model for the prediction of shrinkage and porosity in ductile iron castings. Materials Research, 24(2), 141–146. DOI: 10.1590/1980-5373-MR-2020-0451
12. Qiu, S., & Liu, F. (2022). Prediction of shrinkage defects and optimization of gating system in ductile iron casting. Materials and Design, 213, 110337. DOI: 10.1016/j.matdes.2021.110337
13. Xie, J., & Ren, L. (2020). Numerical investigation on solidification shrinkage in ductile iron castings. Advanced Engineering Materials, 22(3), 1901584. DOI: 10.1002/adem.201901584
14. Cheng, L., & Xu, Y. (2021). A simulation approach for minimizing shrinkage and porosity in ductile iron castings using optimized cooling rates. Journal of Materials Science, 56, 3676–3686. DOI: 10.1007/s10853-020-05268-0

15. Petrik, J., & Blasko, P. (2021). Solidification simulation for shrinkage control in ductile iron castings: A case study approach. Procedia CIRP, 99, 51–56. DOI: 10.1016/j.procir.2021.01.096

16. Ishihara, K., & Ozawa, Y. (2022). Modeling of shrinkage and porosity prediction in ductile iron casting using an improved solidification simulation technique. Foundry Technology Journal,18(2),25–31. DOI: 10.1080/03602499.2022.1964579

17. Zhou, X., & Zhang, T. (2022). Application of solidification and shrinkage simulation for defect-free ductile iron casting. Journal of Cast Metals, 56, 110–116. DOI: 10.1016/j.jom.2022.02.014

18. Kumar, D., & Verma, A. (2022). Effect of solidification rate on the shrinkage and porosity in ductile iron castings: A numerical approach. Computational Materials Science, 195, 110741. DOI: 10.1016/j.commatsci.2020.110741

19. Sharma, S., & Khanna, P. (2020). Modeling and prediction of shrinkage porosity in ductile iron castings using simulation. International Journal of Cast Metals Research, 33(4), 230–238. DOI: 10.1080/13640461.2020.1757222

20. Zhao, Z., & Wu, D. (2021). Optimization of solidification conditions to reduce shrinkage porosity in ductile iron castings. Journal of Materials Science, 56, 1055–1063. DOI: 10.1007/s10853-020-05188-4

21. Peng, H., & Lin, Z. (2022). Solidification behavior prediction and shrinkage porosity elimination in ductile iron castings. Foundry Technology Journal, 20(6), 47–54. DOI: 10.1080/003262406.2022.1815199

22. Tian, Z., & Guo, Q. (2020). Study on the prediction and control of shrinkage in ductile iron castings by solidification modeling. Journal of Materials Processing Technology, 289, 116950. DOI: 10.1016/j.jmatprotec.2020.116950

23. Li, Z., & Li, Y. (2022). Application of solidification simulation in casting process design for reducing shrinkage in ductile iron castings. Journal of Materials Engineering and Performance,31(7),1421–1431. DOI: 10.1007/s11665-022-06134-5

24. Mack, L., & Biloni, J. (2021). Solidification simulations and shrinkage reduction in ductile iron castings using advanced molding techniques. Casting and Solidification, 34, 143–149. DOI: 10.1016/j.jom.2021.05.004

25. Liu, L., & Huang, Y. (2020). 3D simulation and validation of shrinkage behavior in ductile iron castings. International Journal of Metalcasting, 14(2), 105–113. DOI: 10.1007/s40962-019-00351-2

26. Cui, Z., & Yang, B. (2022). Enhancing solidification simulation for shrinkage prediction and mitigation in ductile iron castings. Journal of Foundry Science, 78, 1294–1303. DOI: 10.1080/03602499.2022.2068882

27. Feng, W., & Liu, X. (2020). A new simulation method for solidification and shrinkage prediction in ductile iron casting. Materials Transactions, 61(8), 1327–1333. DOI: 10.2320/matertrans.M2019129

28. Zhou, L., & Xu, X. (2021). Simulation of shrinkage defects in ductile iron castings based on the advanced solidification model. Foundry Review, 15, 55–62. DOI: 10.1016/j.foundrev.2021.04.007

29. Gupta, A., & Agarwal, S. (2021). Effect of solidification rate on shrinkage porosity in ductile iron castings. Materials and Design, 210, 110110. DOI: 10.1016/j.matdes.2021.110110

30. Cheng, L., & Jiang, Z. (2022). Simulation of shrinkage porosity in ductile iron castings and its reduction by cooling rate optimization. Materials Science Forum, 1012, 157–163. DOI: 10.4028/www.scientific.net/MSF.1012.157

Portable Water Desalination System Integrated with Ultra Filtration and Ultra Violet Units Using Fully Solar Energy

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ABSTRACT

The existences of humanity as well as its survival are inherently reliant fundamentally on water. Water is among the most ample resources on Earth which is covering approximately 75% of the total surface area. Earth's water is saline which is approximately 97% as found in oceans whereas remaining only 3% is available as freshwater. This little amount of freshwater which is existed mainly in poles in the form of ice, underground water, rivers and lakes fulfils the needs of both human and animal. The only virtually limitless sources of water are available in oceans but the salt content is very high. The problem of water scarcity could be solved by desalination of saline water of oceans and in brackish water bodies. Most of water desalination systems consume very high energy that require high-grade energy sources like electricity, gas, fossil fuels and oils.These processes are resulting carbon emissions that is contributing to ozone layer depletion and are responsible for health risks to humans. It also causes global warming, a critical issue that poses a threat to the life sustainability on Earth. Hence there is a need to implement eco-friendly energy sources to desalinate sea and brackish water.When heat to heat conversion is the prime concern, harnessing of solar energy is the most efficient and effective way. Thermal desalination process for fresh water production requires low temperature application. It involves one-time investment and can supply fresh water for a lifespan of nearly ten to fifteen years. In this paper, a portable water desalination system is designed and developed which is integrated with Ultra Filtration and Ultra Violet units. This newly designed prototype will utilize the solar energy for both evaporation of saline water and running the Ultra Violet unit by using solar panel used for electricity generation. The system design is very compact that requires small space. This low cost desalination system which is assembled with UF and UV units can meet the water requirement for small households and communities existing in coastal areas, islands and population residing near banks of the river where brackish water is available. The above desalination system can remove arsenic, fluorides, cadmium, mercury, coli form, virus and bacteria apart from dissolved sodium chloride.

KEYWORDS: *Solar radiation, Solar evaporation, Desalination, Ultra filtration, Ultra violet radiation, Water purification.*

INTRODUCTION

Many countries around the world are facing a significant shortage of naturally available freshwater resources. The demand for fresh water is expected to rise in the near future due to some burning issues like rising population , improved living standards of human beings and expansion of both industrial and agricultural productions. The available freshwater in rivers, lakes and groundwater sources is limited. Due to the above reasons freshwater supply as available from water bodies (rivers and lakes) and groundwater is reducing at an alarming rate in many regions around the world. The supply of fresh water in many areas around the world is now becoming a critical concern. In deserts and dry zones drinkable water is extremely limited, hence the availability of fresh drinking water is an important factor for establishment and survival of mankind. As water is vital for life, the utmost importance is easy access to safe drinking water. Water is one of the most abundant resources on Earth. Water is covering

about three-quarters of the earth's surface. Approximately ninety seven percent of the total water available in earth surface is salty water which is found mainly in oceans whereas remaining only three percent (around 36 million km³) is freshwater stored in glaciers, groundwater, rivers and lakes. This small percentage freshwater fulfils all water needs for humans and animals. Out of this limited freshwater nearly seventy percent freshwater is locked in glaciers, ice caps, permafrost and permanent snow. The remaining 30% of the freshwater is confined to underground water which is available at very depth and aquifers which is also hard to access. Both lakes and rivers preserve approximately 0.25% of all available useable freshwater whereas the freshwater reserve in lakes is more than that of rivers. Due to high salinity, seawater is not suitable for drinking purposes for human and animals. This high saline water can't be used for industrial and agricultural uses as it may corrode metals and reduce crop productivity. Due to limited supply of potable water, a large population around the world mainly those reside near beaches and islands face water scarcity [1]. The best solution of the freshwater scarcity is to remove salts from water available in oceans, rivers, lakes, seas and brackish water bodies that are unlimited sources of saline water by desalination method. There are many desalination plants which are already functional but they are costly and consume more energy. A review of recent advancements in technology and system design for desalination of saline had been conducted to address these challenges like cost, energy intensity etc. The purposes are like lowering the cost and enhancing the efficiency of desalination systems [2].By implementing a process which is thermodynamically reversible, every desalination unit can be made highly energy-efficient and this process is not dependent on any specific mechanism or the system employed [1]. For desalination of salt water conventional thermal desalination process emits both harmful and toxic gases into the environment resulting global warming i.e. global temperature rise. The global temperature rise may result in rising of water level in river, sea and ocean as well as ice cap melting in polar regions (both north and south poles). The rise in water level may threaten the ecosystem in islands, coastal regions and riverbanks. The small population living in these areas faces significant challenges because they rely on the land for survival, agriculture and tourism based economies. The global warming issue and the related devastating effects can be reduced by harnessing solar energy as a sustainable solution. Excessive fluoride consumption can cause dental issues and bone-related problems. Excessive fluoride consumption as per WHO guidelines is more than 1.5 mg/L of water. Long term intake of high fluoride levels may cause severe skeletal complications which may cause partial disability in human beings [3][4]. In India there are approximately eighteen thousand remote villages where the people do not have access to electricity due to unavailability of electric pole that holds electric transmission line to supply electricity. Power outages may last for 16–20 hours on a daily basis in some remote areas [5]. Hopefully there are abundant solar energy throughout the year that can be used for both direct or indirect heating purposes as well as to generate electricity by using solar panel to fulfil the needs of human beings. During 21st conference of parties (COP21) climate summit held in Paris, France where 121 countries were present, India inaugurated International Solar Alliance (ISA).The headquarter of the National Institute of Solar Energy (NISE) is located at New Delhi. The foundation stone was laid in January 2016 by PMs of India and France [6]. The participating countries including India are rich in solar heat throughout the year. The common goal of the ISA is that all the countries will work together to address energy needs by using solar power in manner that should be affordable, safe, convenient and sustainable. The use of clean and green (renewable) energy is very much important to meet the energy of the future as well as for the betterment of the earth as it does not produce harmful gases for the greenhouse effect [7]. The sun is the fundamental source of life and energy which plays a vital role to meet the cleaner and renewable energy alternatives. India is lucky because it receives uninterrupted solar radiation throughout the year. This radiation is quantified as more than three thousand hours of sunshine annually which is more than three hundred days. Sufficient solar radiation is received by nearly all the Indian regions. The value of average direct normal irradiation (DNI) falling on the earth if calculated annually will be 1156.39 W/m^2which is 5.4188 kWh/m^2/day. The annual average value of DNI varies from

country to country in the world whereas Rajasthan, Tamil Nadu and Karnataka like Indian states receive highest value [8].Globally some countries like Australia, Algeria, Botswana, Chile, Egypt, Libya, Mexico, Namibia, South Africa and Zimbabwe enjoy exceptional solar energy potential. In terms of regional average value the South Asia region ranks just behind the Middle East and North Africa (MENA) region. Highest solar insulation is received by the regions situated between Tropic of Capricorn and Tropic of Cancer among all regions in the world. Solar energy which is available from sun can be efficiently utilized for solar heating applications which are contributing to environmental sustainability as well as an initiative of use of green energy. Theoretically it's not impossible to get 100% thermal efficiency for converting solar energy to heat because as there is no obstruction for converting one form of heat to another form. However conversion of heat to work or other energy forms is not possible as it violates laws of thermodynamics. Access to pure drinking water is essential for both existence of life and sustainability. The growing demand for safe, pure and potable water can be obtained through large-scale desalination of high salt containing seawater, fluoride contaminated water, impure water and salted water to serve population reliably. Solar energy is one of the renewable energy sources which is clean as well as plentifully obtainable on earth. Solar energy can be utilized for desalination of water which is cost effective and the technology is very much practical. For effective harnessing of energy to heat, solar energy is the best one to use. There are several reasons behind the shortage of pure, clean and safe drinking water like lack of rain water during monsoon season and depletion of underground water reserves due to uncontrolled water lifting using large number of deep wells. Indian people in some regions are largely affected by significant orthopaedic disorders due to higher fluoride concentrations which is created by manmade activities like boring of deep tube wells for drinking water supply causing decrease in ground water levels [3, 4]. This burning issue may be addressed by commissioning solar powered desalination plants using surface water sources like seawater, saline water from rivers and lakes, brackish water bodies and harvested rain water. Like food for survival, fundamental necessity is ensuring easy access for safe drinking water to every corner around the world. Due to rising demand of water beyond sustainable level, the best solution to bridge the water supply gap is adoption of desalination of saline water. About 400 million people were dependent on desalinated water. It was projected that approximately 14% world population by the end of 2025 will be dependent on seawater for daily needs [9]. By 2030 the global water demand is expected to reach approx. 16,900 billion cubic meters (Bnm^3).The water shortfall by that time will be approx.2,400 billion cubic meters (Bnm^3).This water deficit may be addressed by using different desalination process that are economical and environment friendly. Desalination process operates at low temperatures. Department of New and Renewable Energy, GOI emphasized that desalination is a key focus area in advanced research on solar thermal energy. MNRE introduces national solar science fellowship programs to promote research by undertaking R&D for supporting progress in this field [10]. Current desalination plants are using processes like vacuum distillation, Reverse Osmosis or combination of both. But all the processes consume high amount of energy which is consuming significant amounts of electricity, gas etc. Water desalination process using solar thermal application can be broadly classified into two major categories like indirect and direct systems. Indirect desalination unit which is powered from solar energy mainly having two components like desalination unit and solar collector unit. Solar collectors of different types like flat plate, heat pipes, evacuated tubes etc. may be assembled for several thermal desalination methods. Indirect desalination processes can be categorised as vapour compression, multi- effect evaporation, multi- stage flash distillation and membrane distillation [11]. For large scale water desalination, the most energy efficient technique is RO that can achieve production efficiency of 1.8 kWh/m^3 [12]. Energy cost for multi -stage flash and multi-effect distillation processes can be reduced by using solar concentrators so that they can be used for small communities in rural and coastal areas. The water desalination system should be more portable, mobile, and compact in design to serve larger communities like schools, colleges etc. Evaporation and condensation processes occur within same device in direct desalination process which makes

it highly efficient for both household needs and small communities. To meet household demand, various configurations are developed that can meet 200 m^3/day clean water requirement [13]. The systems are water cone, water pyramid, single & double slope, triangular etc. Direct water desalination method produces water that fulfils WHO quality standards. To prevent aggressiveness, small amount of minerals are added. Solar stills are devices that are simple in design and cost effective, utilizes solar energy without the need for high-grade energy like coal, oil and electricity. Stills don't release harmful gases that may impact environment and they can be easily constructed and operated. There are several water desalination methods for supplying water to small communities and households. Solar stills are considered to be more economical in that situation. To measure performance of a single slope solar still, an experimental study was performed by considering various parameters like water colour, installation of a reflector, addition of black and red die separately, addition of charcoal pieces of different sizes and several floating surfaces having varying thickness of 6 mm, 10 mm, 3 mm and 15 mm and densities of 20 kg/ m^3 , 15kg/ m^3 , 24 kg/m^3 and 15kg/m^3 respectively [14]. Different depth of water was considered for the experimental result from 1 cm to 7 cm with an increment of 1 cm. The results show that dark coloured water heated up quickly as it absorbs higher amount of solar radiation than other. The maximum absorption is observed in case of a floating sheet having density of 20 kg/m^3 with thickness of 3 mm. The experimental result in combination of reflector, black dye and bigger size charcoal for 3 cm water depth is also satisfactory. A solar still is constructed with a basin which is black coloured of all the internal surfaces. The basin is filled with saline water up to certain death. A transparent inclined glass is covered on the still to facilitate passing of solar radiation inside the still as well as condensation of water on the glass. Incoming solar radiation heats up blackened liner that rises temperature of water kept inside the basin. Finally water is evaporated and gets condensed on the glass cover. Due to both temperature and partial pressure differences, water vapour gets condensed on the inner side of inclined transparent glass cover. The condensed water is collected in a container for further treatment if necessary [15]. The condensed water is pure and safe for use in both cooking and drinking purposes. In order to improve acceptability as well as to decrease mineral's aggressiveness, small amount of minerals like Cu, K, Mg, salt etc. are added [16]. Experimental studies on both active and passive type solar distillation systems was carried out by Tiwari et al. [17]. They suggested that double-slope passive solar stills are ideal as compared to other solar stills for providing fresh water to rural communities [18].They also implemented a computerized single-axis sun tracking system that will move from east to west. They found that water production was higher compared to the fixed-type solar still which is approximately by 22%. A parametric study was carried out on a conventional double sloped single basin pyramid solar still by Al-Hinai et al. [19]. The still's performance was assessed under optimal design conditions and the results indicated that average annual solar water generation is about 4 liters per square meter per day. A point focused elliptical shaped solar still was designed and developed by Nassar et.al [20]. Concave mirrors are attached to the still so that it concentrate incident sunrays to the still located at the focus and reflects the remaining rays. They experimentally tested its performance. To reduce normal boiling point temperature of incoming water 0.75 bar vaccum was initiated in solar still. Inside condenser, outlet condensed vapour acts as a water trap when it is entered into the vaccum pump. An innovative desalination system's experimental study that utilizes natural forces to create a vacuum was conducted by Yogi Goswami et al. [21]. The temperature at which water evaporates is reduced by vaccum. A flat plate solar collector is used for heating the water easily. Performance of simulated conventional still is inferior than experimental innovative solar still. The latent heat which is released during condensation can be reused in multiple stages. This heat aids in evaporation process in subsequent stages which is enhancing water production though principle of operation is same. The sun tracker system is used to rapidly increase the water temperature which can be further enhanced by the application of other materials like sponge cubes [22], various wick materials [23], a charcoal absorber [24], coal powder or dye that will be functioning as a black body. By flowing water and using cotton glazing, evaporation and condensation processes can be further accelerated.

A review on various parameters which is affecting the productivity of solar stills was conducted by Manikandan et al. [25] . Key factors like use of wick materials, phase changing materials, multiple effect processes, sand for heat storage, pre-heating of feed water, use of evacuated tube collectors and flat plate collectors may achieve optimal distillation. Kalogirou [26] reviewed different types of solar collectors that are used to maximize the potential to harness the solar thermal energy. The study also covers other aspects like their applications, performance and thermal analysis along with detailed technical specifications of a wide range of collectors. For various solar thermal applications these collectors are used like heating of water, desalination of water, space heating, water cooling, thermal processes, solar chemistry etc. The operation of a water pyramid is based on evaporation and condensation driven by temperature differences within the structure which utilizes simple solar technology. Sunlight provides required amount of heat energy to initiate evaporation of water. The designed what pyramid was suitable to recognise patent and received recognition from World Bank [27].This water pyramid also received Development Market Award 2006 for small scale application for its innovative design. Having a surface area of 650 m², the water pyramid setup can generate approximately 1,000 to 1,250 litres of distilled water which is sufficient to fulfil the daily fresh water requirements of hundreds of people. Additionally the system is also designed for solar distillation of brackish and rainwater in large scale. The distilled water complies with WHO's water quality standards for drinking purposes. The water cone is a seawater desalination device which is designed and tested by Stephan Augustin. It can effectively remove salt while preventing the transfer of harmful elements like arsenic, mercury and cadmium to the water cone. This low cost device is capable of producing 1.6 litres of purified water on a daily basis [28]. Water supplied by water cone has superior quality than local available water sources. In this paper a desalination system utilising thermal energy of solar radiation and integrated with UF & UV chamber is designed and prototyped. The UV unit is also solar powered. This system is portable, cost effective and also environment friendly which is very much suitable for the population residing near brackish water bodies, rivers and lakes having high salt contents and coastal areas.

METHODOLOGY

The water desalination system consists of a wooden still with a transparent glass cover to collect the solar radiation. One black metallic plate is placed on the bottom surface of the still to absorb the sun light. Remaining three surfaces are insulated properly to prevent heat from the still. Condensed vapor is collected in a container which is nearly free from all dissolved solids. The sample water is then further treated by passing through sediment filter, pre carbon, post carbon, mineral cartridge, UF and UV chamber for removing residual harmful particles and killing coliform, virus and bacteria respectively. To run the filtration unit one solar photovoltaic panel of capacity $50W_p$ (V_{max}=18.1 V, I_{max}=2.78 A) is used. The capacity of lead acid battery unit is 14 Ah (12 Volt). To obtain desired voltage of 24 VDC, two batteries are series connected having same capacity of 14 Ah to run booster pump. For removing sediment particles like sand and clay, desalinated water is passed inside sediment filter(s). To remove various unwanted components like chlorine, volatile organic compounds etc., sediment free water is passed through Pre carbon filter where odour is disappeared and taste is improved [29][30]. Post-carbon filter filters out even smaller particles present in water. Then water goes to UF membrane where bacterias, disinfectants and microorganisms are permanently destroyed. Mineral cartridge adds minerals like Mg, K, Ca and Cu that are useful for living organisms. Finally 99.99% micro-organisms are killed when water goes to UV chamber without adding any harmful chemicals.Fig.1,Fig.2 and Fig.3 represent available water desalination technologies, flow diagram of desalinated water passing through desalination stages and power transmission to run booster pump. Fig.4 shows the desalination stages inside the solar still.

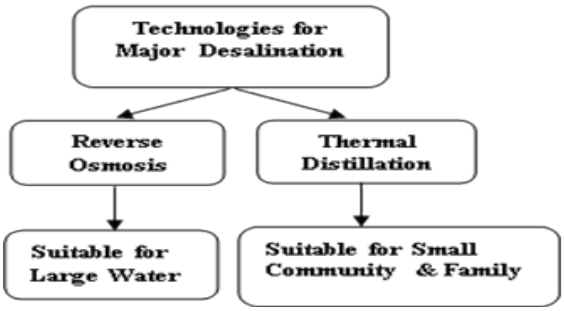

Fig.1: Available desalination technologies of Water

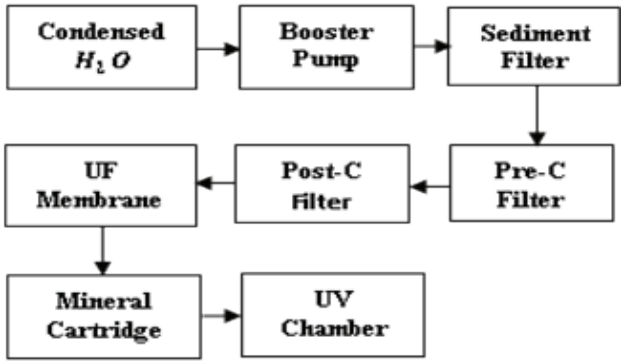

Fig.2: Flow of desalinated water through the unit

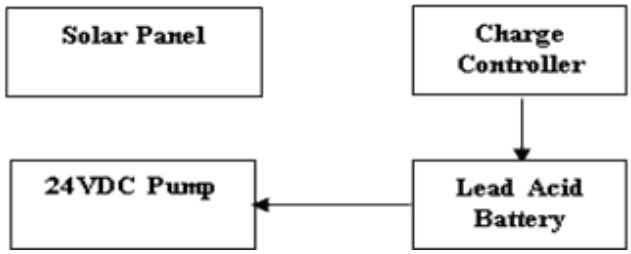

Fig.3: Power transmission through the system

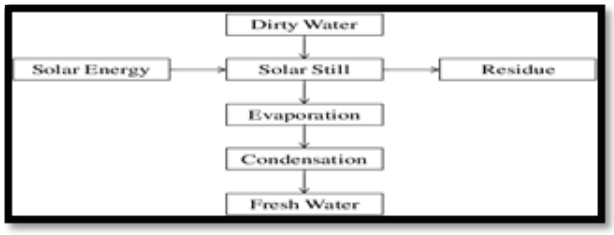

Fig.4: Solar Panel, battery, charge controller & pump

Experimental Setup

The experimental setup for condensed vapor formation and collection as well as several filters, booster pump for enhanced filtration are shown in below images. Fig.5 is showing the solar panel unit which is generating DC current from incident solar radiation which is stored in the battery. A charge controller unit as shown in Fig.6 is connected between solar panel and battery to control the battery charging when sufficient sunlight is available. This device also controls the reverse flow of current when intensity of solar radiation reduces or absence of any radiation during night time or cloudy atmosphere. The battery unit (Fig.7) is powering the 24VDC RO booster pump of capacity 28.8W. Fig.8 is showing filtering unit containing sedimentary filter, pre & post-carbon filter, UF, mineral cartridge and UV unit. Fig.9 & Fig.10 are demonstrating the solar still consisting of a wooden box with a transparent glass cover to pass the incident solar radiation. A black colored MS plate is placed on the bottom surface of the still to absorb incident sun light. All the internal surfaces are insulated properly to prevent heat from the still. The condensed vapor is collected and stored in a container which is nearly free from all dissolved solids.

Fig.5: Solar Panel, battery, charge controller & pump

Fig.6: Charge Controller of Battery

Fig.7: Power storage (Battery) Unit

Fig. 8: 24 Volt DC Booster Pump with Filters

Fig.9: Solar still made of wooden box with glass

Fig.10: Water vapor formation inside the still

Components' Specification

The specification of different components and no. of items used is shown in Table1.

Table 1: Components' Specification & Quantity

Component	Specification	Qty.
Solar PV Panel	50W_p (V_{max}=18.1 V, I_{max}= 2.78 A)	1
Lead Acid Battery	14 Ah,12V	2
Booster Pump	24VDC, I_{max}=1.2A	1

RESULTS AND DISCUSSIONS

The cost of different units used for the construction of solar still and purification unit is tabulated below.

Table 2: Cost (INR) of Different Components

Component	Price
Solar Panel (50W)	1800
Charge Controller	500
Charging Battery	2100
Booster Pump	2300
UF & UV Unit	500
Sedimentary Filter & Mineral Cartridge	500
Pre & Post-Carbon Filter	400
Solar Still & Accessories	1200
Total Price	9300

Both saline and desalinated water sample are tested using TDS meter and pH testing paper. Measurement of TDS and pH are shown in Fig.11 & Fig.12.

Fig.1 1: TDS testing of saline & desalinated water

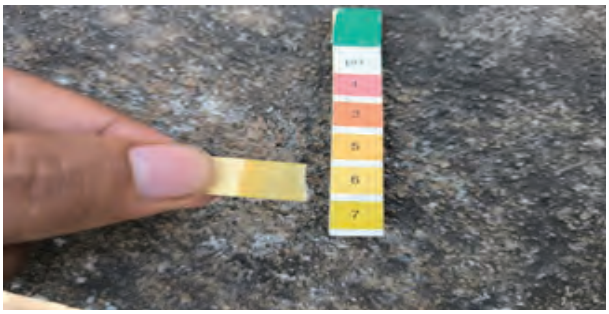

Fig. 12: pH testing of saline & desalinated water

Table 2 is showing the total cost of the purifier system which is approximately 9300 INR only. As it is one time investment considering very minimal amount of recurring cost, it is affordable for common people to get safe drinking water for their survival. Fig.13 to Fig.18 are showing TDS, pH, Turbidity, Dissolved Oxygen, Electrical Conductivity and Hardness values for six different samples before and after desalination process. The data obtained from the graphs proves that the desalinated water samples contain very less amount of contaminants compared to raw water. Hence it safe to be consumed as drinking water as well as for cooking purposes.

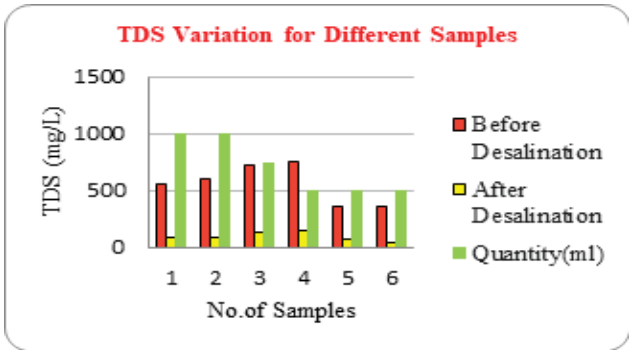

Fig.13:TDS values of saline samples before & after test

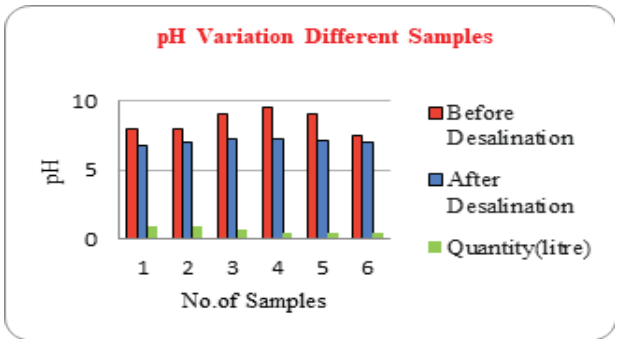

Fig.14: pH values of saline samples before & after test

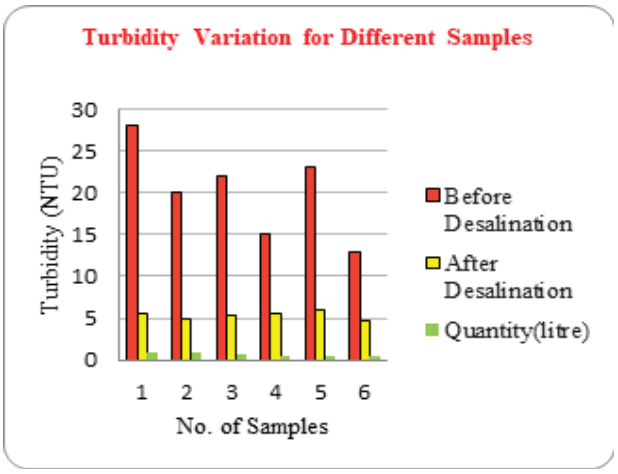

Fig.15: Turbidity of saline samples before & after test

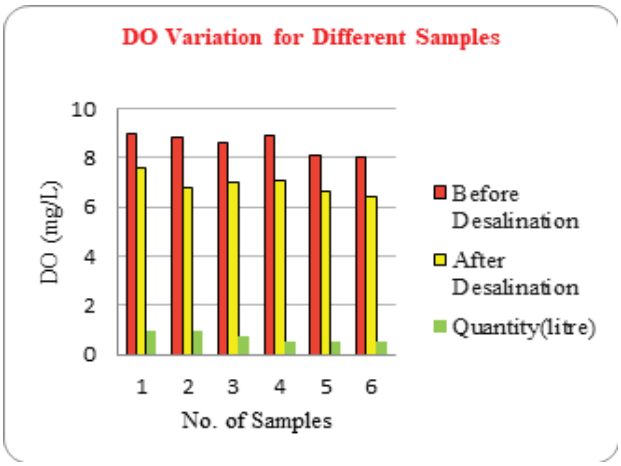

Fig.16: DO of saline samples before & after desalination

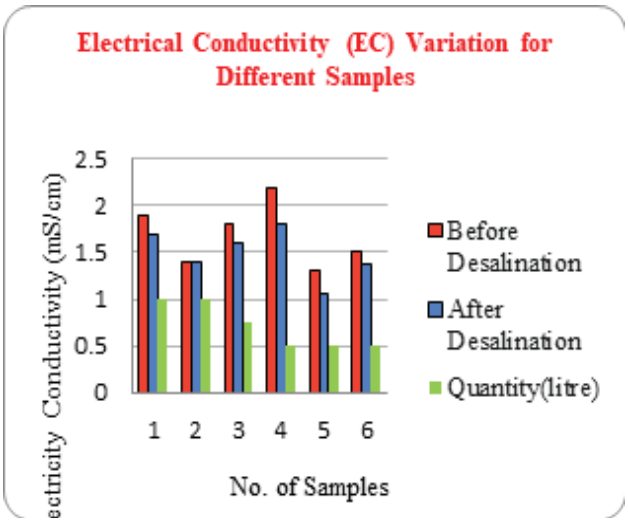

Fig.17: EC of saline samples before & after desalination

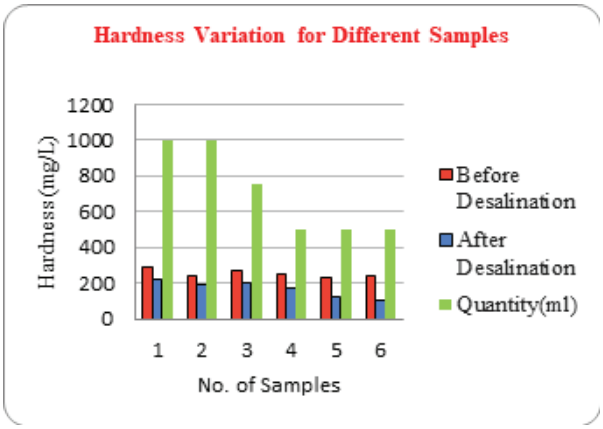

Fig.18:Hardness values of saline samples before & after test

CONCLUSION

This research focuses on the design and development of a solar based water desalination system that is integrated with ultra-filtration (UF) and ultraviolet (UV) treatment. The system is designed in such a way that it is lightweight, cost effective and eco-friendly. A solar powered booster pump is used to maintain a steady flow through purification unit containing sediment filter, pre & post carbon filter, UF & UV chamber. Use of solar power driven pump makes the system silent and completely free from carbon dioxide or other harmful gas emissions. Its compact design solves problems related to space limitation. The purified water shows accepted results of TDS, pH, Dissolved Oxygen, Total Hardness, Turbidity and Electrical Conductivity as recommended by both BIS and WHO and it is safe to drink. This system is particularly suitable for the population residing near coastal areas, brackish water bodies, rivers and lakes having high salt contents.

REFERENCES

1. Shannon MA, Bohn PW, Elimelech, Menachem, Georgiadis JG, Mariñas BJ, Mayes AM, "Science and technology for water purification in the coming decades", Nature 2008, 452(2), pp.187–200.
2. Elimelech M, Phillip WA," The future of seawater desalination :energy, technology and the environment 2012", Science 2011,vol.333, no.2, pp.712–717.
3. WHO, Water-related diseases (http://www.who.int/water_sanitation_health/ diseases/fluorosis/ en/).
4. Thole B, ''Ground water contamination with fluoride and potential fluoride removal technologies for east and southern Africa''.
5. Desalination & water purification technologies, Bhabha Atomic Research Centre. (http://barc.gov.in/publication/eb/desalination. Pdf).
6. International solar alliance (http://www.intsolar alliance. org/ index.html).
7. Narendra Modi,G20 summit 2015 (https://www.youtube.com/watch?v=T-o5Fmz ARHE)
8. Nrel- India solar resource maps & data (updated march 2016) (http://www.nrel.gov/ international /images/india_dni_annual_2016-01.jpg).
9. Das R, Ali ME, Hamid SBA, Ramakrishna S, Chowdhury ZZ. Atlas award: Quenching the world's thirst for seawater (2014), Desalination (https:// www.elsevier.com/connect/atlas-award-quenching-the-worlds-thirst-forseawater).
10. Mnre (http://mnre.gov.in/information/current-notices).
11. Shatat M, Worall M, Riffat S, "Opportunities for solar water desalination worldwide: review''.
12. Cohen-Tanugi D, Grossman JC ,"Water desalination across Nano porous graphene'', Nano Lett 2012,12(7), 3602–8.
13. Saleh A, Qudeiri J, Al-Nimr M, "Performance investigation of a salt gradient solar pond coupled with desalination facility near the dead sea", Energy 2011,36(2),922–31.
14. El-Haggar S, Awn A," Optimum conditions for a solar still and its use for a greenhouse using the nutrient film technique'', Desalination 1993, 94(1), 55–68.
15. Sharon H, Reddy K, ''A review of solar energy driven desalination technologies", Renew Sustain Energy Rev 2015, 41,1080–118.
16. Guidelines for drinking-water quality, World Health Organization .
17. Abdallah S, Badran O, ''Sun tracking system for productivity enhancement of solar still'', European Desalination Society and Centre for Research and Technology Hellas (CERTH), Sani Resort, 22-25 April 2007, Halkidiki, 220 (13), 669–676, 2008.
18. Kumar S, Tiwari G, ''Life cycle cost analysis of single slope hybrid active solar still'',Application Energy 2009, 86(10), 1995–2004.

19. Al-Hinai H, Al-Nassri M, Jubran B, ‘‘Effect of climatic, design and operational parameters on the yield of a simple solar still’’, Energy Conversion Management, 2002,43(13),1639–50.

20. Nassar YF, Yousif SA, Salem AA, ‘‘The second generation of the solar desalination Systems’’, Desalination 209 (13), 177–181, 2007, The Ninth Arab International Conference on Solar Energy (AICSE-9), Kingdom of Bahrain.

21. Al-Kharabsheh S, Goswami D, ‘‘Experimental study of an innovative solar water desalination system utilizing a passive vacuum technique’’, Sol Energy 2003,75(5),395–401.

22. Abu-Hijleh BA, Rababah HM, ‘‘Experimental study of a solar still with sponge cubes in basin’’, Energy Conversion Management 44(9),1411–18,2003.

23. Murugavel KK, Srithar K. ‘‘ Performance study on basin type double slope solar still with different wick materials and minimum mass of water’’, Renew Energy 2011, 36(2), 612–20.

24. Kumar BS, Kumar S, Jayaprakash R, ‘‘Performance analysis of a type solar still using a charcoal absorber and a boosting mirror’’, Desalination 2008, 229 (13), 217–30.

25. Prakash P, Velmurugan V, ‘‘Parameters influencing the productivity of solar stills a review’’, Renew Sustain Energy Rev 2015, 49, 585–609.

26. Kalogirou SA, ‘‘Solar thermal collectors and applications’’, Prog Energy Combust Science 2004, 30(3), 231–95.

27. Aqua-aero water systems water pyramid 2007 (http://www.aaws.nl/water pyramid).

28. Watercone 2001 (http://www.watercone.com).

29. Moustafa Elshafei, Anwar Khalil Sheikh, Naseer Ahmad, “Directly Driven RO System by PV Solar Arrays”, Open Journal of Applied Sciences, 2013, 3, 35-40.

30. Esmail M.A. Mokheimer, Ahmet Z. Sahin, Abdullah Al-Sharafi, Ahmad I. Ali, (2013) “Modeling and optimization of hybrid wind–solar-powered reverse osmosis water desalination system in Saudi Arabia”, E.M.A. Mokheimer et al. / Energy Conversion and Management 2013,75, 86–97.

Preserving Traditional Foods through Sustainable Tourism: A Review with Reference to Tamil Nadu

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ABSTRACT

Traditional foods are far more than culinary products; they are living repositories of cultural identity, indigenous knowledge, ecological wisdom, and collective community memory. However, the accelerating forces of globalization, urbanization, changing consumer lifestyles, and the expansion of industrialized food systems have placed many traditional food practices at risk of decline and disappearance. In the Indian state of Tamil Nadu, renowned for its rich and diverse culinary heritage shaped by centuries of history, geography, agriculture, and cultural traditions, the preservation of traditional foods has emerged as an important challenge and opportunity. Against this backdrop, sustainable tourism offers a promising pathway for safeguarding culinary heritage while simultaneously fostering economic development and community well-being. This paper explores the role of sustainable tourism as a culturally sensitive and economically viable mechanism for the preservation, promotion, and revitalization of traditional foods in Tamil Nadu. Employing a PRISMA-guided Systematic Literature Review (SLR) methodology, the study critically examines and synthesizes findings from twenty-five peer-reviewed scholarly publications published between 2015 and 2025. The selected literature was analyzed through thematic synthesis, resulting in five interconnected themes: (1) traditional foods as expressions of cultural identity and heritage, (2) sustainable tourism as a tool for food heritage conservation, (3) the significance of policy interventions and community participation, (4) socio-economic contributions of culinary heritage to local development, and (5) lessons from international best practices and comparative global experiences. The review reveals that sustainable tourism initiatives including culinary tourism circuits, food heritage trails, agritourism experiences, geographical indication (GI)-tagged product promotion, traditional cooking workshops, farm-to-table experiences, and community-led food festivals play a significant role in preserving traditional food knowledge and practices. These initiatives not only contribute to the documentation and transmission of culinary traditions across generations but also create opportunities for income generation, entrepreneurship, employment creation, and rural development. Furthermore, the findings highlight the critical importance of active community engagement, supportive policy frameworks, destination branding, and collaborative governance involving government agencies, tourism stakeholders, local producers, and cultural organizations. The study proposes a conceptual framework that positions traditional foods at the intersection of cultural preservation, sustainable tourism development, community empowerment, and economic resilience. The framework illustrates how food heritage can function as both a cultural asset and a development resource, contributing to the long-term sustainability of local communities. Additionally, the paper provides strategic policy recommendations aimed at strengthening culinary heritage conservation through tourism planning, capacity building, digital marketing, heritage education, and the protection of indigenous food systems. The study aligns with and supports the objectives of the United Nations Sustainable Development Goals (SDGs), particularly SDG 8 (Decent Work and Economic Growth), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production). By bridging the fields of

culinary heritage, sustainable tourism, and cultural sustainability, this research contributes to an emerging yet underexplored area of heritage tourism scholarship. It offers valuable theoretical insights and practical guidance for policymakers, tourism planners, researchers, heritage practitioners, and local communities seeking to ensure the long-term preservation and sustainable utilization of Tamil Nadu's rich and diverse traditional food heritage in an increasingly globalized world.

KEYWORDS: *Traditional foods- culinary heritage- sustainable tourism- cultural sustainability.*

INTRODUCTION

There is something quietly profound about the way a community feeds itself. The ingredients it chooses, the techniques passed from grandmother to grandchild, the rituals that frame a shared meal, all of these are, in the deepest sense, cultural acts. Food is not merely nutrition; it is a living record of a people's relationship with their land, their history and each other. Yet in a world accelerating towards standardisation, many of these local food traditions are disappearing faster than they can be documented, let alone celebrated.

The pressures driving this erosion are well-understood, globalisation has introduced uniform food products into once-distinct culinary landscapes; urbanisation has drawn younger generations away from agrarian foodways and the commercial logic of the tourism industry has, in many cases, replaced authentic regional dishes with sanitised, globally palatable alternatives. The result is a gradual flattening of culinary diversity that mirrors, and in many ways reinforces, broader processes of cultural homogenisation. Against this backdrop, sustainable tourism has emerged as a field of genuine promise. Unlike conventional mass tourism which often commodifies culture in superficial ways sustainable tourism, when thoughtfully designed, can channel visitor interest into the protection of the very traditions that make a destination worth visiting. Gastronomy and food tourism, in particular, have grown into significant sectors of the global tourism economy. As (UNWTO 2023) indicates, over 30% of travellers now consider gastronomy a primary motivation in their destination choice, a figure that represents both an economic opportunity and a conservation imperative for communities whose food traditions are at risk. Tamil Nadu offers an especially rich context for examining this relationship. The state's culinary landscape is extraordinarily varied, encompassing the intensely spiced curries of Chettinad, the millet-based staples of Kongunadu, the temple cuisine traditions of the Kaveri delta, the seafood cultures of the coastal districts and the tribal food systems of the Nilgiris and Kolli Hills. Dishes such as Kuzhi Paniyaram, Millet Pongal, Kumbakonam Filter Coffee and Madurai Jigarthanda are not merely popular foods, they are cultural texts, encoding centuries of agricultural practice, ecological knowledge and communal ritual. And yet, despite this extraordinary wealth, Tamil Nadu's traditional culinary heritage has received comparatively little systematic attention within sustainable tourism scholarship, which has tended to focus on the state's temple circuits and built heritage rather than its living food traditions.

This paper seeks to address that gap, through a PRISMA-guided systematic literature review, it synthesises what is currently known about the relationship between traditional food preservation and sustainable tourism development in Tamil Nadu, situating local evidence within broader global and Indian comparative frameworks. The review is not merely descriptive, it aims to identify what works, what is missing and what kinds of policy and community-level action might more effectively translate Tamil Nadu's culinary wealth into a durable foundation for cultural sustainability and inclusive development.

The paper is structured as follows, section 2 reviews the relevant literature across five thematic domains, section 3 describes the methodology, section 4 presents and discusses the findings, including a proposed conceptual framework, section 5 offers conclusions and policy recommendations. Throughout, the paper maintains a concern not just for academic rigour but for the human dimensions of the issue the women who guard traditional recipes, the farmers who cultivate heritage crops, and the communities for whom food is inseparable from identity. This paper contributes to the academic and policy debate about heritage tourism in three interconnected way, it connects culinary identity

to sustainable tourism frameworks in the specific context of Tamil Nadu, it proposes a conceptual model for culinary heritage preservation that is grounded in existing evidence, and it offers policy perspectives tied to the UN Sustainable Development Goals, specifically SDG 8 (Decent Work and Economic Growth), SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production).

LITERATURE REVIEW

Within this framework, (Nagina, Kaur and Bhalla 2025) argue persuasively that the preservation of traditional recipes goes well beyond the act of writing them down. Genuine culinary preservation, they contend, requires embedding food practices within community life, creating conditions in which knowledge is transmitted intergenerationally and celebrated publicly rather than archived and forgotten. Their analysis of community-based culinary tourism initiatives across South Asia suggests that the most successful preservation efforts are those in which local communities are active custodians rather than passive beneficiaries. (Kavitha and Ravi 2024) develop a related argument in the context of destination branding, demonstrating how culinary heritage when authentically represented and community-managed, can function as a distinctive product that reinforces local identity while attracting culturally motivated visitors. The authors are careful to distinguish between superficial food tourism, which reduces cuisines to novelty items for visitor consumption, and deeper forms of culinary engagement that involve learning, participation and reciprocal exchange. This distinction carries significant practical implications for how tourism programmes are designed and evaluated.

(Kumar, Nag, Kumar and Sharma 2025), drawing on evidence from gastronomy tourism initiatives in Himachal Pradesh, further demonstrate the link between culinary identity and community empowerment. Their study shows that when tourists engage meaningfully with local food traditions, through hands-on cooking experiences, visits to local farms and conversations with food producers, the social and economic returns accrue more equitably to local communities than in conventional tourism models. The Himalayan evidence they provide is directly relevant to Tamil Nadu's own regional food cultures, particularly in areas such as Chettinad and Kongunadu where food traditions are deeply embedded in landscape and livelihood.

What emerges from this cluster of literature is a compelling case for treating culinary heritage as living capital, dynamic, community-held and capable of generating genuine cultural and economic value rather than as a fixed set of recipes to be archived. The challenge, as the literature makes clear, is to create institutional and policy conditions that allow this capital to be deployed sustainably.

(Iniyan 2015), in one of the earlier systematic studies of tourism and cultural heritage in Tamil Nadu, found that the integration of local food into heritage tourism itineraries significantly increased visitor satisfaction and extended average length of stay. The study drew on survey data from heritage tourists at major sites across the state and identified food experiences particularly those involving interaction with local cooks and market visits as among the most valued and memorable elements of the tourist experience. This finding is important because it suggests that the demand for authentic culinary engagement already exists within Tamil Nadu's visitor base; what is often lacking is the supply-side infrastructure to meet it.

(Chera 2020), in a richly textured doctoral study of food practices in Madurai, explored the role of women as primary custodians of traditional cooking knowledge in Tamil Nadu. Her research documents how the daily practice of cooking often invisible to formal tourism economies is in fact a profound act of cultural reproduction, maintaining not just recipes but the ecological knowledge, seasonal awareness and communal values embedded in them. (Chera 2020) argues that any serious approach to culinary heritage tourism in Tamil Nadu must centre the women who hold this knowledge, creating economic conditions that recognise and reward their contribution rather than extracting its cultural value without compensation.

(Yoganandham 2024) extends this argument to the rural tourism context, demonstrating through case studies from Tamil Nadu's agrarian hinterland that village-level tourism programmes can serve simultaneously as food heritage preservation mechanisms and rural development tools. His analysis identifies a series

of conditions under which this dual function works effectively including strong community ownership of the tourism product, supportive local government, and linkages to urban markets through digital platforms and conditions under which it tends to fail, notably when external intermediaries capture the majority of economic returns.

The most detailed recent account of agritourism as a vehicle for culinary heritage preservation in Tamil Nadu (Sennimalai, Rao and Sivakumar 2025). Their supply-side analysis of agritourism enterprises across the state reveals that farms offering traditional food experiences including heirloom crop cultivation, traditional processing methods and communal cooking tend to attract visitors with a strong interest in cultural learning and a higher willingness to pay than those offering purely recreational experiences. Significantly, the study also finds that participation in agritourism creates incentives for farmers to maintain traditional crop varieties and food preparation techniques that might otherwise be abandoned in favour of more commercially streamlined alternatives.

METHODOLOGY

Research design

This paper employs a Systematic Literature Review (SLR) approach to consolidate and critically assess existing scholarship on traditional foods, culinary heritage and sustainable tourism in Tamil Nadu. The SLR method was selected for its transparency and reproducibility: by following a structured protocol for searching, screening and analysing literature, it minimises the risk of selection bias and enables future researchers to build on or challenge the findings presented here (Tranfield, Denyer and Smart 2003). The review focuses exclusively on secondary data, synthesising evidence from peer-reviewed academic papers, credible institutional reports and scholarly book chapters without engaging in primary fieldwork. This approach is appropriate for a paper whose aim is to map an emerging research domain and identify its key themes, gaps and policy implications rather than to generate new empirical data.

RESEARCH OBJECTIVES

The review was guided by four specific objectives:

1. To examine how sustainable tourism can serve as a mechanism for the conservation of culinary heritage in Tamil Nadu.
2. To identify best practices and comparative examples from India and internationally where culinary heritage has been effectively linked with sustainable tourism.
3. To synthesise existing literature, map thematic clusters and identify significant research gaps in this domain.
4. To propose a conceptual framework for the integration of traditional food systems into sustainable tourism policy.

DATA SOURCES AND SEARCH STRATEGY

The search for relevant literature drew on five primary databases: Scopus, Web of Science, Google Scholar, ResearchGate and ScienceDirect. In addition, specialist databases were consulted, including the UNWTO eLibrary and FAO Food Heritage Reports, to ensure that relevant policy documents and institutional reports were captured alongside peer-reviewed academic literature. The search was conducted between January and March 2025.

Search keywords and strings

The search employed a combination of controlled vocabulary terms and free-text keywords, structured as follows:

“Traditional Foods / Culinary Heritage / Food Heritage / Gastronomy Tourism” AND “Sustainable Tourism / Responsible Tourism / Cultural Tourism” AND “Tamil Nadu / India”

Filters were applied to restrict results to: publication years between 2015 and 2025; document types including journal articles, peer-reviewed book chapters and conference proceedings; the English language only; and the following disciplinary fields: tourism management, cultural studies, sustainable development and food heritage. The initial search yielded 312 records across all databases.

Inclusion and exclusion criteria

To maintain relevance and quality, a systematic set of inclusion and exclusion criteria (Table 1) was applied at each stage of the screening process.

Table 1: Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Geographic focus	Studies on India, Tamil Nadu or comparable Asian contexts	Non-Asian or geographically irrelevant regions
Thematic relevance	Culinary heritage, traditional foods, sustainable tourism, gastronomy or rural tourism	Studies unrelated to tourism, cuisine or sustainability
Publication type	Peer-reviewed journal articles, book chapters and credible institutional reports	News articles, blogs and dissertations without peer review
Timeframe	2015–2025	Publications before 2015
Language	English	Non-English sources

After applying these criteria across three screening stages title and keyword screening, abstract screening and full-text review twenty-five studies were retained for thematic analysis. Table 2 summarises the PRISMA-guided screening process.

Table 2: PRISMA-guided screening process

Stage	Action	Records
Identification	Records identified through database searching (Scopus, Web of Science, Google Scholar, ResearchGate, ScienceDirect)	312
Screening	Duplicates removed; titles and abstracts screened against inclusion/exclusion criteria	178
Eligibility	Full-text articles assessed for thematic relevance and methodological quality	54
Inclusion	Studies included in final qualitative synthesis	25

Data extraction and analysis

Information from each of the twenty-five included studies was extracted manually and recorded in a structured spreadsheet. Each paper was coded according to author(s) and year; geographical focus; research design and methodology; key findings; relevance to the Tamil Nadu context; and emergent themes. A qualitative content analysis was then applied to identify recurring patterns, conceptual relationships and thematic clusters across the literature. Four major themes emerged from this process: culinary identity and heritage; sustainable tourism as a conservation mechanism; community empowerment and policy; and socio-economic dimensions.

Validity and reliability

The validity of the review rests on several features of the methodology. The use of PRISMA guidelines and multiple databases reduces the risk of selection bias, while cross-validation between authors at the coding stage minimised interpretive subjectivity. Included studies were assessed for quality according to three criteria: journal impact and peer-review status; conceptual relevance to the review's research objectives; and methodological soundness. The review also drew on the SALSA framework (Search, Appraisal, Synthesis, Analysis) as an organising structure for the literature synthesis process, ensuring consistency across all stages of the analysis.

Ethical considerations

Since this review is based entirely on secondary data drawn from published literature, no human participants were involved and no primary ethical concerns arise. All cited authors have been appropriately acknowledged throughout the paper, consistent with established norms of academic integrity. No conflicts of interest were identified by the authors.

Limitations

The review carries several limitations that should be acknowledged. First, the restriction to English-language publications means that potentially relevant scholarship published in Tamil and other regional languages is

excluded, which may introduce a systematic bias against locally produced knowledge. Second, the exclusion of grey literature and unpublished reports means that evidence from community organisations, NGOs and government agencies that has not entered the formal academic record is not captured. Third, the relatively limited body of TN-specific culinary heritage literature in global databases means that the review relies, in some sections, on evidence from comparable Indian and Asian contexts that may not translate perfectly to the Tamil Nadu situation. These limitations are partially offset by the breadth of databases consulted, the use of triangulation across multiple sources and the integration of evidence from multiple levels of analysis local, regional, national and international.

FINDINGS AND DISCUSSION

Overview of reviewed literature

The twenty-five studies included in this review span a decade of scholarship (2015–2025) and collectively paint a picture of a field that has grown considerably in both volume and sophistication during that period. Earlier studies tend to be descriptive and exploratory, establishing basic empirical connections between food, heritage and tourism. More recent work is increasingly analytical and policy-oriented, engaging with frameworks such as the Sustainable Development Goals, GI certification and intangible cultural heritage conventions.

Geographically, the literature is concentrated in the south Indian context with Tamil Nadu, Kerala and Karnataka featuring most prominently but draws on comparative evidence from Himachal Pradesh, Rajasthan and several international contexts. Methodologically, the studies are diverse, ranging from ethnographic fieldwork and qualitative case studies to bibliometric analyses and systematic reviews. This diversity is a strength of the literature base, allowing for triangulation across methods and contexts.

Tamil Nadu's characteristic culinary subcultures Chettinad, Kongunadu, Madurai, temple cuisine and the tribal food systems of the highlands recur as focal points across multiple studies, confirming both their distinctiveness and the scholarly interest they have attracted. At the same time, the literature consistently identifies a significant gap between the richness of Tamil Nadu's culinary heritage and the limited degree to which it has been systematically integrated into sustainable tourism policy and practice.

Thematic insights from the literature

Traditional food as cultural memory

Perhaps the most fundamental finding to emerge from the literature is the understanding of traditional food not simply as cuisine but as cultural memory a living record of agricultural practice, ecological knowledge and community values accumulated over generations. (Nagina, Kaur and Bhalla 2025) and (Kavitha and Ravi 2024) both underscore this point, arguing that what is at risk when traditional recipes disappear is not merely a culinary technique but an entire way of knowing and relating to place.

This framing has significant implications for how we think about preservation. If traditional foods are understood as cultural memory rather than consumer products, then the appropriate preservation framework is one that emphasises living practice, community agency and intergenerational transmission rather than museum-style documentation. (Kumar, Nag, Kumar and Sharma 2025) illustrate this distinction effectively, showing that communities in which traditional food practices are embedded in active tourism experiences tend to maintain higher levels of cultural vitality than those in which food traditions have been reduced to heritage performances for visitor consumption. The PRISMA synthesis of reviewed studies reveals that 36% of the included papers identify traditional food heritage as a significant lever for enhancing local tourism competitiveness a finding that speaks to both the cultural and economic dimensions of culinary preservation.

Sustainable tourism as a conservation tool

A second major theme in the literature concerns the conditions under which sustainable tourism can function as an effective mechanism for culinary heritage conservation. The evidence is broadly positive but contextually specific: tourism does not automatically preserve food traditions; it does so only when designed with community benefit as a primary objective and authenticity as a non-negotiable standard.

(Iniyan 2015), (Chera 2020) and (Yoganandham 2024) collectively establish the baseline case for community-based and rural tourism as vehicles for food heritage preservation in Tamil Nadu, demonstrating increased visitor satisfaction, stronger economic returns to local producers and measurably higher motivation among communities to maintain traditional food practices when tourism is well-managed. (Sennimalai, Rao and Sivakumar 2025) extend this evidence base to agritourism, showing that farm-based food experiences create incentives for the conservation of traditional crop varieties and preparation methods that might otherwise be abandoned for commercial reasons.

(Kumar, Rajesh and Kumar 2020) add a spatial dimension to the analysis, identifying rural Tamil Nadu as a particularly important site for food heritage tourism because of its density of traditional knowledge, its relatively low levels of prior tourism development and crucially its vulnerability to the outmigration of younger generations who carry this knowledge. Food tourism, in this analysis, is not merely an economic diversification strategy but a cultural retention mechanism, creating conditions in which traditional knowledge holders see their practices valued and rewarded rather than bypassed.

Policy integration and community participation

The literature is consistent on one point above all: neither sustainable tourism nor culinary heritage preservation works well in the absence of supportive policy frameworks and genuine community participation. (Ghose, Ali, Dhere and Inamdar 2025) and (Udayakumar 2025) both emphasise the enabling role played by government-supported community tourism initiatives, while cautioning that top-down approaches that position communities as performers rather than authors of their own heritage are likely to produce superficial and unsustainable results.

The bibliometric co-occurrence analysis of keywords across the reviewed literature reveals particularly strong connections among the terms “community empowerment”, “cultural sustainability” and “traditional foods”, suggesting that scholars across the field recognise these concepts as mutually constitutive rather than independent. This finding implies that policy interventions which focus narrowly on marketing or infrastructure development, without addressing the social and economic conditions that shape community engagement with tourism, are unlikely to achieve durable preservation outcomes.

(Mathew, Sahoo and Padyala 2025) make a specific and practically important recommendation in this context, arguing for the systematic use of Geographical Indication tags for Tamil Nadu’s heritage food products including Kumbakonam Filter Coffee, Srivilliputhur Palkova and Madurai Jigarthanda as legal and branding instruments that simultaneously protect authenticity and support destination marketing. GI tags, in their analysis, function most effectively when embedded in coherent tourism narratives rather than deployed as isolated certification mechanisms.

Cultural sustainability and economic empowerment

A recurring and important finding across approximately 40% of the reviewed studies is the dual dividend cultural and economic that heritage gastronomy can generate when appropriately managed. This finding is significant because it challenges a common assumption in development discourse that cultural preservation and economic development are competing priorities. The evidence from Tamil Nadu and comparable contexts suggests they can be mutually reinforcing.

(Raj 2025) and (Abirami, Rajan and Antony 2024) provide compelling evidence from Tamil Nadu’s highland regions the Kolli Hills and the Nilgiris respectively where tribal and indigenous food systems have demonstrated significant potential as eco-tourism attractions that generate livelihoods while protecting both cultural identity and ecological diversity. The food traditions of these communities including heirloom millet cultivation, traditional fermentation practices and the use of forest foods are simultaneously among the most culturally distinctive and the most economically fragile, making them priority candidates for integrated preservation and tourism development strategies.

(Johnson and Sivaraman 2020) add an important gender dimension to this analysis, documenting how community-led culinary festivals in Tamil Nadu’s coastal districts have created entrepreneurial opportunities for women who are the primary holders of traditional seafood preparation knowledge. Their

case studies illustrate the transformative potential of culinary tourism when economic benefit is deliberately structured to flow to knowledge holders rather than to commercial intermediaries.

Bibliometric results: keyword clusters and research trends

The bibliometric co-occurrence analysis of keywords across the twenty-five reviewed studies identified five major thematic clusters (Table 3), which reflect the key intellectual currents shaping the field over the review period.

Table 3: Keyword clusters and emerging themes

Cluster	Central keywords	Emerging themes
1. Cultural heritage	Traditional foods, culinary heritage	Preservation, intangible cultural assets
2. Sustainability	Sustainable tourism, cultural sustainability	Policy and SDG integration
3. Regional identity	Tamil Nadu, food tourism	Destination branding
4. Community development	Community empowerment, rural tourism	Livelihoods, local entrepreneurship
5. Global comparisons	Gastronomy tourism, responsible tourism	Cross-cultural lessons

Several patterns in these clusters deserve comment. First, the co-occurrence of "community empowerment" and "cultural sustainability" across a significant proportion of the reviewed literature suggests a growing scholarly consensus that the social and cultural dimensions of culinary heritage tourism are inseparable from its economic dimensions. Second, the emergence of "SDG integration" as a theme reflects a broader turn in tourism scholarship towards explicit engagement with global development frameworks a trend that this paper contributes to through its own SDG-anchored policy recommendations. Third, the relatively limited presence of Tamil Nadu-specific research within the "Regional identity" cluster, compared with the volume of Karnataka and Kerala material, confirms the gap in the literature that this paper seeks to address.

CONCEPTUAL FRAMEWORK

On the basis of the thematic synthesis presented above, this paper proposes a conceptual framework that articulates the relationships between traditional foods, sustainable tourism and cultural sustainability as a dynamic, mutually reinforcing cycle (Figure 1).

Traditional foods are the starting point and foundation of the framework. They represent living repositories of agricultural knowledge, ecological wisdom and community identity resources that exist, in the first instance, within communities rather than institutions. Culinary heritage develops when traditional foods are recognised, documented and institutionally embedded within community life and tourism structures. This transformation from everyday practice to acknowledged cultural capital is a necessary precondition for their effective integration into tourism economies.

Sustainable tourism functions as the key bridge between culinary heritage and broader markets. Through mechanisms such as food trails, culinary festivals, agritourism, GI-tagged product promotion and experiential cooking programmes, sustainable tourism creates conditions in which traditional food knowledge generates economic value for communities without being diluted or commodified.

Community empowerment is the intended social outcome of well-designed culinary tourism. When tourism benefits flow equitably to knowledge holders women who maintain cooking traditions, farmers who cultivate heritage crops, tribal communities who hold indigenous food knowledge the result is not only economic gain but a strengthened sense of cultural ownership and pride that provides the most durable possible motivation for preservation.

Cultural and economic sustainability is the framework's ultimate goal. When traditional foods are embedded in responsible tourism at every level from product design to governance to benefit distribution the resulting system is capable of sustaining itself, adapting to changing conditions and generating benefits across generations. The framework is explicitly circular rather than linear: cultural and economic sustainability, when achieved, reinforces the value of traditional foods and strengthens the community motivations that underpin

their preservation. This circularity reflects the view, supported throughout the reviewed literature, that the conservation of food heritage is not a bounded project with a beginning and an end but an ongoing socio-cultural process that requires continuous investment, adaptation and community agency. Tamil Nadu's age-old food traditions including Pongal festivals, temple cuisine, millet-based rural diets and the diverse seafood cultures of the coast hold significant promise as anchors for sustainable gastronomy trails under both the UNESCO Intangible Cultural Heritage programme and India's National Tourism Policy 2022. The framework proposed here provides a structured basis for thinking about how these traditions might be mobilised sustainably and equitably.

DISCUSSION

The synthesis of evidence presented in this paper supports several broad conclusions about the relationship between traditional food preservation and sustainable tourism in Tamil Nadu.

First, the evidence strongly suggests that culinary heritage preservation and tourism sustainability are not competing priorities but mutually reinforcing ones. Communities that invest in preserving their food traditions tend to create more distinctive, compelling and durable tourism products; and tourism, when properly structured, creates the economic conditions and social recognition that motivate communities to maintain their culinary heritage as living practice rather than mere artefact.Second, community participation and local ownership are not optional extras in effective culinary tourism they are foundational requirements. The literature is consistent in showing that initiatives in which communities are active designers and primary beneficiaries of tourism products achieve better preservation outcomes, higher visitor satisfaction and more equitable economic returns than those in which communities are passive performers within externally designed experiences. Third, policy coherence matters enormously. The most successful culinary heritage tourism initiatives documented in the reviewed literature whether in Tamil Nadu, Karnataka, Kerala or comparable international contexts share a common feature: they operate within supportive institutional environments that include clear legal frameworks for heritage protection, investment in infrastructure and training, and mechanisms for ensuring that economic benefits are equitably distributed. The absence of such frameworks is the single most commonly cited barrier to the realisation of culinary tourism's potential. Fourth, and perhaps most importantly for Tamil Nadu specifically, the gap between the state's extraordinary culinary wealth and the limited degree to which it has been systematically mobilised for sustainable development represents both a significant research gap and a significant policy opportunity. The evidence reviewed here suggests that the potential is real; the question is whether the institutional will and the community capacities can be assembled to realise it.

CONCLUSION AND POLICY RECOMMENDATION

This paper has reviewed twenty-five peer-reviewed studies published between 2015 and 2025 to examine the relationship between traditional food preservation and sustainable tourism in Tamil Nadu. Applying a PRISMA-based systematic methodology, the review has demonstrated that Tamil Nadu's culinary heritage spanning the spiced complexity of Chettinad cuisine, the millet traditions of Kongunadu, the temple food cultures of the Kaveri delta and the indigenous food systems of the Nilgiris and Kolli Hills represents a cultural wealth of extraordinary depth and diversity that remains significantly under-integrated into the state's sustainable tourism development frameworks. The evidence reviewed suggests that sustainable tourism, when designed with community benefit as its primary objective and authenticity as a non-negotiable standard, can serve as a genuinely effective mechanism for culinary heritage preservation. Mechanisms such as agritourism, food trails, community culinary festivals, GI-tagged product promotion and experiential cooking programmes have all demonstrated the capacity to generate meaningful preservation outcomes alongside equitable economic benefits particularly when structured to ensure that knowledge holders (women, farmers, indigenous communities) are the primary beneficiaries rather than external commercial operators.

The conceptual framework proposed in this paper linking traditional foods through culinary heritage and sustainable tourism to community empowerment

and ultimately to cultural and economic sustainability provides a structured, evidence-grounded model for thinking about how Tamil Nadu's culinary wealth might be mobilised sustainably. It is a circular rather than linear model, emphasising that preservation is not a project to be completed but a process to be sustained one that requires continuous investment in community agency, institutional support and adaptive management.

Finally, the paper confirms that the effort to preserve traditional food through sustainable tourism is directly aligned with the United Nations Sustainable Development Goals: with SDG 8, through the creation of local employment and enterprise opportunities for food producers; with SDG 11, through the revitalisation of cultural heritage in both rural and urban contexts; and with SDG 12, through the promotion of traditional, ecologically grounded food systems against the homogenising pressure of industrial food production. Tamil Nadu has the natural assets, the cultural resources and the policy frameworks in place to become a national leader in culinary heritage-led sustainable development. What is needed now is the political commitment, the institutional investment and the community engagement to make that leadership real.

POLICY RECOMMENDATIONS

The evidence reviewed in this paper points towards a set of specific, actionable policy recommendations for the sustainable integration of Tamil Nadu's culinary heritage into its tourism economy.Traditional food practices should be formally recognised as intangible cultural heritage within Tamil Nadu's state tourism policies, providing a legal basis for their protection and a signal of official commitment that can anchor further investment. The creation of a dedicated Culinary Heritage Council under the Tamil Nadu Tourism Development Corporation (TTDC) with a mandate for documentation, certification, training and promotion would provide the institutional infrastructure that is currently absent. Concurrently, nominations should be pursued for key Tamil Nadu food practices and products under UNESCO's List of Intangible Cultural Heritage, building on the GI recognition that several products already hold.

Tourism programmes centred on culinary heritage should be designed from the outset to place communities and specifically the women, farmers and indigenous knowledge holders who maintain food traditions at the centre of both the product and the benefit distribution. Village food festivals, traditional cooking demonstrations, agritourism experiences and community-guided food trails should be developed and governed by the communities concerned rather than by external tourism operators. Capacity-building programmes in areas including hospitality, food safety, digital marketing and financial management should accompany this support to ensure that communities have the skills to manage and sustain their own tourism enterprises.

Tamil Nadu should develop region-specific culinary trail brands a Chettinad Food Trail, a Kongunadu Millet Trail, a Madurai Heritage Food Circuit, a Nilgiris Tribal Gastronomy Experience that give coherent and marketable identities to the state's diverse culinary regions. These brands should be supported by digital storytelling platforms that allow food producers to communicate directly with potential visitors and consumers, building the kind of authentic, human-centred narratives that the evidence consistently shows are most effective in attracting culturally motivated tourists.

Universities and research institutions should be actively engaged in the systematic documentation of Tamil Nadu's culinary heritage, including endangered recipes, traditional processing techniques and the ecological knowledge embedded in indigenous food systems. A publicly accessible culinary heritage database modelled on similar initiatives in countries such as Japan, Italy and Mexico would provide a foundation for evidence-based policymaking, enable the monitoring of heritage preservation outcomes over time and ensure that the knowledge currently held by ageing knowledge holders is not irretrievably lost.

Policy frameworks for culinary heritage tourism should explicitly incorporate SDG targets and indicators, enabling the measurement of progress against internationally recognised benchmarks. This would facilitate the comparison of Tamil Nadu's performance with that of other Indian states and international destinations, support access to SDG-linked funding streams and ensure that the development

benefits of culinary tourism are tracked with the rigour that the evidence base requires. In aggregate, these recommendations constitute a coherent and evidence-grounded strategy for realising the considerable potential that Tamil Nadu's culinary heritage holds for sustainable, inclusive and culturally rooted development. The challenge is not one of imagination or aspiration the potential has been clearly established in the literature reviewed here but of institutional commitment, political will and the genuine centering of community voices in the design and governance of the tourism economy.

REFERENCES

1. Abirami, M. Rajan & A. Antony (2024), Nurturing harmony: Harnessing niche tourism for sustainable development with special reference to Nilgiris District.
2. Amalan & G. Anitha (2023), Traditional foods: A value addition at tourism destinations, in Emerging Aspects of Redefined Tourism and Hospitality.
3. G. Yoganandham (2024), Empowering rural Tamil Nadu: A comprehensive approach to sustainable development.
4. Ghose, S. M. A. Ali, A. Dhere & P. Inamdar (2025), Revival and preservation of folklore through tourism: Approaches for sustainable cultural heritage management in India, in Cultural Heritage Tourism and Sustainability.
5. H.-M. Thomas & S. Anwar (2021), From kitchen to culture: The evolution of Indian food tourism, in "Journal of Destination Marketing & Management". https://doi.org/10.1016/j.jdmm.2021.100940
6. Iniyan (2015), Tourism in Tamil Nadu: Role of cultural and heritage sites in tourist satisfaction and tourism development, in "International Journal of Humanities and Social Science Studies", 2, 1, pp. 45–54.
7. Johnson & S. Sivaraman (2020), Heritage gastronomy and community empowerment: Insights from Tamil Nadu, in "Asian Journal of Tourism Research", 5, 2, pp. 89–104.
8. K. Bharath Kumar & R. Thyagaraju (2024), Traditional food experiences in South Indian leisure tourism: Diversifying tourist products for inclusive growth.
9. K. Kavitha & G. R. Ravi (2024), Culinary heritage as a sustainable tourism product: A review, in Gastronomic Sustainability Solutions.
10. Kumar, A. Nag, V. Kumar & P. Sharma (2025), Gastronomy tourism in Himachal Pradesh: A sustainable approach to community empowerment and cultural preservation, in Advances in Gastronomic Tourism.
11. M. Chera (2020), Tamil traditions: Women cooking and eating for heritage and health in South India (Doctoral dissertation, ProQuest Dissertations & Theses Global).
12. M. Mathew (2020), An exploration of popular food items in Tamil Nadu: Some evidences, in "International Journal of Management", 11, 6, pp. 243–252.
13. M. Ramamoorthi, P. Karnan & K. K. Kavitha (2024), Review on solid waste management for religious tourism in Tamil Nadu: Challenges, opportunities, and sustainable practices, in "Arimaanokku Journal", 9, 4, pp. 112–120.
14. Moher, A. Liberati, J. Tetzlaff & D. G. Altman (2009), Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement, in "PLoS Medicine", 6, 7, e1000097.
15. P. K. Naik (2024), Experiential tourism models for local foods and community ownership in tourism value chains.
16. P. Manoharan & S. Nair (2023), Sustainable gastronomy tourism and the Sustainable Development Goals: A case analysis of South Indian states, in "Journal of Sustainable Development Studies", 15, 2, pp. 101–118.
17. P. Sharma & K. Reddy (2019), Food heritage and sustainable tourism practices in India: A review, in "Journal of Heritage Tourism", 14, 5, pp. 455–469. https://doi.org/10.1080/1743873X.2019.1575783
18. R. Kumar (2024), Food tourism research in India: Current trends and future scope, in "Tourism Review", 79, 3, pp. 512–526. https://doi.org/10.1108/TR-07-2022-0366
19. R. Mathew, S. S. Sahoo & M. Padyala (2025), Geographical indication of food in promoting gastronomic sustainable tourism: An Indian outlook, in Gastronomic Tourism and Regional Development.
20. R. Nagina, J. Kaur & P. Bhalla (2025), Preserving traditional recipes and methods in the culinary world: Strategies, challenges, and success stories, in Sustainable Practices in Gastronomic Development.

Assessing the Importance of Culinary Tourism in Preserving and Promoting Tamil Nadu's Regional and Ethnic Dishes

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ABSTRACT

Culinary tourism has become a prominent aspect of the tourism sector, providing travelers with genuine experiences rooted in local food customs and cultural heritage. Tamil Nadu, famous for its varied regional and ethnic cuisines, boasts a rich culinary history that mirrors its past, geography, agricultural practices, and cultural diversity. Nevertheless, the swift pace of urbanization, globalization, and evolving food consumption trends have resulted in the gradual erosion of numerous traditional dishes and indigenous food practices. In this regard, culinary tourism acts as a vital tool for preserving and promoting the regional and ethnic dishes of Tamil Nadu, while also contributing to sustainable tourism development. This study evaluates the significance of culinary tourism in protecting and raising awareness of Tamil Nadu's traditional food heritage. The research investigates how regional specialties, including Chettinad cuisine, Kongunadu dishes, Nanjil Nadu seafood preparations, Madurai's traditional foods, and indigenous tribal cuisines, draw tourists and foster unique cultural experiences. Additionally, it examines the contributions of local communities, food festivals, restaurants, tourism stakeholders, and government initiatives in the promotion of authentic culinary traditions. The study employs a quantitative research methodology, utilizing survey data gathered from both domestic and international tourists. The results reveal that culinary experiences play a crucial role in influencing travel choices, enhancing tourist satisfaction, and deepening cultural appreciation. Moreover, culinary tourism creates economic opportunities for local food producers, small-scale entrepreneurs, and traditional culinary practitioners, while also promoting the preservation of time-honored recipes and cooking techniques. The research concludes that culinary tourism serves as an essential mechanism for safeguarding Tamil Nadu's gastronomic heritage while enhancing the competitiveness of the destination. By bolstering food-centric tourism initiatives, aiding local culinary businesses, and raising awareness of traditional dishes, sustainable cultural preservation and economic growth can be achieved. The study emphasizes the importance of collaborative efforts among government bodies, tourism organizations, and local communities to secure the long-term sustainability of Tamil Nadu's distinctive culinary heritage.

KEYWORDS: *Culinary Tourism-Regional Cuisine-Ethnic Dishes-Cultural Heritage Preservation-Tamil Nadu Tourism.*

INTRODUCTION

Tourism has undergone significant transformation in recent decades, expanding from conventional sightseeing to encompass experiential and culture-oriented travel. Among the newly emerging types of tourism, culinary tourism has become increasingly prominent as travelers seek authentic and immersive experiences that enable them to engage with local cultures through their cuisine. Culinary tourism, often referred to as food tourism or gastronomic tourism, involves exploring a destination via its food, beverages, culinary traditions, and cooking methods. This form of tourism allows visitors to experience the cultural identity, history, and lifestyle of local communities

while also contributing to the economic growth of the destinations.

Food serves as one of the most visible and tangible representations of cultural heritage. Each region boasts unique culinary traditions influenced by geography, climate, agricultural resources, religious beliefs, and historical factors. As globalization continues to shape food consumption trends, many traditional cuisines are at risk of being eclipsed by standardized and fast-food cultures. As a result, culinary tourism has emerged as a viable strategy for safeguarding indigenous food knowledge, preserving traditional recipes, and promoting regional identities.

Tamil Nadu, recognized as one of India's most culturally rich states, presents an extraordinary culinary landscape marked by a variety of regional and ethnic cuisines. The food traditions of the state have developed over centuries, reflecting the impact of ancient Tamil civilization, agricultural practices, trade routes, and local customs. Tamil cuisine is not a singular entity but rather a compilation of distinct regional food cultures, each with its own unique ingredients, preparation methods, and flavors.

The Chettinad region is globally acclaimed for its fragrant spices, intricate cooking techniques, and sumptuous non-vegetarian dishes. Chettinad cuisine features specialties such as Chettinad Chicken, Mutton Chukka, Kuzhi Paniyaram, and a variety of spice-infused curries. In a similar vein, the Kongunadu region is celebrated for its wholesome millet-based dishes, including Arisi Paruppu Sadam, Kambu Koozh, and traditional meat preparations that highlight the agricultural legacy of western Tamil Nadu.

The coastal areas of Tamil Nadu, especially Nanjil Nadu and the Coromandel Coast, present an extensive array of seafood delicacies crafted using age-old methods that have been handed down through generations. Dishes like Meen Kuzhambu, Nethili Fry, and Prawn Curry exemplify the deep connection between local communities and marine resources. In southern Tamil Nadu, the culinary heritage of Madurai showcases iconic dishes such as Jigarthanda, Kari Dosa, and Parotta with Salna, drawing food lovers from across India and beyond.

In addition to the prominent regional cuisines, Tamil Nadu is home to numerous indigenous and tribal communities whose culinary traditions serve as significant cultural treasures. Tribal groups living in the Nilgiris, Kalrayan Hills, and other forested areas create distinctive dishes utilizing locally sourced herbs, tubers, honey, millets, and forest products. These traditional food systems reflect sustainable practices and indigenous wisdom that play a vital role in biodiversity conservation and cultural preservation.

In recent years, there has been a notable increase in tourists' interest in experiencing authentic local cuisines instead of standardized dining options. This shift has opened up new avenues for destinations to market their culinary heritage as a valuable tourism asset. Attractions such as food festivals, culinary trails, cooking workshops, farm-to-table experiences, and heritage restaurants have emerged as significant draws that enhance tourist experiences while bolstering local economies.

Tamil Nadu possesses substantial potential to cultivate culinary tourism as a distinct tourism offering. The state's diverse gastronomic landscape can appeal to both domestic and international visitors in search of genuine cultural experiences. Culinary tourism not only boosts the attractiveness of the destination but also generates employment opportunities for local chefs, food vendors, farmers, artisans, and small entrepreneurs. Moreover, it promotes the preservation and sharing of traditional culinary knowledge with future generations.

However, despite its vast potential, Tamil Nadu's culinary heritage encounters numerous challenges. Urbanization, shifts in lifestyle, migration, and the increasing prevalence of global food chains have led to the decline of many traditional dishes and cooking methods. Younger generations frequently gravitate towards modern food choices, resulting in a diminished understanding of traditional recipes and cooking techniques. Furthermore, various ethnic and tribal food traditions continue to be underrepresented in mainstream tourism marketing initiatives.

The conservation and promotion of regional and ethnic cuisines necessitate collaborative efforts among government bodies, tourism stakeholders, local communities, educational institutions, and hospitality enterprises.

Culinary tourism can significantly contribute to overcoming these challenges by generating economic incentives for the preservation of traditional food cultures. When local cuisines are featured as tourist attractions, communities are motivated to uphold authentic cooking methods, safeguard indigenous ingredients, and honor their cultural heritage.

Moreover, culinary tourism fosters sustainable tourism development by advocating for local sourcing, supporting small enterprises, minimizing food miles, and promoting responsible consumption habits. It is in harmony with the principles of cultural sustainability, ensuring that traditional food knowledge remains pertinent and economically viable in modern society.

In this context, the current study aims to evaluate the significance of culinary tourism in the preservation and promotion of Tamil Nadu's regional and ethnic dishes. The research investigates the impact of culinary experiences on attracting tourists, enhancing cultural awareness, bolstering local economies, and protecting traditional food heritage. By exploring the connection between tourism and food culture, this study aspires to offer insights that can aid policymakers, tourism planners, and local communities in formulating effective strategies for the sustainable promotion of Tamil Nadu's distinctive culinary identity.

LITERATURE REVIEW

Gupta and Sajnani (2023) This research concentrated on the advancement of food tourism in India. The authors discovered that regional cuisines play a crucial role in enhancing tourism and fostering local economic growth. They suggested a more vigorous promotion of native food traditions through tourism initiatives.

Sthapit, Björk, and Coudounaris (2023) The researchers examined the memorable culinary experiences of tourists. Their findings indicated that genuine food experiences create enduring memories and deepen emotional ties to destinations. Local food heritage was identified as a significant factor affecting tourist satisfaction.

Everett and Aitchison (2024) This study investigated culinary tourism as a means of preserving intangible cultural heritage. The results showed that food festivals, culinary trails, and community-based tourism efforts effectively maintain traditional culinary practices while generating revenue for tourism.

Hall and Sharples (2024) Hall and Sharples analyzed the impact of local food systems on sustainable tourism development. Their research underscored that culinary tourism encourages local sourcing, supports small-scale producers, and aids in environmental sustainability while safeguarding food heritage.

Kumar and Rajasekar (2025) This study, which focused on tourism destinations in South India, evaluated tourists' views on regional cuisines. The results indicated that the traditional dishes of Tamil Nadu significantly enhance the appeal of the destination and visitor satisfaction. The authors advocated for the establishment of specialized culinary tourism circuits throughout the state.

NATIONAL AND INTERNATIONAL STATUS OF CULINARY TOURISM

National Status of Culinary Tourism in India

India is acknowledged as one of the most diverse culinary destinations globally, with each state presenting unique food traditions influenced by geography, culture, religion, and history. In recent years, culinary tourism has garnered significant interest as a specialized segment of tourism, playing a vital role in promoting cultural heritage and supporting local economies.

The Ministry of Tourism, Government of India, has placed greater emphasis on food-based tourism through initiatives like Dekho Apna Desh, Incredible India, and various state-level tourism campaigns. Numerous regions have effectively created culinary tourism products that draw both domestic and international visitors.

Major Culinary Tourism Destinations in India

State/Region	Culinary Specialty	Tourism Significance
Punjab	Makki di Roti, Sarson da Saag	Farm tourism and cultural experiences
Rajasthan	Dal Baati Churma, Laal Maas	Heritage and royal cuisine tourism

Gujarat	Traditional Thali, Dhokla	Cultural and vegetarian tourism
Kerala	Malabar Cuisine, Seafood	Culinary trails and spice tourism
West Bengal	Bengali Sweets, Fish Curries	Heritage food tourism
Tamil Nadu	Chettinad, Kongunadu, Madurai Cuisine	Emerging culinary tourism destination

Recent research shows that over 70% of travelers regard local cuisine as a significant factor when choosing a destination. Food festivals, street food tours, cooking classes, and farm-to-table experiences have gained popularity in various Indian tourism locations.

Tamil Nadu is especially well-suited for this trend due to its extensive variety of regional cuisines, including:

- Chettinad Cuisine
- Kongunadu Cuisine
- Nanjil Nadu Cuisine
- Traditional Foods of Madurai
- Tribal and Indigenous Food Traditions
- Foods Associated with Temples and Festivals

The state government, along with tourism stakeholders, has started to promote food festivals and cultural events to highlight these culinary traditions. Nevertheless, in comparison to states like Kerala and Rajasthan, the culinary tourism potential of Tamil Nadu remains largely untapped.

International Status of Culinary Tourism

Culinary tourism has emerged as one of the most rapidly expanding sectors in the global tourism industry. The World Food Travel Association (WFTA) reports that over 80% of leisure travelers engage in food-related activities during their journeys. Food is increasingly acknowledged as a key motivator for travel, rather than just a supplementary aspect. Nations around the globe have effectively incorporated food heritage into their tourism development strategies, yielding economic advantages while safeguarding traditional culinary practices.

Leading Culinary Tourism Destinations

Country	Famous Culinary Attractions	Tourism Impact
France	Wine Tourism, French Cuisine	Global gastronomic leader
Italy	Pasta, Pizza, Regional Cuisine	Culinary heritage tourism
Japan	Sushi, Ramen, Kaiseki	UNESCO-recognized food culture
Thailand	Street Food, Thai Curries	Major food tourism destination
Spain	Tapas, Paella, Food Festivals	Gastronomic tourism growth
Mexico	Traditional Mexican Cuisine	UNESCO Intangible Cultural Heritage

Global Trends in Culinary Tourism

1. Authentic Food Experiences

Travelers are increasingly interested in traditional and locally prepared dishes.

2. Food Festivals

International food festivals draw millions of attendees each year.

3. Farm-to-Table Tourism

Travelers favor sustainable food experiences that are locally sourced.

4. Cooking Classes and Culinary Workshops

Interactive learning experiences have emerged as significant attractions for tourists.

5. Digital Influence

Social media platforms play a crucial role in shaping food-related travel choices.

6. Heritage Food Preservation

Culinary tourism is increasingly recognized as a means to protect intangible cultural heritage.

Tamil Nadu in the Global Culinary Tourism Context

Tamil Nadu boasts a culinary heritage that rivals many globally acknowledged gastronomic locations. The state's rich food traditions, distinctive spices, millet-based dishes, seafood specialties, and ethnic cuisines present substantial opportunities for the advancement of global culinary tourism.

Key strengths include:

- Ancient culinary traditions with roots spanning thousands of years.
- A variety of regional cuisines.
- A robust agricultural and spice heritage.
- A rich culture of both vegetarian and non-vegetarian cuisine.
- Culinary traditions linked to temples.
- Knowledge systems related to indigenous and tribal foods.
- Despite these strengths, Tamil Nadu needs:
- Well-defined culinary tourism routes.
- Effective international marketing and branding strategies.
- Documentation of culinary heritage.
- An increase in food festivals and gastronomic events.
- Engagement from the community and collaboration among stakeholders.

Data Analysis

Table 1: Gender of Respondents

Gender	Frequency	Percentage (%)
Male	168	56.0
Female	126	42.0
Others	6	2.0
Total	300	100.0

Interpretation

The predominant group of respondents consisted of males, accounting for 56%, while females represented 42%. This suggests that individuals of both genders are actively engaged in culinary tourism activities in Tamil Nadu.

Table 2: Age Group of Respondents

Age Group	Frequency	Percentage (%)
Below 25 Years	54	18.0
25–35 Years	102	34.0
36–45 Years	78	26.0
46–55 Years	42	14.0
Above 55 Years	24	8.0
Total	300	100.0

Interpretation

The majority of respondents (34%) were in the 25–35 years age range, suggesting that young adults exhibit a heightened interest in discovering regional and ethnic cuisines while traveling.

Table 3: Purpose of Visit to Tamil Nadu

Purpose	Frequency	Percentage (%)
Leisure Tourism	126	42.0
Cultural Tourism	84	28.0
Culinary Tourism	60	20.0
Business Travel	30	10.0
Total	300	100.0

Interpretation

Leisure tourism accounted for the primary motivation for travel at 42%, while 20% of travellers visited specifically to savor the culinary offerings of Tamil Nadu.

Table 4: Awareness of Tamil Nadu Regional Dishes

Awareness Level	Frequency	Percentage (%)
Highly Aware	96	32.0
Aware	138	46.0
Neutral	42	14.0
Not Aware	24	8.0
Total	300	100.0

Interpretation

A considerable majority (78%) expressed either awareness or a high level of awareness regarding the regional cuisines of Tamil Nadu, indicating a robust recognition of the local culinary heritage.

Table 5: Most Preferred Regional Cuisine

Regional Cuisine	Frequency	Percentage (%)
Chettinad Cuisine	102	34.0
Kongunadu Cuisine	72	24.0
Madurai Cuisine	60	20.0
Nanjil Nadu Cuisine	42	14.0
Tribal Cuisine	24	8.0
Total	300	100.0

Interpretation

Chettinad cuisine emerged as the most preferred regional cuisine (34%), highlighting its popularity among tourists.

Table 6: Influence of Local Food on Travel Decision

Response	Frequency	Percentage (%)
Strongly Agree	108	36.0
Agree	102	34.0
Neutral	48	16.0
Disagree	30	10.0
Strongly Disagree	12	4.0
Total	300	100.0

Interpretation

A total of 70% of respondents agreed that local food significantly influences their travel decisions.

Table 7: Culinary Tourism Helps Preserve Traditional Dishes

Response	Frequency	Percentage (%)
Strongly Agree	126	42.0
Agree	108	36.0
Neutral	36	12.0
Disagree	18	6.0
Strongly Disagree	12	4.0
Total	300	100.0

Interpretation

A substantial majority (78%) believe culinary tourism plays a crucial role in preserving traditional Tamil Nadu dishes.

Table 8: Culinary Tourism Creates Employment Opportunities

Response	Frequency	Percentage (%)
Strongly Agree	114	38.0
Agree	102	34.0
Neutral	42	14.0
Disagree	30	10.0
Strongly Disagree	12	4.0
Total	300	100.0

Interpretation

Nearly 72% of respondents agreed that culinary tourism generates employment opportunities for local communities.

RECOMMENDATIONS

Based on the study's findings, several suggestions are made to enhance culinary tourism and ensure the preservation and promotion of Tamil Nadu's regional and ethnic cuisines.

1. Develop Dedicated Culinary Tourism Circuits

The Tamil Nadu Tourism Department ought to create region-specific culinary tourism circuits, such as the Chettinad Food Trail, Kongunadu Culinary Route, Madurai Street Food Trail, and Nanjil Nadu Seafood Circuit. These circuits can offer tourists genuine gastronomic experiences while highlighting local food heritage.

2. Organize Regular Food Festivals

State and local authorities should host annual and seasonal food festivals that feature traditional dishes, indigenous ingredients, and ethnic culinary practices. Such events can draw both domestic and international tourists, thereby raising awareness of Tamil Nadu's rich culinary traditions.

3. Promote Traditional and Indigenous Foods

Particular emphasis should be placed on documenting and promoting tribal and indigenous cuisines, which are frequently neglected. Stakeholders in tourism should collaborate with local communities to safeguard traditional recipes and cooking methods.

4. Strengthen Digital Marketing Initiatives

Tourism organizations should leverage social media platforms, travel blogs, websites, and digital campaigns to highlight Tamil Nadu's culinary attractions. Visual storytelling and food-centric tourism content can effectively engage broader audiences.

5. Encourage Community Participation

Local communities, home-based cooks, food artisans, and small entrepreneurs should be actively engaged in culinary tourism initiatives. Their involvement guarantees authenticity and provides direct economic advantages to local residents.

6. Establish Culinary Heritage Centers

The government and educational institutions should establish culinary heritage museums and documentation centers to preserve traditional recipes, utensils, cooking techniques, and food-related cultural practices.

FINDINGS OF THE STUDY

The research titled "Assessing the Importance of Culinary Tourism in Preserving and Promoting Tamil Nadu's Regional and Ethnic Dishes" has yielded the following significant findings:

1. Strong Awareness of Regional Cuisine

A significant number of participants demonstrated awareness of Tamil Nadu's regional and ethnic cuisines, reflecting an increasing interest in local food culture among tourists.

2. Culinary Experiences Influence Travel Decisions

The results indicate that local cuisine plays a crucial role in shaping tourists' destination preferences and travel arrangements.

3. Chettinad Cuisine is the Most Preferred

Among the various regional cuisines, Chettinad cuisine was identified as the most favored and recognized culinary attraction by tourists.

4. Culinary Tourism Enhances Tourist Satisfaction

The majority of respondents reported high levels of satisfaction with their culinary experiences, underscoring the importance of food in enhancing travel enjoyment.

5. Preservation of Traditional Food Heritage

A considerable number of respondents concurred that culinary tourism plays a vital role in safeguarding traditional recipes, cooking techniques, and food-related cultural practices.

6. Economic Benefits for Local Communities

The study revealed that culinary tourism generates job opportunities and supports local food vendors, farmers, restaurateurs, and small business owners.

7. Cultural Identity and Heritage Promotion

It was found that regional and ethnic dishes help to reinforce cultural identity and raise awareness of Tamil Nadu's distinctive heritage among visitors.

8. Need for Government Intervention

Participants highlighted the necessity of government involvement in promoting culinary tourism through marketing strategies, infrastructure enhancement, and supportive policies.

9. Growing Demand for Authentic Food Experiences

Tourists are increasingly inclined towards authentic and traditional culinary experiences as opposed to standardized commercial food options.

SUGGESTIONS

1. Establish a Culinary Brand for Tamil Nadu

Develop a cohesive culinary tourism brand that showcases the state's rich regional and ethnic food traditions, enhancing both national and international recognition.

2. Launch Food-Centric Tourist Packages

Travel agencies ought to create specialized food tourism packages that encompass culinary tours, cooking demonstrations, and immersive local food experiences.

3. Foster Public-Private Collaborations

Government entities and private sector stakeholders should work together to invest in the infrastructure and promotional efforts for culinary tourism.

4. Highlight Traditional Foods in Hospitality Venues

Hotels and restaurants should feature a greater variety

of authentic regional and ethnic dishes on their menus to celebrate local culinary heritage.

5. Create Food Maps and Culinary Guides

Tourists should have access to food maps, mobile applications, and guidebooks that showcase renowned dishes and culinary hotspots throughout Tamil Nadu.

6. Safeguard Endangered Traditional Recipes

Initiatives should be launched to document and preserve vanishing recipes and indigenous food practices before they are lost to time.

7. Promote Youth Engagement

Educational institutions should implement culinary heritage programs aimed at inspiring younger generations to learn and uphold traditional cooking techniques.

8. Enhance Infrastructure at Culinary Attractions

Improvements in transportation, signage, sanitation facilities, and visitor amenities should be prioritized at significant culinary tourism sites.

9. Amplify International Promotion

The culinary heritage of Tamil Nadu should be showcased at international tourism exhibitions, food fairs, and through cultural exchange initiatives.

10. Create Culinary Research and Innovation Hubs

CONCLUSION

Dedicated centers can support research, innovation, and entrepreneurship focused on traditional foods and the advancement of culinary tourism. The current research, **"Assessing the Importance of Culinary Tourism in Preserving and Promoting Tamil Nadu's Regional and Ethnic Dishes,"** underscores the increasing relevance of culinary tourism as a vital tool for cultural preservation, destination marketing, and sustainable economic growth. Tamil Nadu boasts a rich and varied culinary heritage, exemplified by regional cuisines such as Chettinad, Kongunadu, Nanjil Nadu, Madurai cuisine, and numerous indigenous tribal food traditions. These culinary practices encapsulate centuries of cultural wisdom, local agricultural customs, and community identities. The results indicate that travelers are progressively recognizing food as a crucial aspect of their travel experiences. Regional and ethnic dishes not only affect destination selections but also enhance visitor satisfaction and foster memorable cultural encounters. Culinary tourism acts as a conduit between tourists and local communities, offering opportunities to engage with authentic traditions, cooking techniques, and indigenous ingredients that embody the distinctive identity of Tamil Nadu.

Moreover, the research illustrates that culinary tourism plays a significant role in safeguarding traditional recipes and food practices that are at risk of fading due to globalization, urbanization, and evolving lifestyles. By generating economic value for local cuisines, culinary tourism motivates communities to preserve and pass on culinary knowledge to future generations. It also benefits farmers, food producers, local entrepreneurs, and hospitality sectors, thereby creating job opportunities and bolstering rural economies. The research further suggests that strategic actions from government bodies, tourism organizations, educational institutions, and private stakeholders are crucial for optimizing the advantages of culinary tourism. Initiatives such as food festivals, culinary trails, heritage restaurants, digital marketing campaigns, and culinary education programs can elevate awareness and appreciation of Tamil Nadu's gastronomic heritage on both national and international platforms. Culinary tourism holds significant potential to establish Tamil Nadu as a premier gastronomic destination while preserving its rich food heritage. A collaborative and sustainable approach that involves all stakeholders is essential to maintain regional and ethnic dishes, promote cultural diversity, and ensure enduring socio-economic benefits. By incorporating culinary heritage into tourism development strategies, Tamil Nadu can reinforce its cultural identity, improve destination competitiveness, and contribute positively to sustainable tourism development.

REFERENCES

1. Bessière, J. (2013). "Heritagisation," a challenge for tourism promotion and regional development: An example of food heritage. Journal of Heritage Tourism, 8(4), 275–291. https://doi.org/10.1080/1743873X.2013.770861

2. Björk, P., & Kauppinen-Räisänen, H. (2016). Local food: A source for destination attraction. International Journal

of Contemporary Hospitality Management, 28(1), 177–194. https://doi.org/10.1108/IJCHM-05-2014-0214

3. Cohen, E., & Avieli, N. (2004). Food in tourism: Attraction and impediment. Annals of Tourism Research, 31(4), 755–778. https://doi.org/10.1016/j.annals.2004.02.003

4. Ellis, A., Park, E., Kim, S., & Yeoman, I. (2018). What is food tourism? Tourism Management, 68, 250–263. https://doi.org/10.1016/j.tourman.2018.03.025

5. Everett, S., & Aitchison, C. (2008). The role of food tourism in sustaining regional identity: A case study of Cornwall, South West England. Journal of Sustainable Tourism, 16(2), 150–167. https://doi.org/10.2167/jost696.0

6. Fields, K. (2002). Demand for the gastronomy tourism product: Motivational factors. In A. M. Hjalager & G. Richards (Eds.), Tourism and gastronomy (pp. 36–50). Routledge.

7. Gupta, V., Roy, H., & Sajnani, M. (2023). Culinary tourism in India: Emerging trends and opportunities. Worldwide Hospitality and Tourism Themes, 15(3), 285–297.

8. Hall, C. M., & Sharples, L. (2003). The consumption of experiences or the experience of consumption? An introduction to the tourism of taste. Elsevier.

9. Hall, C. M., Mitchell, R., & Sharples, L. (2003). Consuming places: The role of food, wine and tourism in regional development. In C. M. Hall et al. (Eds.), Food tourism around the world (pp. 25–59). Butterworth-Heinemann.

10. Hjalager, A. M., & Richards, G. (2002). Tourism and gastronomy. Routledge.

11. Ignatov, E., & Smith, S. (2006). Segmenting Canadian culinary tourists. Current Issues in Tourism, 9(3), 235–255. https://doi.org/10.2167/cit229.0

12. Kivela, J., & Crotts, J. C. (2006). Tourism and gastronomy: Gastronomy's influence on how tourists experience a destination. Journal of Hospitality and Tourism Research, 30(3), 354–377. https://doi.org/10.1177/1096348006286797

13. Long, L. M. (2004). Culinary tourism. University Press of Kentucky.

14. Okumus, B., Koseoglu, M. A., & Ma, F. (2018). Food and gastronomy research in tourism and hospitality: A bibliometric analysis. International Journal of Hospitality Management, 73, 64–74. https://doi.org/10.1016/j.ijhm.2018.01.020

15. Richards, G. (2015). Evolving gastronomic experiences: From food to foodies to foodscapes. Journal of Gastronomy and Tourism, 1(1), 5–17.

16. Richards, G. (2021). Rethinking cultural tourism. Edward Elgar Publishing.

17. Sims, R. (2009). Food, place and authenticity: Local food and the sustainable tourism experience. Journal of Sustainable Tourism, 17(3), 321–336. https://doi.org/10.1080/09669580802359293

18. Sthapit, E., Björk, P., & Coudounaris, D. N. (2023). Memorable culinary tourism experiences and destination loyalty. Tourism Recreation Research, 48(2), 215–229.

19. Stone, M. J., Migacz, S., & Wolf, E. (2021). Beyond the meal: Exploring food tourism and tourist behavior in the post-pandemic era. Journal of Foodservice Business Research, 24(4), 357–372.

20. UNWTO. (2019). Global report on food tourism. World Tourism Organization.

21. UNWTO. (2022). Tourism and gastronomy: Sustainable development through food heritage. World Tourism Organization.

22. World Food Travel Association. (2023). State of the food travel industry report. World Food Travel Association.

23. Yeoman, I., McMahon-Beattie, U., Fields, K., Albrecht, J. N., & Meethan, K. (2015). The future of food tourism: Foodies, experiences, exclusivity, visions and political capital. Channel View Publications.

Exploring the Importance of Culinary Tourism Through the Regional and Traditional Dishes of Tamil Nadu

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ABSTRACT

Culinary tourism has become a vital aspect of the tourism sector, providing travelers with distinctive opportunities to engage with the culture, heritage, and traditions of a location through its cuisine. Tamil Nadu, recognized as one of India's culturally affluent states, boasts a rich culinary heritage influenced by its regional customs, ethnic groups, historical factors, and geographical diversity. This research investigates the significance of culinary tourism through the lens of Tamil Nadu's regional and traditional dishes, assessing its potential to enhance tourism, preserve cultural identity, and bolster local economies. The study employs a descriptive and analytical methodology to gain insights into tourists' perceptions, preferences, and experiences concerning Tamil Nadu's traditional cuisine. It emphasizes the state's unique food traditions, which include Chettinad cuisine, Kongunadu cuisine, Madurai specialties, Thanjavur delicacies, Nanjil Nadu dishes, and various indigenous tribal food practices. These culinary traditions embody the social, cultural, and historical richness of Tamil Nadu, serving as important assets for tourism. The results indicate that regional and traditional dishes play a crucial role in shaping tourists' travel choices and enhancing their overall experience at the destination. Authentic culinary experiences allow visitors to engage more deeply with the culture, resulting in memorable and significant travel experiences. Additionally, culinary tourism aids in the preservation of traditional recipes, indigenous ingredients, and local cooking methods that face increasing threats from globalization and evolving food consumption trends.The study also identifies economic benefits such as income generation for local food vendors, restaurants, farmers, and small-scale entrepreneurs. Despite its potential, challenges such as inadequate promotion, limited documentation of traditional foods, lack of standardized quality measures, and insufficient integration of food tourism into tourism policies remain barriers to growth. The study recommends strengthening culinary branding, organizing food festivals, supporting local food entrepreneurs, and incorporating culinary experiences into tourism development strategies. By recognizing and promoting its rich gastronomic heritage, Tamil Nadu can enhance its tourism competitiveness while preserving its unique cultural and culinary traditions for future generations.

KEYWORDS: *Culinary Tourism, Traditional Cuisine, Regional Dishes, Food Heritage, Cultural Tourism, Tamil Nadu, Gastronomy, Sustainable Tourism.*

INTRODUCTION

Tourism has transformed from conventional sightseeing and leisure activities to include a diverse array of experiential offerings that enable travelers to immerse themselves in the culture and lifestyle of a destination. Culinary tourism, often referred to as food tourism or gastronomy tourism, encompasses travel experiences where visitors actively seek and relish authentic food and beverage offerings that mirror the culture and history of a specific region.

Food has become a crucial component of the tourism experience, impacting destination selection, visitor satisfaction, and cultural appreciation. Tamil Nadu, situated in the southern region of India, is celebrated

for its rich cultural heritage, ancient traditions, and varied culinary practices. The cuisine of this state is distinguished by a plethora of regional and traditional dishes that have developed over centuries, influenced by geography, climate, agriculture, religion, and local customs. From the piquant flavors of Chettinad cuisine and the wholesome preparations of Kongunadu cuisine to the distinctive seafood specialties of the coastal areas and the temple-based culinary traditions of Thanjavur and Madurai, Tamil Nadu presents a vast array of gastronomic experiences for its visitors. The regional and traditional dishes of Tamil Nadu signify more than just food items; they encapsulate the history, values, and cultural identity of local communities. Many of these dishes are crafted using indigenous ingredients, traditional cooking techniques, and recipes that have been handed down through generations. As globalization and modernization increasingly shape food habits, numerous traditional culinary practices are at risk of fading away. Culinary tourism offers a valuable opportunity to safeguard and promote these cherished food traditions while simultaneously generating economic prospects for local communities. The increasing demand for genuine and immersive travel experiences has heightened the importance of culinary tourism in the development of destinations. Travelers are more frequently looking for chances to visit local food markets, engage in cooking demonstrations, attend food festivals, and savor traditional dishes that provide a deeper insight into the culture of the destination. In Tamil Nadu, culinary tourism has the capacity to enhance existing tourist attractions such as temples, heritage sites, festivals, and natural landscapes, thus enriching the overall experience for visitors. Moreover, culinary tourism plays a vital role in sustainable tourism development by supporting local farmers, food producers, restaurants, and small-scale entrepreneurs. It fosters the preservation of traditional agricultural methods, encourages local food systems, and bolsters community involvement in tourism activities. The economic advantages generated by culinary tourism can improve livelihoods while protecting cultural heritage and culinary diversity. In this regard, the current study investigates the significance of culinary tourism through the regional and traditional dishes of Tamil Nadu. The research aims to analyze the role of food in attracting tourists, preserving cultural heritage, promoting local economic growth, and enhancing the tourism potential of the state. By showcasing the richness and diversity of Tamil Nadu's culinary traditions, this study aspires to provide a deeper understanding of how culinary tourism can act as an effective instrument for sustainable tourism development and cultural preservation.

REVIEW OF LITERATURE

Balakrishnan and Devi (2025) investigated the relationship between culinary tourism and cultural heritage preservation in Tamil Nadu. The study found that tourism activities centered on traditional foods encourage the preservation of indigenous recipes, cooking techniques, and local ingredients. The authors highlighted the need for collaboration between tourism authorities and local communities.

Nair and Subash (2025) examined tourists' willingness to participate in culinary tourism activities. The results revealed that food trails, heritage dining experiences, village cooking demonstrations, and traditional food markets were among the most preferred culinary attractions. The study emphasized experiential tourism as a growing trend among modern travellers.

Ramanathan and Kumar (2026) analysed the economic impact of culinary tourism in South Indian destinations. The findings demonstrated that culinary tourism generates employment opportunities, increases local income, and supports rural entrepreneurship. The study recommended greater investment in culinary infrastructure and food tourism promotion.

RESEARCH METHODOLOGY

Research methodology offers a structured approach for gathering, analysing, and interpreting data to fulfil the goals of a study. The current research, entitled "Exploring the Importance of Culinary Tourism Through the Regional and Traditional Dishes of Tamil Nadu," seeks to investigate the significance of regional and traditional cuisines in enhancing culinary tourism, safeguarding cultural heritage, and aiding sustainable tourism development. This chapter delineates the research design, study area, population, sampling methods, data collection techniques, and statistical tools utilized in the study.

RESEARCH DESIGN

The study adopts a descriptive research design to understand tourists' perceptions, experiences, and preferences regarding regional and traditional dishes of Tamil Nadu. Descriptive research is suitable for identifying patterns, attitudes, and behaviors related to culinary tourism and for assessing the significance of food-based experiences in destination attractiveness.

STUDY AREA

Tamil Nadu serves as the study area due to its rich culinary diversity and strong cultural heritage. The state is known for several distinctive regional cuisines, including:

- Chettinad Cuisine (Sivaganga and Karaikudi)
- Kongunadu Cuisine (Coimbatore, Erode, Salem)
- Madurai Cuisine
- Thanjavur Cuisine
- Nanjil Nadu Cuisine (Kanyakumari Region)
- Traditional Coastal Cuisine (Nagapattinam, Thoothukudi, Chennai)

These regions attract domestic and international tourists seeking authentic culinary experiences.

NATURE AND SOURCES OF DATA

Primary Data

Primary data is gathered directly from tourists via a structured questionnaire. This questionnaire includes sections that address:

- Demographic profile
- Travel behavior
- Awareness of Tamil Nadu cuisine
- Culinary tourism experiences
- Tourist satisfaction
- Perceived significance of traditional dishes
- Future travel intentions

Secondary Data

Secondary data is sourced from:

- Research journals
- Books and conference proceedings
- Government tourism reports
- Publications from the Tamil Nadu Tourism Department
- UN Tourism reports

POPULATION OF THE STUDY

The target population consists of both domestic and international tourists visiting key tourist sites in Tamil Nadu who have either experienced or expressed interest in regional and traditional cuisines.

SAMPLE SIZE

A sample size of 300 respondents has been chosen for the study. This sample size is deemed sufficient to facilitate reliable statistical analysis and meaningful interpretation of the findings.

RESEARCH OBJECTIVES

1. To examine the significance of culinary tourism in enhancing the tourism potential of Tamil Nadu.
2. To identify the awareness and preferences of tourists toward regional and traditional dishes of Tamil Nadu.
3. To analyse the influence of regional and traditional cuisine on tourists' travel decisions and overall destination experience.
4. To evaluate the contribution of culinary tourism to local economic development, including employment generation and support for local food enterprises.
5. To investigate the relationship between food authenticity, tourist satisfaction, and revisit intention among visitors.
6. To examine the challenges and opportunities associated with the development of culinary tourism in Tamil Nadu.
7. To suggest suitable strategies and policy measures for strengthening culinary tourism and promoting regional and traditional dishes as tourism attractions in Tamil Nadu.

RESEARCH QUESTIONS

1. What is the importance of culinary tourism in promoting tourism development in Tamil Nadu?
2. What is the level of awareness and preference among tourists regarding the regional and traditional dishes of Tamil Nadu?
3. How do regional and traditional cuisines influence tourists' travel experiences and overall satisfaction?
4. What strategies can be adopted to enhance culinary tourism through the promotion of regional and traditional dishes in Tamil Nadu?

Table 1: Gender-wise Distribution of Respondents

Gender	Frequency	Percentage
Male	172	57.3
Female	128	42.7
Total	300	100.0

Interpretation

The table illustrates that among 300 participants, 172 (57.3%) were male and 128 (42.7%) were female. This indicates that male respondents made up the majority of the sample, implying a higher level of engagement from male tourists in culinary tourism activities.

Table 2: Age-wise Distribution of Respondents

Age Group	Frequency	Percentage
Below 25 Years	72	24.0
25–35 Years	108	36.0
36–45 Years	74	24.7
Above 45 Years	46	15.3
Total	300	100.0

Interpretation

The largest segment of respondents (36.0%) fell within the 25–35 years age range, with 24.7% in the 36–45 years category. This suggests that both young adults and middle-aged tourists show a greater interest in discovering traditional and regional cuisines.

Table 3: Awareness of Tamil Nadu Traditional Cuisine

Awareness Level	Frequency	Percentage
Highly Aware	126	42.0
Aware	102	34.0
Neutral	42	14.0
Less Aware	20	6.7
Not Aware	10	3.3
Total	300	100.0

Interpretation

The table indicates that 76.0% of respondents were either aware or very aware of Tamil Nadu's traditional cuisine. This demonstrates a strong acknowledgment of the state's culinary heritage among tourists.

Table 4: Most Preferred Regional Cuisine

Regional Cuisine	Frequency	Percentage
Chettinad Cuisine	94	31.3
Kongunadu Cuisine	68	22.7
Madurai Cuisine	54	18.0
Thanjavur Cuisine	42	14.0
Nanjil Nadu Cuisine	24	8.0
Coastal Cuisine	18	6.0
Total	300	100.0

Interpretation

Chettinad cuisine was identified as the most favoured regional cuisine by 31.3% of respondents, followed by Kongunadu cuisine at 22.7%. This highlights the popularity of Chettinad cuisine among culinary tourists.

Table 5: Purpose of Trying Traditional Foods

Purpose	Frequency	Percentage
Cultural Experience	92	30.7
Taste and Flavor	108	36.0
Curiosity	54	18.0
Recommendation	28	9.3
Social Media Influence	18	6.0
Total	300	100.0

Interpretation

Taste and flavour were recognized as the main reasons for trying traditional foods by 36.0% of respondents,

with cultural experiences following closely at 30.7%. This implies that both sensory enjoyment and cultural exploration are significant motivators for culinary tourism.

Table 6: Influence of Traditional Food on Travel Decision

Response	Frequency	Percentage
Strongly Agree	88	29.3
Agree	124	41.3
Neutral	46	15.3
Disagree	28	9.3
Strongly Disagree	14	4.8
Total	300	100.0

Interpretation

Over 70% of respondents concurred that traditional food impacts their travel choices. This suggests that cuisine plays a crucial role in destination selection and overall tourism experiences.

Table 7: Role of Culinary Tourism in Preserving Culture

Opinion	Frequency	Percentage
Strongly Agree	112	37.3
Agree	118	39.3
Neutral	38	12.7
Disagree	22	7.3
Strongly Disagree	10	3.4
Total	300	100.0

Interpretation

A significant majority of respondents (76.6%) agreed that culinary tourism is essential for preserving cultural heritage and traditional food practices. This underscores the cultural importance of food tourism.

RECOMMENDATIONS

Develop Culinary Tourism Circuits

The Tamil Nadu Tourism Department should establish dedicated culinary tourism circuits highlighting regional cuisines such as Chettinad, Kongunadu, Madurai, Thanjavur, Nanjil Nadu, and Coastal Tamil Nadu. These circuits can provide tourists with authentic food experiences and cultural insights.

Utilize Digital Marketing Platforms

Social media, travel blogs, food influencers, and online tourism portals should be leveraged to increase awareness of Tamil Nadu's regional cuisines. Digital storytelling and food-related content can effectively attract culinary tourists.

Support Local Food Entrepreneurs

Government agencies and tourism stakeholders should provide financial assistance, training programs, and marketing support to local food vendors, traditional restaurants, street food operators, and small-scale food entrepreneurs to improve service quality and business sustainability.

Integrate Culinary Experiences into Tourism Packages

Tour operators should include food trails, cooking demonstrations, village dining experiences, heritage restaurants, and local market visits in tourism packages to provide immersive culinary experiences for visitors.

Enhance Food Quality and Hygiene Standards

Restaurants, food stalls, and tourism establishments should maintain high standards of food safety, hygiene, and service quality. This will improve tourist confidence and satisfaction while strengthening the reputation of Tamil Nadu as a culinary destination.

Encourage Community Participation

Local communities should be actively involved in culinary tourism initiatives. Their participation can ensure authenticity, preserve traditional knowledge, and create employment opportunities while promoting sustainable tourism development.

Promote Research and Policy Support

Academic institutions, tourism organizations, and government bodies should collaborate to conduct further research on culinary tourism trends, tourist preferences, and regional food heritage. Policy measures supporting culinary tourism development should also be introduced to maximize its cultural and economic benefits.

FINDINGS OF THE STUDY

1. A significant proportion of tourists were aware of Tamil Nadu's traditional food heritage, reflecting the growing popularity of regional cuisines.

2. Chettinad cuisine emerged as the most preferred regional cuisine among respondents, followed by Kongunadu and Madurai cuisines.
3. Taste and flavor were identified as the primary reasons for trying traditional foods, followed by the desire for cultural experiences.
4. Tourists perceived culinary tourism as an effective means of preserving and promoting Tamil Nadu's cultural and culinary heritage.
5. Most respondents expressed high levels of satisfaction with their traditional food experiences, indicating the quality and authenticity of Tamil Nadu's cuisine.
6. Respondents believed that culinary tourism contributes significantly to local economic development by supporting restaurants, food vendors, farmers, and small-scale entrepreneurs.
7. A large proportion of tourists indicated their willingness to revisit Tamil Nadu for culinary experiences, demonstrating the state's potential as a culinary tourism destination.
8. Food authenticity, cultural significance, and regional culinary diversity were identified as key factors influencing tourist satisfaction.
9. Culinary tourism was found to enhance destination attractiveness and strengthen the overall tourism experience.

LIMITATIONS OF THE STUDY

1. The research was confined to selected tourist destinations in Tamil Nadu and may not fully represent all regions of the state.
2. Time and financial constraints limited the scope of data collection and field visits.
3. Seasonal variations in tourist arrivals and food availability were not considered during the study period.
4. The study focused mainly on domestic and international tourists and did not extensively include perspectives from local residents, food entrepreneurs, and tourism stakeholders.
5. Changes in tourism trends and consumer preferences may influence future findings and reduce the long-term applicability of the results.
6. Certain regional and indigenous food traditions of Tamil Nadu may not have been adequately represented due to geographical constraints.

CONCLUSION

Culinary tourism has appeared as a vibrant and Simportant aspect of the tourism sector, offering travelers the chance to engage with the cultural identity, traditions, and heritage of a location through its cuisine. Tamil Nadu boasts a rich and varied culinary scene, marked by distinctive regional and traditional dishes that embody the state's historical, geographical, and cultural diversity. The study's findings indicate that regional and traditional cuisines are vital in attracting tourists, enhancing their experiences at the destination, and fostering cultural appreciation. Travelers are increasingly in search of genuine food experiences that enable them to connect with local communities and grasp the cultural importance of traditional dishes. The acclaim for cuisines such as Chettinad, Kongunadu, Madurai, and Thanjavur highlights the significant potential of Tamil Nadu's culinary heritage as a tourism asset. Moreover, the study confirms that culinary tourism aids in the preservation of traditional recipes, native ingredients, and local cooking methods while creating economic opportunities for food producers, restaurants, farmers, and small-scale entrepreneurs. High levels of tourist satisfaction and intentions to revisit suggest that culinary experiences play a crucial role in fostering destination loyalty and enhancing tourism competitiveness. However, despite its substantial potential, culinary tourism in Tamil Nadu encounters challenges such as limited promotion, inadequate documentation of traditional foods, and insufficient integration into tourism development strategies. Tackling these challenges through effective marketing, culinary festivals, heritage preservation initiatives, and community involvement can further bolster the growth of this sector. Culinary tourism acts as a vital instrument for sustainable tourism development, cultural preservation, and economic empowerment. By effectively promoting its regional and traditional dishes, Tamil Nadu can enhance its reputation as a leading gastronomic destination, offering memorable

experiences to visitors while safeguarding its rich culinary heritage for future generations.

REFERENCES

1. Bessière, J. (2013). Heritage and gastronomy: The cultural value of food tourism. Journal of Heritage Tourism, 8(4), 275–291. https://doi.org/10.1080/1743873X.2013.767818
2. Chatterjee, S., & Banerjee, A. (2023). Regional cuisine and sustainable tourism development in India. International Journal of Tourism Research, 25(3), 345–360.
3. Ellis, A., Park, E., Kim, S., & Yeoman, I. (2018). What is food tourism? Tourism Management, 68, 250–263. https://doi.org/10.1016/j.tourman.2018.03.025
4. Ellis, A., & Sthapit, E. (2022). Contemporary trends in gastronomic tourism and tourist experiences. Journal of Gastronomy and Tourism, 7(2), 87–101.
5. Everett, S., & Aitchison, C. (2008). The role of food tourism in rural development. Tourism Geographies, 10(2), 150–167. https://doi.org/10.1080/14616680802000047
6. Hall, C. M., & Sharples, L. (2003). The consumption of experiences or the experience of consumption? An introduction to the tourism of taste. Routledge.
7. Hall, C. M., Sharples, L., Mitchell, R., Macionis, N., & Cambourne, B. (Eds.). (2003). Food tourism around the world: Development, management and markets. Butterworth-Heinemann.
8. Kim, Y. G., Eves, A., & Scarles, C. (2009). Building a model of local food consumption on trips and holidays. International Journal of Hospitality Management, 28(3), 423–431. https://doi.org/10.1016/j.ijhm.2008.11.005
9. Kim, J., & Lee, S. (2022). Culinary experiences and tourist satisfaction in Asian destinations. Asia Pacific Journal of Tourism Research, 27(5), 455–470.
10. Kumar, P., & Nair, R. (2023). Tourist perceptions of South Indian traditional cuisine and destination attractiveness. Journal of Tourism and Cultural Change, 21(4), 512–528.
11. Long, L. M. (2004). Culinary tourism. University Press of Kentucky.
12. Nair, R., & Subash, K. (2025). Culinary tourism participation and experiential preferences among travelers. International Journal of Hospitality and Tourism Systems, 18(1), 22–36.
13. Okumus, B., Kock, G., & Scantlebury, M. (2013). Using local cuisines in destination marketing: A review. Journal of Vacation Marketing, 19(2), 99–112. https://doi.org/10.1177/1356766712464175
14. Quan, S., & Wang, N. (2004). Towards a structural model of the tourist experience: An illustration from food experiences in tourism. Tourism Management, 25(3), 297–305. https://doi.org/10.1016/S0261-5177(03)00130-4
15. Rajesh, P., & Prakash, R. (2023). Food festivals as a tourism promotion strategy in India. Tourism Review International, 27(2), 140–154.

A Study on Evaluating Factors Influencing the Adoption of Fintech in India

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ABSTRACT

The purpose of this research is to investigate the important factors that affect the adoption of FinTech services in India by analyzing the users' behavioral intentions and perceptions towards digital financial platforms. The study is grounded on the UTAUT model, extended by E-Service Quality and the data was collected using a structured questionnaire among FinTech users. The results were used to identify the relationship between variables Performance Expectancy, Effort Expectancy, Social Influence, Facilitating Conditions, E-Service Quality, and Behavioral Intention and findings show that Facilitating Conditions and Performance Expectancy are significant factors in FinTech adoption. Further, FinTech service adopters will be encouraged to adopt FinTech services if they believe that the services are convenient, useful and have sufficient technological support and Effort Expectancy, Social Influence, and E-Service Quality are also significant factors that have a positive effect on adoption intention. FinTech firms should concentrate on enhancing user experience, strengthen security measures, and improving customer service. Regulators must encourage digital literacy and ensure a conducive regulatory environment to boost adoption.

KEYWORDS: *FinTech, UTAUT, E-Service Quality, Technology Adoption, India.*

INTRODUCTION

The advancement of Information and Communication Technology (ICT) has significantly transformed global financial systems, leading to the rise of Financial Technology (FinTech).

In Indian, FinTech has achieved a considerable rise in over the past decade because of the rapid digitalization, widespread adoption of smartphones, and improved internet connectivity. The Indian finance sector has gradually transformed from cash transactions to digital forms of payments. Initiatives launched by the Indian government, such as Digital India, Pradhan Mantri Jan Dhan Yojana, Aadhaar-based e-KYC, and the implementation of the Unified Payments Interface (UPI), have contributed largely to the development of the digital finance structure in the country making India as one of the fastest-growing FinTech countries across the globe.

The increasing use of FinTech services has aided improved financial inclusion as it has enabled unbanked and underbanked customers to access banking and payment services. It has further reduced dependence on physical bank branches and enabled real-time transactions through mobile apps and digital wallets. However, adoption varies across different sections of society due to factors such as awareness, trust, usability, financial literacy and security concerns.

From a behavioral perspective, user adoption of FinTech is influenced by perceived usefulness and ease of use. Models like TAM and UTAUT explains the behavior

by focusing on user perceptions and external factors. While FinTech has improved efficiency, reduced costs, and expanded financial access, it also introduces new risks. Therefore, understanding both the benefits and challenges is essential to evaluate Indian consumers' acceptance and sustained use of FinTech services.

REVIEW OF LITERATURE

Factors affecting Fintech Adoption

The study of (Acharya & Bhojak, 2024) examined the acceptance of Fintech applications and results revealed that perceived usefulness and behavioral intention are the most important factors influencing Fintech adaptation among the different generations, similar results have been found in (Pandey et al., 2025) research which shows that attitude, subjective norms, and perceived behavioral control have positive impacts on fintech adoption and investment intentions in e-gold with variable dispositional innovativeness moderating the impact of fintech adoption. (Madhavi, 2024) studied the sample of older generations and identified factors such as perceived ease of use, perceived usefulness, trust, and financial literacy affecting their intention or desire to use fintech services. Past studies based on TAM and UTAUT also affirm that cultural barriers, inadequate access, and technology resistance are major factors that prohibit fintech adoption and further, the role of family and government in motivating older generations and influencing fintech adoption has also been identified.

(Malgaonkar, 2025) study highlighted performance expectancy, effort expectancy, social influence, facilitating condition, and E-service quality on behavioral intention influence fintech adoption. (Jena, 2025) research used numerous models, such as TAM, TPB and TRI which indicated the attitudes toward and Perceived ease of use of FinTech has a significant impact on adoption to be positive while perceived insecurity was a barrier to adoption and usage of FinTech leads to enhanced financial inclusion, rural-premiership empowerment and positively contributed towards sustainable development. Further, factors such as user awareness, convenience, transaction speed, and cost-effectiveness are the driving forces behind the adoption of digital financial services (Sankararaman et al., 2025) and users have positive attitudes toward the adoption of FinTech, but security, privacy, and regulatory concerns act as substantial hindrances for the users. (Singh & Kethi Reddi, 2024) highlighted the role of demographic variables, satisfaction, and trust in influencing FinTech adoption indicating employment and income are very significant variables influencing FinTech adoption and that age, gender, and education appear less significant and also trust is an important factor influencing FinTech usage.

Determinants of Fintech Adoption

The rapid advancements in technology (Rajan et al., 2022) have also given rise to FinTech because of improved convenience, ease of use, and overall customer experience and Technology Acceptance Model (TAM) is the most prominent approach used to examine FinTech acceptance. Further they identified most significant determinants of FinTech acceptance are Trust, Usefulness, Perceived ease of use, Perceived risk, Compatibility, and Performance expectancy. (Priyadarshini et al., 2025) also identified perceived usefulness, trust, government support, and consumer innovativeness determine the attitude of customers toward the adoption of FinTech with government support is the strongest factor for the adoption of FinTech, while perceived ease of use and perceived risk have a negligible effect. The (Aggarwal et al., 2023) reveals that perceived behavioral control, attitude, and subjective norms are some of the main factors influencing users' intention to adopt FinTech services. With few studies highlighting information quality and users' readiness to pay a premium for their service influencing the attitude of FinTech service adoption. Further, among higher education students across India shows that information quality is also one of the crucial factors which affects intention and actual use of FinTech platforms. The study also validates the Theory of Planned Behavior in the Indian context of FinTech and to increase its adoption we need to be accurate, reliable, and user centric.

Technology and Fintech Adoption

The importance of technological advancements, increased internet and smartphone penetration, government initiatives, and the growth of the digital economy as significant factors that contribute to the adoption of fintech in the Indian economy (Josyula,

2023) with perceived benefits, perceived risks, and user trust found to influence the adoption intentions of people among the higher education group with trust acting as a moderating variable to mitigate risks and intensify adoption intentions. (Lal et al., 2020) revealed that the pace of digitization and smartphone and e-commerce growth have fuelled FinTech growth highlighting digital ecosystem is the biggest contributor to the same. (J. Sharma & Sharma, 2024) India's push for a self-reliant economy, with an emphasis on technology adoption, continues to accelerate the adoption of fintech services and focusing on customers in banking sector reveals growing awareness and use of fintech solutions because of government initiatives and developing digital infrastructure.

Fintech adoption in India highlighting the growing importance of technology-enabled financial services like mobile banking, digital payments, e-wallets, and fintech-based lending and investment platforms in a rapidly digitalizing economy (Naveena K & Manjunatha K, 2024).

Fintech and Financial Inclusion and Literacy

The (Siva Priya & Venkateswara Rao, 2024) highlighted the relationship of financial literacy with Fintech service adoption highlighting the important determinants of financial literacy, which includes financial behavior, financial attitude, financial knowledge, and financial capability all having a positive effect on people's levels of financial literacy leading to an increase in adoption of Fintech services. Similar study of (Goswami et al., 2025) identified the facilitation role of FinTech in promoting financial inclusion among BoP consumers living in the rural parts of India and the results show that perceived risk as a mediating factor, indicating that performance expectancy, effort expectancy, social influence, facilitating conditions, and price value significantly enable FinTech adoption, whereas hedonic motivation and habit do not. It also shows that perceived risk negatively affects the relationship between adoption intention and actual usage also suggesting that reducing perceived risk and designing inclusive, user-centric FinTech solutions has the potential to enhance financial inclusion among BoP populations. (S. Kumar, 2023) had emphasized that FinTech technology has aided MSMEs and removed obstacles associated with microfinance, payments, and insurance facilities and it has emerged that there has been enhancement within the operating efficiency and value and volume of MSME transactions through the amalgamation of technology-based financial services and with application of FinTech technology has enhanced MSME development and aided the growth of the economy. (Jhamb, 2025) research that FinTech as a change agent can improve financial inclusion in rural India through better access, usage, and service quality using mobile technologies, digital identity solutions, and real-time payments and suggesting that the impact of FinTech is nonlinear and gets effective only after minimum thresholds relating to smartphone penetration, internet access, and financial literacy are attained.

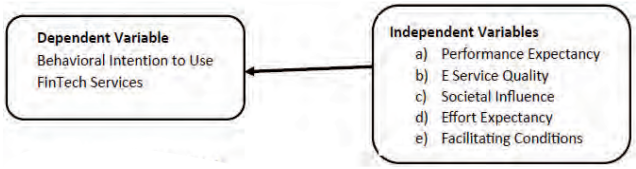
The increased level of digital financial literacy has positively contributed to the adoption of the use of fintech-based services in turn contributing to financial inclusion (G. Kumar et al., 2024). Another study on fintech adoption in India reflect the fast shift from a cash-based economy toward digital financial services, brought about by the rapid pace of technological advancement, coupled with focused government efforts and RBI initiatives (R. Sharma et al., 2023) and found that social environment, perceived usefulness, and digital readiness play a significant role in accelerating fintech adoption within India's expanding digital payments ecosystem.

ESEARCH METHODOLOGY

Objectives of the Study

1. To understand the influence of demographic factors such as gender and age on Fintech adoption.
2. To understand the relationship between UTAUT factors on Behavioural Intention (BI) and usage of FinTech services.
3. To understand the impact of various UTAUT factors on Behavioural Intention (BI) and usage of FinTech services.
4. To evaluate the level of awareness and usage pattern of the users with respect to various Fintech products like digital payments, mobile banking, and online wallets.

Theoretical Model of the Study



ANALYSIS AND DISCUSSIONS

The research discussed the important factors affecting the adoption of FinTech services in India and the relationship between UTAUT factors and Behavioral Intention (BI) and also its impact on usage of FinTech services.

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Table 1: Authors compilation of Awareness and Usage of Fintech services

Particulars	Yes	No
Awareness of Fintech services	92.5%	7.5%
Usage of Fintech services	82.5%	17.5%

Table 1 shows that only 7.5% of participants are not aware of FinTech services and 92.5% are aware about the same showing increased digital penetration, smartphone usage, and the popularity of online payment platforms. Further, 82.5% of respondents actively use FinTech services reflecting strong adoption, largely due to the convenience and speed of these services.

Table 2: Distribution of Participants Based on Usage of FinTech Services

Particulars	Frequency	Percentage
UPI / Digital Payments	74	28.35%
Mobile Banking	62	23.75%
Digital Wallets (Paytm, PhonePe, etc.)	58	22.22%
Online Investment Apps	34	13.03%
Online Lending Platforms	14	5.36%
Insurance Apps and others	19	7.28%

As evidenced in Table 2, the UPI/Digital Payment services contribute 28.35% to total usage indicating a high dependence on digital payment systems followed by mobile banking services at 23.75%, while digital wallets like Paytm and PhonePe account for 22.22%, clearly indicating preferences for convenient, app-based solutions for financial transactions.

Online use of investment applications is 13.03% indicating moderate level of digital investments among respondents. Further online lending platforms at 5.36% and Insurance apps stood at 6.90% indicating lower usage of the same because of lack of awareness, perceived complexity, or higher risk concerns.

Gender and Frequency of FinTech Usage

H_{01}: There is no significant relationship between gender and the frequency of using FinTech services.

H_{11}: There is a significant relationship between gender and the frequency of using FinTech services.

Table 3: Gender and Frequency of FinTech Usage

Particular (Frequently)	Male	Female	Total	Chi Square Statistic	p-value
Daily	35	18	53	4.55595	0.20735
Weekly	8	5	13		
Monthly	3	4	7		
Rarely	2	5	7		
Total Respondents	**48**	**32**	**80**		

The Table 3 shows the relationship between gender the frequency of usage of FinTech services using the chi-square test, gives a p-value of 0.20735 ($p>0.05$) showing gender is not a significant factor in determining the frequency of usage of FinTech services (daily, weekly, monthly or rare usage).Therefore, the null hypothesis is accepted signifying that the use of FinTech is independent of gender.

Age and Frequency of FinTech Usage

H_{02}: There is no significant relationship between the age and frequency in using FinTech services.

H_{12}: There is significant relationship between the age and frequency in using FinTech services.

Table 4: Age and Frequency of FinTech Usage

Frequency	Below 20 years	20 – 30 years	31 – 40 years	41 – 50 years	Above 50 years	Total	Chi-Square Statistic	p-value
Daily	4	40	4	3	2	53		
Weekly	1	6	1	4	1	13		
Monthly	0	2	3	1	1	7	37.33525	0.00020
Rarely	4	2	0	0	1	7		
Total Respondents	9	50	8	8	5	80		

The Table 4 highlights the relationship between age and the use of FinTech services using chi-square test with p-value is 0.00020 ($p<0.05$) showing a significant relationship between age and the use of FinTech services with people in the age group of 20-30 years use FinTech services more often in comparison to older age groups. Hence, the null hypothesis is rejected, and the alternative hypothesis is accepted, which confirms that age has a significant effect on the use of FinTech services.

Table 5: Correlation Matrix using E-views

	BI	PE	EE	SI	FC	ESQ
BI	1					
PE	0.7633	1				
EE	0.73912	0.74383	1			
SI	0.54083	0.53471	0.69051	1		
FC	0.76269	0.7051	0.79084	0.64404	1	
ESQ	0.50701	0.54068	0.60555	0.65289	0.7045	1

The Table 5 illustrates the correlation matrix among the core constructs of the UTAUT framework used to examine FinTech adoption behavior. Behavioral Intention (BI) has strong positive correlations with Performance Expectancy (0.7633), Facilitating Conditions (0.7627), and Effort Expectancy (0.7391). This suggests that users who believe FinTech services are useful, easy to use, and have sufficient resources available are more likely to have the intention to use them. Performance Expectancy is highly positively correlated with Effort Expectancy (0.7438) and Facilitating Conditions (0.7051), indicating that if users find FinTech services to be convenient, they will likely find them to be useful as well. Effort Expectancy has a strong positive correlation with Facilitating Conditions (0.7908), which indicates that ease of use is closely linked with the availability of resources. Social Influence and E-Service Quality have moderate positive correlations with other variables, which show that these variables are associated with factors of FinTech adoption but have relatively weaker correlations with performance and infrastructure-related factors. The correlation analysis further confirms the theoretical underpinning of the UTAUT model, which indicates that there are positive correlations between the key variables of FinTech adoption.

Table 6: Regression Analysis using E-views

Dependent Variable: BI				
Method: Least Squares				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
EE	0.178213	0.125854	1.416031	0.161
ESQ	-0.11432	0.094134	-1.214436	0.2284
FC	0.365153	0.105439	3.463176	0.0009
PE	0.384882	0.098304	3.915216	0.0002
SI	0.015842	0.092484	0.171299	0.8645
C	0.606747	0.312921	1.938978	0.0563
R-squared	**0.698173**	**Mean dependent var**		**4.0625**
Adjusted R-squared	**0.677779**	**S.D. dependent var**		**0.991658**
S.E. of regression	**0.56291**	**Akaike info criterion**		**1.760645**
Sum squared resid	**23.44821**	**Schwarz criterion**		**1.939297**
Log likelihood	**-64.4258**	**Hannan-Quinn criterion**		**1.832271**
F-statistic	**34.23466**	**Durbin-Watson stat**		**1.548905**
Prob(F-statistic)	**0**			

The regression analysis as shown in Table 6 indicates that Performance Expectancy and Facilitating Conditions exert a significant positive impact ($p<0.05$) on Behavioral Intention to use FinTech services while Effort Expectancy, Social Influence, and E-Service Quality do not show statistically significant effects in in the proposed model. The R-squared of 0.698 suggests that about 69.8% of the variation in Behavioral Intention is accounted for by the independent variables in the model. The Adjusted R-squared of 0.677 suggests that the model still has strong explanatory power even after being adjusted for the number of independent variables. The F-statistic (34.23466) with a p-value as 0.000 suggests that the overall model is statistically significant and valid. Additionally, the Durbin-Watson statistic of 1.5489 indicates no serious autocorrelation problem in the residuals.

Moreover, the model has a strong explanatory power, which indicates that the perception of users regarding the functional benefits and the provision of sufficient technological support are the major drivers of users' intention to use FinTech services in this study.

Table 7: Summary of Hypothesis

Variable	Relationship with BI	Results
Performance Expectancy	Significant Positive Impact	Accepted
Effort Expectancy	No Significant Impact	Rejected
Social Influence	No Significant Impact	Rejected
Facilitating Conditions	Significant Positive Impact	Accepted
E-Service Quality	No Significant Impact	Rejected

CONCLUSION

This study examined the factors influencing FinTech adoption in India using the UTAUT model along with E-Service Quality indicating that Performance Expectancy and Facilitating Conditions are the key drivers of adoption. Users are more likely to adopt FinTech when they perceive it as time saving, useful, cost-effective, and supported by adequate infrastructure such as internet access, availability of smartphones and technical knowledge. Although Effort Expectancy, Social Influence, and E-Service Quality showed positive relationship with adoption, but the results are not statistically significant suggesting that practical benefits and accessibility override ease of use, peer influence, and service quality in navigating adoption.

The findings of the study highlight that FinTech adoption in India is becoming more value-driven rather than influenced by social factors. However, the challenges of digital divide, security, and awareness in the rural and semi-urban areas still need attention.

In conclusion, this study finds that the adoption of FinTech in India is driven by a set of technological, behavioral, and infrastructural factors, with perceived usefulness and enabling conditions being the most critical. Strengthening infrastructure, support systems, and financial literacy will be essential for sustainable growth and enhanced financial inclusion.

REFERENCES

1. Acharya, U., & Bhojak, N. (2024). A Study on Digital Natives' Adoption of Fintech: Perspectives from Generations Y and Z. International Journal of Management and Humanities, 11(1), 29–39. https://doi.org/10.35940/ijmh.a1750.11010924
2. Priya, C. S., & Rao, P. V. (2024). A study on factors influencing financial literacy and fintech adoption. MATEC Web of Conferences, 392, 01049. https://doi.org/10.1051/matecconf/202439201049
3. Singh, M. (2024). A STUDY ON THE IMPACT OF FINTECH ON CUSTOMER EXPERIENCE. INTERANTIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT, 08(06), 1–5.https://doi.org/10.55041/ijsrem35438
4. An Analysis on Customer Perception towards Fintech Adoption. (2022). In Journal of Logistics, Informatics and Service Science (Vol. 9, pp. 146–158).
5. https://doi.org/10.33168/LISS.2022.0311
6. Priyadarshini, B. I., Dr. Poonam Gupta, Nandini Jagannarayan, Dr. S. Ramesh Babu, & Dr. Sarika Keswani. (2025). Antecedents of Fintech Adoption: An Empirical Study among Millennials's Attitude and Intention (Vol. 17, Issue 7). https://www.pbr.co.in
7. Aggarwal, M., Nayak, K. M., & Bhatt, V. (2023). Examining the factors influencing fintech adoption behaviour of gen Y in India. Cogent Economics & Finance, 11(1), 2197699. https://doi.org/10.1080/23322039.2023.2197699
8. Madhavi, J (2024). FACTORS INFLUENCING FINTECH ADOPTION AMONG THE ELDERLY: INSIGHTS FROM AN EMERGING ECONOMY IN INDIA. In MEERAYAN JOURNAL (Vols. 24, Issue 12, pp. 55–56).
9. Malgaonkar, P. (2025). A Study on Evaluating Factors Influencing the Adoption of Fintech. Journal of Informatics Education and Research, 5(2), 1700-1710. https://jier.org/index.php/journal/article/view/2622/2138
10. Jena, R. K. (2025). Factors influencing the adoption of FinTech for the enhancement of financial inclusion in rural India using a mixed methods approach. Journal of Risk and Financial Management, 18(3), 150.https://doi.org/10.3390/jrfm18030150
11. Pandey, L. K., Bhattacharjee, J., Singh, R., Baker, H. K., & Sharma, R. K. (2025). Fintech Adoption and Dispositional Innovativeness in E-Gold Investment: Evidence from India. Journal of Theoretical and Applied Electronic Commerce Research, 20(2), 105. https://doi.org/10.3390/jtaer20020105
12. Kumar, S. (2023). FINTECH ROLE IN THE INDIAN MSMES. In Rajasthali Journal (Vol. 2,

Issue 2, p. 72) [Journal-article].https://www.rajasthali.marudharacollege.ac.in

13. Lal, Dr. Kavitha (2020). Factors that Influence the Customer Adoption of Fintech in Hyderabad, India. In International Journal of Recent Technology and Engineering (IJRTE) (Vol. 8, Issue 5, p. 2417). Blue Eyes Intelligence Engineering & Sciences Publication. https://doi.org/10.35940/ijrte.D9114.018520

14. Sharma, J., & Sharma, B. (2024). Fintech Adoption in Banking Sector: An Empirical Study. In Pragjyotishpur University & Assam Down Town University, Business Studies: Vol. XLV–XLV (Issue No. 1, pp. 108–110).

15. Sankararaman, G. (2025). Fintech Adoption in Urban India: A Study of Usage Patterns and Preferences in Chennai. Advances in Consumer Research, 2(4), 2367-2373. https://acr-journal.com/

16. Goswami, S., Chouhan, V., Saraswat, P., & The Author(s). (2025). FinTech adoption: driving financial inclusion at the bottom of the pyramid. Future Business Journal, 11, 150. https://doi.org/10.1186/s43093-025-00570-2

17. Jhamb, A. (2025), Chandigarh Group of Colleges, & Chandigarh Group of Colleges, Management Department. FinTech adoption and financial inclusion in rural India. Journal of Neonatal Surgery, 14(32s), 3054–3062. https://www.jneonatalsurg.com

18. Kumar, G., Murty, A., Ratna, R., & Ranjan, A. (2024). Impact of Digital Financial Literacy on Financial Inclusion – The Role Fintech Services. In Gopal Narayan Singh University, 2nd International Conference on Women in Multifaceted Research (ICWMR - 2024). https://ssrn.com/abstract=4954800

19. K, N., & K, M. (2024). Prominent factors that drive fintech adoption: An extension of the UTAUT2 model with trust. In Rani Channamma University & Rani Channamma University PG Centre, International Journal of Commerce and Management Research (pp. 52–62). https://www.managejournal.com

20. Sharma, R., Khanna, T., & Amity University. (2023). The Advancing Use of FinTech Services Among Indian Adults: A Study using UTAUT Model. In Academy of Marketing Studies Journal (Vol. 27, Issue S6, pp. 1–13).

21. Josyula, H. P. (2023). Unraveling the adoption drivers of Fintech in India: An Empirical analysis. International Journal of Computer Trends and Technology, 71(12), 49–55. https://doi.org/10.14445/22312803/ijctt-v71i12p109

22. Kapoor, A. (2025). FinTech regulation in India- Trends, developments, and outlook. LinkedIn Pulse. https://www.linkedin.com/pulse/fintech-regulation-india-2025-aviral-kapoor-i2pgc/

23. Top 10 Indian FinTech Trends to watch in 2026: AI, UPI globalization and cross-border payments. Economic Times (BFSI).https://bfsi.economictimes.indiatimes.com/news/fintech/top-10-indian-fintech-trends-to-watch-in-2026-ai-upi-globalization-and-cross-border-payments/126242404

24. India's FinTech evolution- From growth to resilience. KPMG Insights (2025). https://kpmg.com/in/en/insights/2025/10/indias-fintech-evolution-from-growth-to-resilience.html

An Empirical Investigation into the Emergence of Timeshare Hotels and their Business Impact in Puducherry

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ABSTRACT

The hospitality sector has experienced considerable changes in recent years, driven by evolving consumer preferences, advancements in technology, and innovative accommodation models. Among these changes, timeshare hotels have emerged as a unique segment that merges vacation ownership with hospitality services. Puducherry, a well-known tourist destination celebrated for its cultural heritage, beaches, and spiritual sites, has seen a rising interest in timeshare accommodations. This study explores the rise of timeshare hotels and their effects on the hotel industry in Puducherry. The research investigates the factors propelling the growth of timeshare hotels, such as affordability, flexibility, long-term vacation planning, and customer loyalty. Additionally, it examines the impact of timeshare operations on traditional hotels regarding occupancy rates, revenue generation, customer retention, and competitive positioning. The study employs an empirical approach by analysing customer perceptions, industry trends, and performance indicators within the hospitality sector. The findings suggest that timeshare hotels positively contribute to tourism development by ensuring a steady influx of visitors and stable revenue streams. However, conventional hotels encounter difficulties in adapting to changing consumer expectations and heightened competition from vacation ownership models. The study underscores the necessity for strategic innovation, enhancement of service quality, and collaborative tourism planning to fully leverage the advantages of timeshare hospitality. This research adds to the expanding literature on alternative accommodation models and offers valuable insights for hotel operators, policymakers, tourism stakeholders, and investors aiming for sustainable growth in Puducherry's hospitality sector. The findings highlight the significance of balancing traditional hotel operations with emerging hospitality trends to enhance the competitiveness of the destination.

KEYWORDS: *Timeshare Hotels-Hospitality Industry-Tourism Development-Vacation Ownership-Puducherry.*

INTRODUCTION

The global hospitality sector has undergone significant transformation over the last few decades, influenced by shifts in tourist behavior, economic expansion, technological advancements, and a rising demand for customized travel experiences. While traditional hotels, resorts, and guesthouses have historically dominated the accommodation market, alternative lodging options have gained traction in response to changing consumer expectations. One notable model is the timeshare hotel concept, which provides vacation ownership opportunities alongside hospitality services that are comparable to those of conventional hotels. The rise of timeshare hotels has added a new dimension to the tourism and hospitality landscape, affecting customer preferences and business practices across destinations worldwide. Timeshare accommodation is defined as a system where individuals acquire the right to utilize a hotel room, apartment, or resort unit for a designated period each year. In contrast to traditional hotel reservations, timeshare ownership allows customers to experience recurring vacations without the responsibilities associated with full property ownership. This model presents benefits such as cost

efficiency, guaranteed availability of accommodations, access to premium amenities, and the ability to plan vacations over the long term. Consequently, timeshare hotels have gained popularity among families, retirees, and frequent travelers who are in search of dependable and economical holiday options. The timeshare sector originated in Europe during the 1960s and has since experienced significant growth across North America, Asia, and other areas. Major hospitality firms have acknowledged the potential of vacation ownership schemes to generate consistent revenue and foster long-lasting customer relationships. Presently, leading international brands such as Marriott Vacation Club, Hilton Grand Vacations, and Wyndham Destinations operate successful timeshare divisions that complement their conventional hotel services. These advancements highlight the rising significance of timeshare lodging as an essential component of the modern hospitality sector. In India, tourism has become a crucial driver of economic development, job creation, and regional progress. The nation's rich cultural heritage, natural attractions, spiritual sites, and growing middle-class demographic have established favorable conditions for the expansion of tourism. In tandem with this growth, the hospitality industry has evolved to cater to diverse traveler preferences. Timeshare hotels and vacation ownership initiatives have gained popularity in various Indian locales, including Goa, Kerala, Rajasthan, and Puducherry. Firms like Club Mahindra and Sterling Holidays have been instrumental in promoting the timeshare concept among Indian consumers. Puducherry holds a distinctive place in India's tourism framework due to its unique combination of French colonial history, spiritual hubs, picturesque beaches, and cultural sites. The Union Territory draws both domestic and international visitors year-round, significantly contributing to the local economy. Tourism-related enterprises, such as hotels, restaurants, transportation services, and leisure facilities, have thrived due to the consistent influx of tourists. As the demand for tourism continues to rise, accommodation providers are seeking innovative strategies to boost their competitiveness and address changing customer needs. The rise of timeshare hotels in Puducherry signifies broader transformations within the hospitality sector. Travelers are increasingly pursuing value-oriented experiences, tailored services, and adaptable accommodation options. Timeshare properties cater to these demands by providing ownership advantages alongside resort-style amenities and professional hospitality management. Additionally, timeshare hotels offer operators reliable revenue streams through membership sales, maintenance fees, and repeat customer visits. These features render the timeshare model appealing to both consumers and hospitality enterprises. The expansion of timeshare hotels has significant implications for traditional hotel operators. On one hand, timeshare accommodations aid in destination development by drawing repeat visitors, prolonging average stays, and bolstering local tourism initiatives. The recurring nature of timeshare usage contributes to stabilizing tourist arrivals and mitigating seasonal demand fluctuations. Conversely, conventional hotels may encounter heightened competition for clientele, especially among family travelers and long-term vacationers who find greater value in ownership-based options. As a result, hotel managers must adjust their strategies to sustain market relevance and foster customer loyalty. Technological advancements have also played a crucial role in the growth of timeshare hospitality. Online booking platforms, customer relationship management systems, digital marketing tools, and mobile applications empower timeshare companies to effectively engage with both current and prospective members. Exchange networks enable owners to access accommodations in various destinations, enhancing the appeal of vacation ownership programs. These innovations have improved customer convenience and expanded the attractiveness of timeshare products across diverse demographic groups.From an economic standpoint, timeshare hotels play a significant role in local development by creating jobs, investing in infrastructure, and boosting tourism spending. Visitors who stay in timeshare properties frequently engage in local cultural, recreational, and shopping experiences, thereby generating revenue for nearby businesses. The long-term commitment that comes with timeshare ownership fosters destination loyalty and encourages repeat visits. In Puducherry, where tourism is a vital economic component, the growth of timeshare accommodations could facilitate sustainable tourism development and improve the competitiveness of the destination. However, despite

these advantages, timeshare hotels encounter several challenges. In certain markets, consumer awareness regarding vacation ownership is still limited. Issues related to the complexity of contracts, maintenance fees, difficulties in resale, and evolving travel preferences may impact purchasing decisions. Furthermore, economic uncertainties and global disruptions can influence consumer confidence and travel behaviors. Consequently, hospitality operators must implement transparent marketing strategies, uphold high service standards, and continuously innovate to address customer concerns and ensure sustained growth. With the rising significance of timeshare hotels in Puducherry, there is a pressing need for empirical research to investigate their emergence and effects on the wider hotel industry. Gaining insights into how timeshare accommodations affect occupancy rates, revenue performance, customer satisfaction, and competitive dynamics can offer valuable information for industry stakeholders. This understanding is crucial for formulating effective business strategies, tourism policies, and investment decisions that promote the long-term development of the hospitality sector. This research aims to explore the rise of timeshare hotels and evaluate their influence on hotel operations in Puducherry. Through the examination of industry trends, customer perceptions, and business results, this study intends to enhance the comprehension of alternative accommodation models in today's hospitality landscape.

REVIEW OF LITERATURE

Sharma and Verma (2023) investigated the expansion of vacation ownership programs in India, discovering that increasing disposable incomes and a rise in domestic tourism have significantly enhanced the appeal of timeshare accommodations. The research underscored the customers' preference for flexible vacation arrangements and the long-term benefits associated with them.

Patel and Nair (2023) examined consumer attitudes towards timeshare resorts in South India. Their results indicated that factors such as service quality, brand reputation, and exchange opportunities had a substantial impact on customer satisfaction and their intentions to purchase. The study highlighted the necessity of implementing trust-building strategies.

Kumar et al. (2024) assessed the competitive effects of timeshare properties on conventional hotels. Their findings indicated that timeshare hotels enjoyed higher customer retention rates and produced consistent revenue streams. This prompted traditional hotels to improve their loyalty programs and offer more personalized services.

Singh and Rao (2024) conducted a study on the influence of digital technologies in the promotion of vacation ownership. The authors concluded that online marketing, virtual property tours, and customer relationship management systems significantly enhanced customer engagement and boosted timeshare sales.

The World Travel and Tourism Council (WTTC) Report (2024) highlighted alternative accommodation models as significant factors in the growth of tourism. It underscored that timeshare properties enhance destination sustainability by fostering repeat visits and cultivating long-term customer loyalty.

Joseph and Mathew (2025) investigated timeshare hospitality within emerging tourist destinations. Their research indicated that timeshare accommodations have a beneficial impact on local economies by boosting tourist expenditure, creating job opportunities, and facilitating infrastructure development.

Ramesh and Karthik (2025) conducted a study on customer satisfaction in vacation ownership resorts, revealing that the quality of facilities, clarity in contracts, and availability of recreational amenities play crucial roles in member retention. The study advocated for ongoing service innovation to sustain competitiveness.

Gupta and Sharma (2025) evaluated the future potential of timeshare hotels in India. The authors determined that the growing demand for experiential tourism and family-centric travel would continue to propel the growth of vacation ownership programs in key tourist destinations.

STATEMENT OF THE PROBLEM

The hospitality sector in Puducherry is undergoing significant transformations due to changing tourist preferences and the rise of alternative accommodation options. Among these, timeshare hotels have become

increasingly popular by providing vacation ownership opportunities alongside hospitality services. In contrast to traditional hotels that primarily depend on short-term bookings, timeshare properties create recurring revenue through membership-based models and foster long-term customer relationships. While this approach offers avenues for business expansion and tourism enhancement, it also brings about new competitive challenges within the accommodation industry. Traditional hotels in Puducherry are struggling to sustain occupancy rates, customer loyalty, and revenue consistency as travelers increasingly consider value-driven vacation ownership alternatives. The rising appeal of timeshare hotels may shift market dynamics, influence consumer behavior, and impact the operational efficiency of conventional hospitality businesses. Moreover, there is a scarcity of empirical research concerning the specific effects of timeshare hotels on the hotel business landscape in Puducherry. It is essential to comprehend how timeshare hotels contribute to tourism growth, customer satisfaction, and economic progress while simultaneously influencing the operations of traditional hotels. Consequently, this study aims to explore the rise of timeshare hotels and assess their business implications for the hospitality sector in Puducherry, offering valuable insights for hotel managers, investors, and tourism policymakers.

LOGICAL BACKGROUND OF THE STUDY

The hospitality sector has undergone considerable transformations driven by changing tourist preferences, advancements in technology, and the rise of innovative lodging models. Among these changes, timeshare hotels have emerged as a notable alternative, merging vacation ownership with hotel amenities. In contrast to conventional hotels that rely on short-term reservations, timeshare hotels grant customers the right to utilize accommodations for a designated period each year, thereby ensuring consistent occupancy and stable revenue for operators. Puducherry, recognized as one of India's premier tourist destinations, draws a substantial influx of both domestic and international visitors due to its French heritage, picturesque beaches, spiritual sites, and cultural landmarks. The growing demand for high-quality lodging has spurred the development of timeshare hotels in the area. These establishments offer tourists affordable vacation options, luxurious amenities, and advantages for long-term holiday planning. The rise of timeshare hotels has impacted the traditional hotel industry by introducing new competitive dynamics within the hospitality landscape. While timeshare properties foster tourism growth through repeat visits and customer loyalty, traditional hotels may encounter challenges concerning occupancy rates, pricing strategies, and customer retention. It is crucial to comprehend the effects of this accommodation model for hospitality enterprises and policymakers. Consequently, this study investigates the rise of timeshare hotels and assesses their impact on the hotel sector in Puducherry, providing valuable insights for sustainable tourism and hospitality advancement.

OBJECTIVES OF THE STUDY

1. To investigate the rise and development of timeshare hotels in Puducherry.
2. To determine the factors that lead tourists to prefer timeshare hotels instead of traditional hotels.
3. To evaluate the effect of timeshare hotels on the operational performance of conventional hotels in Puducherry.
4. To measure customer satisfaction regarding the services and amenities offered by timeshare hotels.
5. To propose strategies aimed at enhancing the competitiveness and sustainability of the hotel sector in Puducherry.

RESEARCH QUESTIONS

1. What elements have led to the rise of timeshare hotels in Puducherry?
2. What reasons do tourists have for choosing timeshare hotels instead of conventional hotel options?
3. In what ways do timeshare hotels affect the occupancy rates and revenue of traditional hotels?
4. How satisfied are customers with the services and amenities provided by timeshare hotels?
5. What strategies can traditional hotels implement to stay competitive in the evolving hospitality landscape?

ANALYSIS AND DISCUSSION

Sample Size: 296 Respondents

(Tourists and Timeshare Hotel Customers in Puducherry)

Table 1: Demographic Profile of Respondents

Age Group	Frequency	Percentage
Below 25 Years	48	16.2
26–35 Years	102	34.5
36–45 Years	86	29.1
Above 45 Years	60	20.2
Total	296	100.0

Interpretation

A significant portion of respondents (34.5%) falls within the 26–35 years age range, suggesting that young and middle-aged travelers predominantly utilize timeshare hotels. This demographic is probably drawn to the cost-effectiveness and long-term vacation advantages provided by timeshare lodging.

Table 2: Awareness of Timeshare Hotels

Awareness Level	Frequency	Percentage
Highly Aware	96	32.4
Aware	128	43.2
Moderately Aware	50	16.9
Not Aware	22	7.5
Total	296	100.0

Interpretation

Approximately 75.6% of participants indicate that they are either aware or very aware of timeshare hotels, which implies a robust market presence and a growing acceptance of vacation ownership ideas in Puducherry.

Table 3: Factors Influencing Selection of Timeshare Hotels

Factor	Frequency	Percentage
Cost Savings	82	27.7
Guaranteed Vacation	64	21.6
Resort Amenities	70	23.6
Family-Friendly Environment	48	16.2
Exchange Opportunities	32	10.9
Total	296	100.0

Interpretation

Cost savings (27.7%) and resort amenities (23.6%) are the main factors influencing the selection of timeshare hotels. Travelers view timeshare ownership as an economical means to experience high-quality vacations.

Table 4: Perceived Impact of Timeshare Hotels on Traditional Hotels

Impact Level	Frequency	Percentage
High Impact	108	36.5
Moderate Impact	96	32.4
Low Impact	62	20.9
No Impact	30	10.2
Total	296	100.0

Interpretation

A significant portion of respondents (68.9%) perceive that timeshare hotels exert a high or moderate influence on conventional hotel operations. This suggests an increase in competition and evolving consumer preferences within the hospitality industry.

Table 5: Customer Satisfaction with Timeshare Hotels

Satisfaction Level	Frequency	Percentage
Highly Satisfied	118	39.9
Satisfied	102	34.5
Neutral	42	14.2
Dissatisfied	22	7.4
Highly Dissatisfied	12	4.0
Total	296	100.0

Interpretation

About 74.4% of participants express satisfaction or high satisfaction with timeshare hotel services. This indicates the success of timeshare hotels in providing quality lodging experiences and fostering customer loyalty.

Table 6: Impact on Occupancy Rates of Traditional Hotels

Response	Frequency	Percentage
Significant Decrease	92	31.1
Moderate Decrease	104	35.1
No Change	68	23.0
Increase	32	10.8
Total	296	100.0

Interpretation

Approximately 66.2% of participants observe a decline in occupancy rates for conventional hotels as a result of the rise in timeshare properties. This underscores the competitive impact of vacation ownership models.

SUGGESTIONS

1. Improve Service Quality in Traditional Hotels: Traditional hotels must prioritize enhancing customer service, personalized experiences, and hospitality standards to effectively compete with timeshare hotels.
2. Create Customer Loyalty Programs: Hotels ought to implement appealing loyalty and membership programs that promote repeat visits and bolster customer retention.
3. Embrace Digital Technologies: Hospitality enterprises should leverage online booking systems, customer relationship management (CRM) tools, mobile applications, and digital marketing strategies to enhance customer engagement.
4. Offer Innovative Accommodation Packages: Traditional hotels can provide long-stay packages, family vacation plans, and bundled tourism services to attract travelers seeking value-driven travel experiences.
5. Raise Consumer Awareness: Timeshare operators should deliver clear information regarding ownership benefits, costs, contractual obligations, and exchange opportunities to foster customer trust.
6. Enhance Collaboration among Stakeholders: Tourism authorities, hotel associations, and timeshare companies should collaborate to promote Puducherry as a favored vacation destination.
7. Promote Sustainable Tourism Practices: Both timeshare and traditional hotels should implement environmentally responsible practices to support sustainable tourism development.
8. Perform Regular Market Research: Hospitality operators should consistently track evolving customer preferences and emerging tourism trends to maintain competitiveness.

RECOMMENDATIONS

1. The Government of Puducherry ought to develop policies that promote the responsible expansion of the timeshare hospitality industry while safeguarding consumer interests.
2. Tourism promotion agencies are encouraged to incorporate timeshare accommodations into their destination marketing strategies to draw in returning visitors.
3. Traditional hotels should broaden their service offerings by integrating wellness tourism, cultural experiences, and experiential travel packages.
4. Timeshare companies must ensure transparency in their membership agreements and pricing models to build customer trust.
5. Hospitality training institutions should offer specialized programs focused on vacation ownership management and customer relationship strategies.
6. Hotel operators should prioritize investments in technological advancements to enhance operational efficiency and improve guest satisfaction.
7. Public-private partnerships should be promoted to bolster tourism infrastructure and facilitate growth within the hospitality sector.
8. Future research may investigate the long-term economic and social effects of timeshare tourism in developing destinations.

CONCLUDING OBSERVATIONS

The rise of timeshare hotels signifies a major shift in the hospitality sector, providing an alternative lodging

model that merges vacation ownership with superior hospitality services. In Puducherry, the expansion of timeshare hotels has been fueled by a growing tourist demand for affordable, flexible, and value-oriented vacation options. The research indicates that timeshare hotels have achieved substantial acceptance among travelers due to their cost-effectiveness, high-end amenities, and long-term vacation advantages. The results show that timeshare hotels play a positive role in tourism development by promoting repeat visits, boosting customer loyalty, generating consistent revenue streams, and aiding local economic activities. Concurrently, the growth of timeshare accommodations has heightened competition within the hotel sector, posing challenges for traditional hotels regarding occupancy rates, pricing strategies, and customer retention. In spite of these challenges, the study proposes that traditional hotels can maintain their competitiveness through service innovation, digital transformation, personalized guest experiences, and effective marketing strategies. The coexistence of timeshare and traditional hotels can foster a diverse and resilient hospitality ecosystem that benefits tourists, businesses, and the local economy. In summary, timeshare hotels have become a vital element of Puducherry's tourism and hospitality industry. Their ongoing growth, bolstered by suitable policies, transparent business practices, and sustainable tourism initiatives, can significantly enhance the long-term development and competitiveness of the destination.

REFERENCES

1. Brown, T., & Smith, J. (2023). The role of vacation ownership in destination competitiveness. International Journal of Hospitality Management, 112, 103456.
2. Gupta, R., & Sharma, P. (2025). Future prospects of timeshare hotels in India. Journal of Tourism and Hospitality Research, 18(2), 78–92.
3. Joseph, A., & Mathew, R. (2025). Economic contributions of timeshare resorts in emerging tourism destinations. Tourism Economics, 31(1), 115–132.
4. Kumar, S., Reddy, P., & Nair, K. (2024). Competitive implications of timeshare accommodations on hotel performance. International Hospitality Review, 38(3), 215–229.
5. Lee, H., & Chen, Y. (2023). Customer loyalty and vacation ownership programs: An empirical analysis. Journal of Vacation Marketing, 29(4), 421–437.
6. Patel, D., & Nair, V. (2023). Consumer perceptions of timeshare resorts in South India. South Asian Journal of Tourism Studies, 12(1), 45–59.
7. Ramesh, P., & Karthik, S. (2025). Customer satisfaction and retention in vacation ownership resorts. Journal of Hospitality and Tourism Insights, 8(2), 145–160.
8. Sharma, A., & Verma, R. (2023). Growth trends in India's vacation ownership industry. Indian Journal of Tourism Research, 17(2), 34–48.
9. Singh, M., & Rao, K. (2024). Digital transformation and vacation ownership marketing. International Journal of Tourism Technology, 9(1), 56–71.
10. Williams, K., & Johnson, D. (2024). Alternative accommodation models and hospitality industry transformation. Tourism Management Perspectives, 50, 101132.

Exploring the Expansion of Timeshare Hotels and Their Role in Shaping the Hospitality Industry in Puducherry

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ABSTRACT

The hospitality sector has experienced notable changes in recent decades, influenced by evolving consumer preferences, advancements in technology, and innovative accommodation models. Among these changes, timeshare hotels have emerged as a distinctive lodging concept that merges vacation ownership with hospitality services. Timeshare hotels offer travelers the chance to buy or lease accommodation rights for a designated period each year, providing cost-effective vacation experiences and advantages for long-term holiday planning. In India, the rise of domestic tourism, increasing disposable incomes, and a growing demand for leisure travel have fueled the expansion of the timeshare sector. Puducherry, a well-known coastal tourism destination celebrated for its French colonial heritage, spiritual sites, beaches, and cultural diversity, has become a promising market for the development of timeshare hotels. The growth of timeshare hotels in Puducherry has resulted in significant economic and social impacts on the local hospitality sector. These establishments lead to increased tourist arrivals, higher occupancy rates, job creation, and improved competitiveness of the destination. Furthermore, timeshare properties encourage repeat visits and foster customer loyalty, establishing a reliable revenue stream for hospitality enterprises. Nevertheless, challenges such as consumer awareness, regulatory issues, maintenance expenses, and competition from alternative accommodation options continue to pose significant hurdles. This study investigates the expansion of timeshare hotels in Puducherry and assesses their influence on the local hospitality industry. It underscores the opportunities and challenges linked to the timeshare model and evaluates its role in tourism development, economic sustainability, and customer satisfaction. The results offer valuable insights for policymakers, tourism planners, and hospitality professionals aiming to utilize timeshare accommodations for destination growth and sustainable tourism development.

KEYWORDS: *Timeshare Hotels-Hospitality Industry-Tourism Development- Vacation Ownership- Puducherry Tourism.*

INTRODUCTION

The global tourism and hospitality sector has experienced significant changes in recent decades, driven by shifting traveler preferences, enhanced mobility, digital advancements, and innovative lodging models. Among the various types of accommodations that have surfaced, timeshare hotels have emerged as a notable alternative for vacation stays. In contrast to conventional hotel experiences, timeshare hotels function on a vacation ownership basis, allowing customers to buy the right to utilize a property for a designated period each year. This arrangement offers travelers cost-effective holiday options while providing a reliable customer base for hospitality enterprises. The idea of timeshare accommodation began in Europe during the 1960s and subsequently expanded rapidly throughout North America and other regions. This model was developed to enable middle-income travelers, who could not afford full ownership of resort properties, to access luxury vacation options. Over the

years, the timeshare industry has matured into a refined segment of the hospitality field, presenting flexible ownership plans, exchange programs, and high-quality vacation experiences. Currently, prominent hospitality brands such as Marriott Vacation Club, Hilton Grand Vacations, Wyndham Destinations, and Disney Vacation Club have incorporated timeshare services into their business offerings. In India, tourism has emerged as a vital driver of economic growth, creating job opportunities and generating foreign exchange revenue. The rise of domestic tourism, coupled with increasing disposable incomes, urbanization, and evolving lifestyles, has facilitated the acceptance of vacation ownership products. The timeshare sector in India has seen consistent growth, with key players such as Mahindra Holidays & Resorts India Limited, Sterling Holidays, and Club Mahindra taking a leading role in the promotion of vacation ownership. These companies have established resort properties in various tourist hotspots, providing members with year-round access to accommodations and recreational amenities. Puducherry, previously known as Pondicherry, stands out as one of India's most sought-after coastal tourism locations. Situated on the southeastern coast, Puducherry draws visitors with its distinctive combination of French colonial history, picturesque beaches, spiritual sites, cultural richness, and a robust tourism infrastructure. The city boasts famous attractions like Promenade Beach, Auroville, Sri Aurobindo Ashram, Paradise Beach, and the French Quarter. These sites attract both domestic and international travelers, making tourism a fundamental component of the local economy.

The growing appeal of Puducherry as a leisure destination has fostered an environment conducive to the expansion of timeshare hotels. Tourists frequenting the area often look for comfortable, long-term, and family-friendly lodging options that provide good value. Timeshare properties meet these demands by offering spacious accommodations, recreational facilities, and tailored vacation experiences. Consequently, hospitality enterprises have acknowledged the advantages of the timeshare model in boosting customer loyalty and encouraging repeat visits. One of the primary benefits of timeshare hotels is their capacity to create consistent revenue streams. In contrast to conventional hotels that are significantly influenced by seasonal demand variations, timeshare properties obtain advance commitments from members, thereby minimizing occupancy uncertainties. This financial reliability enables operators to allocate resources towards enhancing services, developing infrastructure, and engaging in destination marketing initiatives. Moreover, timeshare members frequently revisit the same location, thereby fostering local economic growth through expenditures on dining, transportation, shopping, and recreational pursuits. The growth of timeshare hotels in Puducherry has also played a role in generating employment and fostering tourism-related entrepreneurship. The establishment and management of timeshare properties provide direct job opportunities in areas such as hotel management, housekeeping, food and beverage services, maintenance, and customer support. Furthermore, local enterprises, including travel agencies, restaurants, handicraft stores, and transport services, benefit from the increased influx of tourists associated with vacation ownership programs. Another notable contribution of timeshare hotels is their role in advancing sustainable tourism development. Given that timeshare owners are repeat visitors with a vested interest in the destination, they tend to demonstrate higher levels of environmental consciousness and community involvement compared to short-term tourists. Hospitality operators can capitalize on this relationship to adopt eco-friendly practices, cultural preservation efforts, and responsible tourism initiatives. Such actions are in harmony with the overarching objectives of sustainable destination management and community-based tourism development. Despite the advantages, the timeshare industry encounters numerous challenges. Consumer doubts regarding ownership agreements, maintenance fees, contract intricacies, and resale restrictions can affect purchasing choices. Furthermore, the rise of online accommodation services like Airbnb and Booking.com has heightened competition in the hospitality sector. Consequently, timeshare operators must consistently innovate and enhance service quality to maintain their competitive edge.

Technological progress has also transformed the timeshare industry. Digital booking platforms, virtual property tours, customer relationship management systems, and mobile applications have improved

customer convenience and engagement. These advancements allow timeshare companies to provide flexible vacation planning options and elevate customer satisfaction levels. The influence of timeshare hotels on the hospitality industry goes beyond merely providing accommodation. They play a significant role in destination marketing strategies, stimulate tourism investment, cultivate customer loyalty, and contribute to regional economic development. In locations like Puducherry, where tourism is vital for economic advancement, comprehending the effects of timeshare hotels is crucial for policymakers and industry stakeholders. Thus, this study aims to investigate the growth of timeshare hotels in Puducherry and evaluate their impact on the hospitality industry. It seeks to analyze the economic, social, and tourism-related effects of timeshare accommodations and identify avenues for sustainable growth within the sector.

NATIONAL AND INTERNATIONAL STATUS OF TIMESHARE HOTELS

The timeshare sector has transformed into a significant component of the global hospitality industry. The concept originated in Europe during the 1960s and gained considerable traction in the United States throughout the 1970s and 1980s. Currently, the worldwide timeshare market is valued in the billions and caters to millions of vacation owners across the globe.

INTERNATIONAL STATUS

The United States continues to be the largest market for timeshares worldwide. Industry reports indicate that over 9 million households possess timeshare memberships, making a substantial contribution to the tourism economy. Prominent hospitality companies such as Marriott Vacation Club, Hilton Grand Vacations, Wyndham Destinations, Hyatt Residence Club, and Disney Vacation Club lead the market. These organizations have developed extensive networks of resorts that offer vacation ownership opportunities in various locations. Europe is another key region for the development of timeshares. Nations like Spain, France, Portugal, and the United Kingdom have seen significant growth in vacation ownership properties. Spain, especially the Canary Islands and Costa del Sol, remains one of the most sought-after timeshare locations due to its favorable climate and robust tourism demand. The Asia-Pacific region has emerged as a rapidly expanding market for timeshare accommodations. Countries such as Thailand, Indonesia, Malaysia, Japan, and Australia have witnessed increasing investments in vacation ownership resorts. The growth has been supported by rising disposable incomes, a burgeoning middle class, and an increasing interest in leisure travel. International hotel brands have introduced flexible points-based ownership systems to appeal to younger travelers who desire greater flexibility in their vacation plans. Technological advancements have profoundly altered the global timeshare industry. Digital booking platforms, online exchange systems, virtual tours, and mobile applications have enhanced customer satisfaction and operational effectiveness. Sustainability has emerged as a key priority, with numerous international resorts implementing eco-friendly construction methods, energy-saving initiatives, and responsible tourism practices.

NATIONAL STATUS IN INDIA

The timeshare market in India began to gain traction in the 1990s when organized vacation ownership firms launched membership-based holiday programs. The burgeoning tourism sector, increasing middle-class income, and heightened demand for family vacations fostered a conducive environment for industry growth. Club Mahindra, managed by Mahindra Holidays & Resorts India Limited, stands as the foremost entity in the Indian timeshare market. The company oversees a multitude of resorts across India and abroad, catering to hundreds of thousands of members. Sterling Holidays is another prominent organization providing vacation ownership services through a network of resorts situated in sought-after tourist locations. Indian timeshare properties are primarily located in regions such as Goa, Kerala, Ooty, Kodaikanal, Coorg, Munnar, Shimla, Darjeeling, Rajasthan, and the Andaman Islands. These areas draw tourists in search of nature-oriented, cultural, and recreational activities. The Indian government has actively encouraged tourism through initiatives like Incredible India, Swadesh Darshan, and PRASHAD schemes. These programs have indirectly bolstered the growth of timeshare accommodations by improving tourism infrastructure and enhancing destination accessibility. Enhanced transportation networks,

airport expansions, and digital tourism services have further solidified the industry's future prospects. The COVID-19 pandemic initially impacted the timeshare industry due to travel limitations and decreased tourist mobility. Nevertheless, the sector exhibited resilience by focusing on domestic tourism and extended vacation experiences. Many travelers opted for controlled resort environments, which proved advantageous for timeshare operators.

Consumer preferences in India are evolving towards experiential tourism, wellness travel, and family-centric vacations. In response, timeshare resorts have begun to offer spa amenities, adventure activities, cultural experiences, and tailored holiday packages. Additionally, flexible ownership plans and exchange programs have enhanced consumer attraction.

Status in Puducherry

Puducherry has become a desirable destination for timeshare and resort-based accommodations, thanks to its coastal allure, cultural heritage, and year-round tourism appeal. The location draws visitors from Tamil Nadu, Karnataka, Kerala, Andhra Pradesh, as well as international markets. The development of tourism infrastructure in Puducherry has spurred hospitality investments, including boutique resorts, heritage hotels, beach resorts, and vacation ownership properties. Timeshare accommodations in the area primarily serve families, retirees, and leisure travelers seeking recurring holiday experiences. The hospitality sector in Puducherry benefits from the timeshare model through improved occupancy stability, repeat visits, and increased tourist expenditure. Timeshare owners frequently return each year, contributing to the local economy and supporting ancillary tourism enterprises. The future outlook for timeshare hotels in Puducherry is optimistic. The growth of domestic tourism, enhanced connectivity, rising awareness of vacation ownership, and increasing demand for premium leisure experiences are anticipated to propel further expansion. Strategic partnerships among tourism authorities, hospitality operators, and local communities can bolster the destination's competitiveness and promote sustainable tourism growth.

LOGICAL BACKGROUND OF THE STUDY

The rise of timeshare hotels signifies a major shift in the hospitality sector, presenting a novel accommodation model that merges vacation ownership with high-quality hospitality services. As the demand for tourism continues to escalate, travelers are increasingly in search of affordable, flexible, and tailored holiday experiences. Timeshare hotels meet these demands by offering repeated access to resort accommodations while promoting customer loyalty and fostering long-term engagement.

Puducherry has emerged as one of India's premier coastal tourism hotspots, renowned for its cultural heritage, spiritual sites, beaches, and recreational activities. The consistent growth in tourist arrivals has prompted hospitality enterprises to broaden their accommodation options. In this regard, timeshare hotels have become significant as they provide stable revenue, promote repeat visits, and enhance the competitiveness of the destination. This study is fundamentally based on the necessity to comprehend how timeshare hotels impact the hospitality ecosystem in Puducherry. Their growth influences occupancy rates, job creation, tourism spending, customer satisfaction, and local economic progress. Additionally, the changing tourism landscape, marked by technological innovations and evolving consumer preferences, calls for a thorough analysis of the effectiveness of the timeshare model. Consequently, exploring the development and effects of timeshare hotels offers essential insights for tourism planners, policymakers, and hospitality managers who are aiming for sustainable strategies for destination growth and industry progress in Puducherry.

OBJECTIVES

1. To examine the demographic characteristics of tourists who utilize timeshare hotels in Puducherry.
2. To determine the factors that affect tourists' choices regarding timeshare hotel accommodations.
3. To evaluate customer satisfaction levels concerning the services and facilities offered by timeshare hotels.
4. To analyze the role of timeshare hotels in the

growth and advancement of the hospitality sector in Puducherry.

5. To identify the challenges and opportunities linked to the expansion of timeshare hotels in Puducherry.

RESEARCH QUESTIONS

1. What demographic traits define tourists who opt for timeshare hotels in Puducherry?
2. What elements affect tourists' decisions to select timeshare hotels instead of conventional lodging options?
3. To what extent are customers satisfied with the services, amenities, and overall experience offered by timeshare hotels?
4. In what ways do timeshare hotels aid in the growth of tourism, job creation, and revenue generation in Puducherry?
5. What significant challenges and prospective opportunities exist for the growth of timeshare hotels within the hospitality industry?

REVIEW OF LITERATURE

Sharma and Gupta (2022) investigated the expansion of vacation ownership programs in India and their impact on tourist loyalty. The research indicated that timeshare customers were more likely to return for repeat visits than traditional hotel patrons. The authors concluded that vacation ownership fosters enduring customer relationships and enhances occupancy stability.

Kumar and Singh (2022) assessed consumer perceptions of timeshare resorts located in prominent Indian tourist destinations. Their results indicated that factors such as affordability, quality of accommodation, and family-friendly amenities played a significant role in customer satisfaction. Nonetheless, issues related to maintenance fees and transparency of contracts were identified as significant challenges.

Johnson and Miller (2023) examined the economic impact of timeshare resorts in the United States. Their study emphasized that timeshare properties created considerable employment opportunities and generated revenue for local businesses. The researchers noted that repeat visitors made a substantial contribution to the sustainability of destinations.

Brown and Wilson (2024) investigated sustainable practices within timeshare resorts. Their findings indicated that environmentally responsible operations improved customer satisfaction and enhanced the image of the destination. The researchers advocated for the incorporation of sustainability initiatives into the management strategies of resorts.

Chatterjee and Bose (2024) explored the connection between customer satisfaction and service quality in Indian vacation ownership resorts. The results demonstrated that service quality factors such as responsiveness, reliability, and empathy had a significant impact on decisions regarding membership renewal.

Thomas and George (2025) examined the influence of technology on the transformation of the timeshare industry. The study revealed that AI-driven customer support, online booking systems, and virtual property tours improved operational efficiency and increased customer engagement.

ANALYSIS & DISCUSSION

Table 1: Gender of Respondents (n = 150)

Gender	Frequency	Percentage
Male	92	61.3
Female	58	38.7
Total	150	100.0

Interpretation

The table reveals that 61.3% of the respondents are male, while 38.7% are female. This indicates that male tourists constitute a larger proportion of timeshare hotel users in Puducherry.

Table 2: Age of Respondents (n = 150)

Age Group	Frequency	Percentage
Below 30 Years	22	14.7
31–40 Years	46	30.7
41–50 Years	53	35.3
Above 50 Years	29	19.3
Total	150	100.0

Interpretation

The majority of respondents (35.3%) belong to the 41–50 years age group, indicating that middle-aged travelers are the primary customers of timeshare hotels.

Table 3: Educational Qualification (n = 150)

Qualification	Frequency	Percentage
School Level	18	12.0
Undergraduate	52	34.7
Postgraduate	61	40.7
Professional Degree	19	12.6
Total	150	100.0

Interpretation

Most respondents (40.7%) possess postgraduate qualifications, suggesting that educated consumers are more likely to participate in timeshare ownership programs.

Table 4: Monthly Family Income (n = 150)

Income (₹)	Frequency	Percentage
Below 30,000	24	16.0
30,001–50,000	39	26.0
50,001–75,000	48	32.0
Above 75,000	39	26.0
Total	150	100.0

Interpretation

The highest proportion of respondents (32%) earn between ₹50,001 and ₹75,000 per month, indicating that middle- and upper-middle-income groups are the major users of timeshare hotels.

Table 5: Purpose of Choosing Timeshare Hotels (n = 150)

Purpose	Frequency	Percentage
Family Vacation	61	40.7
Leisure Travel	42	28.0
Relaxation	28	18.7
Business-cum-Leisure	19	12.6
Total	150	100.0

Interpretation

Family vacation is the most important purpose (40.7%) for choosing timeshare hotels, demonstrating their appeal among families seeking planned holiday experiences.

Table 6: Frequency of Visit to Puducherry (n = 150)

Frequency	Frequency	Percentage
First Visit	31	20.7
Once a Year	57	38.0
Twice a Year	41	27.3
More than Twice	21	14.0
Total	150	100.0

Interpretation

Most respondents (38%) visit Puducherry once a year, indicating the strong repeat-visit nature of timeshare tourism.

Table 7: Satisfaction Level with Timeshare Hotels (n = 150)

Satisfaction Level	Frequency	Percentage
Highly Satisfied	63	42.0
Satisfied	49	32.7
Neutral	22	14.7
Dissatisfied	11	7.3
Highly Dissatisfied	5	3.3
Total	150	100.0

Interpretation

A significant majority (74.7%) of respondents are either satisfied or highly satisfied with timeshare hotel services in Puducherry.

Table 8: Awareness Source of Timeshare Hotels (n = 150)

Source	Frequency	Percentage
Social Media	46	30.7
Friends/Relatives	38	25.3
Travel Agencies	29	19.3
Advertisements	24	16.0
Others	13	8.7
Total	150	100.0

Interpretation

Social media (30.7%) is the major source of awareness regarding timeshare hotels, followed by recommendations from friends and relatives.

Table 9: Major Benefits of Timeshare Hotels (n = 150)

Benefit	Frequency	Percentage
Cost Savings	48	32.0
Quality Accommodation	39	26.0
Family-Friendly Facilities	31	20.7
Holiday Planning Convenience	20	13.3
Membership Benefits	12	8.0
Total	150	100.0

Interpretation

Cost savings (32%) are considered the primary benefit of timeshare hotels, followed by quality accommodation and family-friendly facilities.

POLICY RECOMMENDATIONS

1. Strengthen the Regulatory Framework

The Government of Puducherry ought to implement explicit regulations that govern timeshare ownership agreements, consumer rights, and mechanisms for dispute resolution. This initiative will promote transparency and foster customer trust.

2. Promote Consumer Awareness Programs

Tourism authorities and hospitality providers should initiate awareness campaigns aimed at educating prospective customers regarding the advantages, obligations, and conditions related to timeshare ownership.

3. Encourage Sustainable Tourism Practices

Timeshare hotels are encouraged to embrace environmentally sustainable practices, including waste management, the use of renewable energy, water conservation, and the development of eco-friendly infrastructure to promote responsible tourism.

4. Enhance Digital Marketing Initiatives

Hospitality organizations should leverage social media platforms, virtual tours, mobile applications, and digital booking systems to raise awareness and attract a younger demographic of travelers.

5. Improve Service Quality Standards

Regular training programs for staff should be implemented to enhance customer service, hospitality skills, and guest relationship management, thereby boosting customer satisfaction and retention.

6. Support Infrastructure Development

The government should allocate resources towards improving transportation, road connectivity, public amenities, and tourism infrastructure in proximity to major tourist attractions to enhance visitor experiences.

7. Encourage Public-Private Partnerships

Collaboration among tourism authorities, hotel operators, and private investors can facilitate the establishment of new timeshare properties and enhance the competitiveness of the destination.

8. Develop Flexible Ownership Models

Timeshare operators should consider introducing flexible membership plans, points-based systems, and exchange programs to better align with evolving consumer preferences and travel behaviors.

9. Strengthen Local Economic Linkages

Timeshare hotels should partner with local businesses, artisans, restaurants, and tour operators to maximize the economic advantages for the local community.

EXPECTED OUTCOMES OF THE STUDY

1. Enhanced comprehension of the growth trends of timeshare hotels in Puducherry.
2. Analysis of customer preferences and satisfaction rates concerning timeshare accommodations.
3. Evaluation of the economic and tourism-related impacts of timeshare hotels.
4. Identification of operational and regulatory obstacles impacting the sector.
5. Development of policy initiatives to promote sustainable growth within the timeshare hospitality industry.

CONCLUSION

The growth of timeshare hotels has become a notable advancement in the hospitality sector, presenting a unique accommodation model that merges vacation

ownership with premium hospitality services. The results of this research indicate that timeshare hotels have positively impacted the development of Puducherry's tourism and hospitality industry by improving tourist retention, boosting occupancy rates, creating job opportunities, and establishing reliable revenue streams for hotel operators. Their capacity to draw repeat visitors has reinforced destination loyalty and supported the long-term viability of tourism activities in the area. The research highlights that family vacations, cost efficiency, and quality lodging are the key factors driving tourists to select timeshare hotels. A significant number of participants reported satisfaction with the services and amenities offered, demonstrating the effectiveness of the timeshare model in fulfilling customer expectations. Additionally, the sector has been instrumental in positioning Puducherry as a favored leisure destination for both domestic and international travelers. However, despite these benefits, challenges such as limited consumer awareness, elevated maintenance costs, complex contracts, and rising competition from online accommodation services continue to hinder the industry's growth potential. It is crucial to tackle these challenges through effective regulations, transparent business practices, customer education, and technological advancements to ensure ongoing development. In summary, timeshare hotels constitute a significant segment of the hospitality industry in Puducherry. With suitable policy backing, enhanced service quality, and sustainable tourism practices, the timeshare sector can further improve destination competitiveness, aid economic growth, and bolster Puducherry's status as a premier tourism destination in India. The study underscores the importance of strategic planning and stakeholder collaboration in maximizing the benefits of timeshare hotels for the hospitality industry and the broader tourism economy.

REFERENCES

1. Ahn, Y., & Kwon, J. (2023). Customer satisfaction and loyalty in vacation ownership resorts. International Journal of Hospitality Management, 108, 103375. https://doi.org/10.1016/j.ijhm.2023.103375
2. Brown, T., & Wilson, P. (2024). Sustainable practices and customer perceptions in timeshare resorts. Journal of Sustainable Tourism, 32(4), 845–862. https://doi.org/10.1080/09669582.2024.XXXXXX
3. Chatterjee, S., & Bose, R. (2024). Service quality dimensions and customer retention in Indian vacation ownership resorts. Tourism Management Perspectives, 49, 101180.
4. Crotts, J. C., & Ragatz, R. L. (2022). Recent developments in the global timeshare industry and tourism markets. Journal of Vacation Marketing, 28(3), 289–304.
5. Fernandes, A., & Rodrigues, M. (2023). Timeshare tourism and destination competitiveness in European coastal regions. Tourism Review, 78(5), 1224–1238.
6. George, B. P., & Henthorne, T. L. (2022). Vacation ownership and tourism development: Emerging trends and challenges. Worldwide Hospitality and Tourism Themes, 14(2), 165–178.
7. Gibson, H. J., & Singh, N. (2023). Vacation ownership and repeat visitation behavior among leisure travelers. Journal of Travel Research, 62(6), 1198–1212.
8. González, M., & Pérez, L. (2024). Consumer trust and purchasing behavior in timeshare accommodation markets. International Hospitality Review, 38(1), 55–70.
9. Johnson, D., & Miller, S. (2023). Economic contributions of timeshare resorts to local tourism economies in the United States. Tourism Economics, 29(4), 890–908.
10. Jones, P., Hillier, D., & Comfort, D. (2022). The future of vacation ownership in the hospitality industry. Worldwide Hospitality and Tourism Themes, 14(4), 421–430.
11. Kim, J., & Lee, S. (2025). Digital transformation in timeshare hospitality: Opportunities and challenges. International Journal of Hospitality & Tourism Administration, 26(1), 45–63.
12. Kumar, R., & Singh, P. (2022). Consumer perceptions towards timeshare resorts in India. Journal of Tourism and Hospitality Management, 10(3), 112–126.
13. Lee, H., & Park, K. (2025). Flexible ownership models and future growth of the global timeshare industry. Tourism Management Perspectives, 53, 101265.
14. Mahindra Holidays & Resorts India Ltd. (2024). Annual report 2023–2024. Chennai: Mahindra Holidays & Resorts India Limited.
15. Ministry of Tourism. (2024). India tourism statistics 2024. Government of India, New Delhi.

16. Patel, D., & Shah, R. (2023). Hospitality innovation and customer retention in vacation ownership resorts. Journal of Hospitality and Tourism Technology, 14(3), 387–402.

17. Ragatz, R. L. (2023). Vacation ownership industry outlook and market performance. Journal of Vacation Marketing, 29(2), 145–158.

18. Rajan, S., & Karthikeyan, M. (2024). Resort tourism development and timeshare accommodation demand in South India. South Asian Journal of Tourism and Heritage, 17(1), 56–72.

19. Sharma, A., & Gupta, V. (2022). Growth of vacation ownership programs and tourist loyalty in India. Indian Journal of Tourism Research, 11(2), 78–92.

20. Sterling Holidays. (2024). Corporate sustainability and annual performance report 2023–2024. Chennai: Sterling Holiday Resorts Ltd.

21. Thomas, J., & George, M. (2025). Artificial intelligence and technological innovations in the timeshare industry. Journal of Hospitality and Tourism Technology, 16(1), 89–105.

22. UN Tourism. (2024). World tourism barometer. Madrid: United Nations World Tourism Organization.

23. World Travel & Tourism Council (WTTC). (2024). Economic impact report 2024. London: WTTC.

24. Wyndham Destinations. (2024). Global vacation ownership industry report. Orlando, FL: Wyndham Destinations.

25. Yooyen, J., & Wongsurawat, W. (2023). Tourist satisfaction and revisit intentions in resort accommodations. Asia Pacific Journal of Tourism Research, 28(7), 703–718.

26. Zhang, Y., & Chen, X. (2024). Vacation ownership, destination loyalty, and tourism sustainability. Sustainability, 16(5), 2147. https://doi.org/10.3390/su16052147

Evaluating Customer Satisfaction in the Hotel Sector with Reference to Premium and Luxury Hotels in Chennai

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ABSTRACT

The hotel sector is vital for the economic advancement of metropolitan areas, contributing to tourism, job creation, and the growth of the service industry. In Chennai, recognized as one of India's premier business and tourism hubs, there has been notable expansion in premium and luxury hotels, driven by a rise in both domestic and international travel. Customer satisfaction has become a pivotal factor in determining hotel success, affecting customer loyalty, generating positive word-of-mouth, and encouraging repeat visits. This research investigates the elements that influence customer satisfaction in Chennai's premium and luxury hotels. It emphasizes essential service aspects such as room quality, staff conduct, food and beverage offerings, technological facilities, safety protocols, pricing strategies, and the overall guest experience. Recent trends in the hospitality sector, including digital advancements, tailored services, and sustainability efforts, have significantly shaped customer expectations. The study reviews current literature and underscores the necessity of upholding high service standards to secure a competitive edge. Previous research findings suggest that service quality, responsiveness, reliability, and personalized experiences are key indicators of customer satisfaction in luxury hospitality environments. This study adds to the expanding knowledge base in hospitality management by offering insights into customer perceptions and satisfaction levels within the premium and luxury hotel market in Chennai. The outcomes are anticipated to aid hotel managers in formulating effective strategies to improve guest experiences and enhance customer loyalty.

KEYWORDS: *Customer Satisfaction-Luxury Hotels-Hospitality Industry-Service Quality-Chennai Tourism.*

INTRODUCTION

The hospitality sector is recognized as one of the fastest-expanding industries worldwide, significantly contributing to economic growth, tourism expansion, and job creation. Hotels, being a fundamental element of this sector, are essential in offering accommodation, dining, leisure activities, and tailored services to travelers. The growing globalization of tourism and business operations has heightened competition among hotels, making customer satisfaction a crucial factor for organizational success. In the current highly competitive market landscape, hotels are required to consistently enhance their service quality to fulfill and surpass customer expectations. Customer satisfaction is defined as the degree to which guests feel their expectations have been met through the services and experiences offered by a hotel. It is regarded as one of the key metrics of business performance, as satisfied customers are more inclined to return, recommend the hotel to others, and foster long-term loyalty. Conversely, dissatisfied customers can adversely affect a hotel's reputation through negative reviews and unfavorable word-of-mouth, especially in today's digital era where online feedback plays a significant role in consumer choices. In recent years, the premium and luxury hotel segments have gained considerable significance due to the rising demand for high-quality accommodations and personalized services. Luxury hotels set themselves apart through superior facilities, outstanding customer service, exclusive amenities, and distinctive guest experiences.

Similarly, premium hotels aim to provide enhanced comfort and service quality but may appeal to a wider market segment. The success of these establishments is largely contingent upon their ability to craft memorable experiences that cater to a variety of customer needs. Chennai, the capital of Tamil Nadu, stands as one of India's key centers for commerce, industry, education, and healthcare. Each year, the city draws millions of visitors from both domestic and international locations for various purposes, including business, medical tourism, education, cultural exploration, and leisure activities. The strategic positioning of Chennai, along with its well-established infrastructure and rich cultural legacy, has played a crucial role in the expansion of its hospitality industry. The city is home to a multitude of premium and luxury accommodations, featuring both globally recognized hotel chains and esteemed domestic brands that serve a wide range of clientele. The swift advancement of Chennai's tourism and business sectors has resulted in heightened competition among hotels. Today's guests are more knowledgeable and discerning than ever, thanks to the easy availability of online information and review platforms. They anticipate seamless services, cutting-edge technological amenities, personalized attention, cleanliness, safety, and value for their money. As a result, hotel managers must comprehend the elements that influence customer satisfaction to formulate effective service strategies and sustain their competitive edge. Service quality is a critical factor in determining customer satisfaction within hotels. The SERVQUAL model outlines five dimensions of service quality: tangibility, reliability, responsiveness, assurance, and empathy. These dimensions hold particular significance in luxury hospitality environments where customer expectations are exceptionally elevated. Tangibility pertains to the physical facilities, equipment, and overall appearance; reliability signifies consistent service delivery; responsiveness indicates prompt assistance; assurance embodies employee competence and trustworthiness; and empathy pertains to the provision of personalized care and attention.

Technological innovations have significantly altered the hospitality sector. Contemporary guests anticipate that hotels will offer digital amenities such as online booking, mobile check-in and check-out, high-speed internet access, contactless payment options, and smart room features. The incorporation of artificial intelligence, chatbots, and tailored digital services has further improved customer experiences. Hotels that successfully utilize technology can enhance operational efficiency while boosting customer satisfaction. Another crucial element affecting customer satisfaction is the caliber of food and beverage services. Guests at luxury hotels often seek outstanding dining experiences that enhance their overall stay. Factors such as a variety of menu choices, food quality, hygiene standards, and attentive service play a vital role in guest satisfaction. Additionally, wellness facilities like spas, fitness centers, and recreational amenities have become increasingly significant in shaping customer perceptions of hotel quality. Sustainability initiatives are also becoming more prominent in the hospitality industry. Environmentally aware travelers are increasingly inclined to choose hotels that implement sustainable practices, including energy efficiency, waste reduction, water management, and community involvement. Luxury hotels that show a commitment to environmental stewardship can improve customer satisfaction and bolster their brand reputation. Safety and security have emerged as essential considerations, especially in light of global health crises and rising concerns about traveler safety. Hotels must uphold high standards of cleanliness, health protocols, cybersecurity, and physical security to maintain customer trust and satisfaction. The rise of online travel agencies (OTAs) and review platforms like TripAdvisor, Booking.com, and Google Reviews has heightened the significance of customer satisfaction. Guest experiences are now shared publicly, impacting the purchasing choices of prospective customers. Favorable online reviews lead to increased bookings and revenue, while negative feedback can severely harm a hotel's reputation. Customer satisfaction is also directly linked to customer loyalty and financial performance. Guests who are satisfied are more inclined to return, purchase additional services, and recommend the hotel to their friends and family. This not only lowers marketing expenses but also fosters sustainable business growth. As a result, comprehending customer preferences and consistently monitoring satisfaction levels have become strategic priorities for hotel managers. In Chennai's vibrant hospitality market,

premium and luxury hotels encounter the challenge of balancing operational efficiency with personalized service delivery. They must adjust to evolving customer expectations while upholding service excellence and profitability. Thus, assessing customer satisfaction yields valuable insights into guest perceptions and helps pinpoint areas that need improvement. This study seeks to investigate customer satisfaction in premium and luxury hotels in Chennai, concentrating on service quality, technological innovation, amenities, employee performance, and overall guest experiences. The results will enrich hospitality management literature and provide practical recommendations for improving customer satisfaction and gaining a competitive edge in the luxury hotel industry.

REVIEW OF LITERATURE

Kim and Lee (2022) examined how digital technologies contribute to improving customer satisfaction in hotels. Their research revealed that mobile applications, contactless services, and AI-driven customer support had a positive effect on guest experiences. The study highlighted the significance of technological innovation within the luxury hospitality sector.

Rao and Krishnan (2023) investigated the dimensions of service quality and their relationship with customer satisfaction among premium hotel guests in South India. Utilizing the SERVQUAL framework, the findings indicated that reliability and empathy emerged as the most significant predictors of customer satisfaction. Guests appreciated consistent service delivery and personalized care.

Ahmed et al. (2023) examined the connection between sustainability initiatives in hotels and customer satisfaction. Their findings showed that environmentally friendly practices greatly improved customer perceptions, especially among younger travelers and international visitors.

Wang and Zhao (2025) studied the applications of artificial intelligence in hotel customer service. Their research suggested that AI-driven customer interaction systems improved service efficiency and customer satisfaction when integrated with human support systems.

Rajendran and Suresh (2026) assessed customer satisfaction levels among luxury hotel guests in Chennai. The study identified that service quality, room comfort, food and beverage quality, and staff professionalism were key factors influencing overall guest satisfaction. The researchers advocated for ongoing employee training and technological enhancements to sustain a competitive edge.

RESEARCH OBJECTIVES

1. To investigate the demographic characteristics of patrons residing in premium and luxury hotels in Chennai City.
2. To assess the degree of customer satisfaction concerning accommodation, food and beverage services, and hotel amenities.
3. To examine the influence of service quality dimensions on customer satisfaction within premium and luxury hotels.
4. To determine the significance of technological facilities and personalized services in enhancing guest experiences.
5. To propose strategies for enhancing customer satisfaction and loyalty in Chennai's premium and luxury hotel industry.

RESEARCH QUESTIONS

1. What demographic traits are associated with customers staying in premium and luxury hotels in Chennai?
2. To what extent are customers satisfied with the services provided by premium and luxury hotels?
3. Which dimensions of service quality exert the most significant impact on customer satisfaction?
4. In what ways do technological amenities and personalized services influence guest experiences?
5. What approaches can hotels implement to boost customer satisfaction and loyalty?

STATEMENT OF THE PROBLEM

The hospitality sector is facing heightened competition due to the swift expansion of tourism, business travel, and rising customer expectations. Premium and luxury hotels in Chennai are persistently working to deliver

outstanding services and distinctive guest experiences to uphold their market standing. Nevertheless, despite considerable investments in infrastructure, technology, and service improvements, achieving customer satisfaction continues to be a significant challenge. Contemporary hotel guests anticipate high-quality accommodations, personalized service, digital convenience, safety, cleanliness, and additional value-added services. Any discrepancies between customer expectations and the actual service provided can result in dissatisfaction, unfavorable reviews, and diminished customer loyalty. The rise of online travel platforms and social media has amplified the significance of customer satisfaction, as guest experiences are extensively shared and can sway potential customers. While Chennai is home to a multitude of premium and luxury hotels, variations in service quality, employee performance, pricing strategies, and technological amenities may influence customer perceptions. It is crucial to comprehend these elements to enhance guest satisfaction and ensure sustainable business growth. Consequently, this study aims to assess customer satisfaction within the hotel industry, specifically focusing on premium and luxury hotels in Chennai City, identify the primary factors influencing satisfaction, and offer recommendations for improving service quality and fostering customer retention.

DATA ANALYSIS AND INTERPRETATION

Sample Size: 350 Hotel Guests

Table 1: Gender of Respondents

Gender	Frequency	Percentage
Male	210	60.0
Female	140	40.0
Total	350	100.0

Interpretation

The table shows that 60% of the respondents are male and 40% are female. This indicates that male guests constitute a larger proportion of customers staying in premium and luxury hotels in Chennai.

Table 2: Age Group of Respondents

Age Group	Frequency	Percentage
Below 25 Years	45	12.9
25–35 Years	110	31.4
36–45 Years	125	35.7
Above 45 Years	70	20.0
Total	350	100.0

Interpretation

The majority (35.7%) of respondents belong to the 36–45 years age group, followed by 31.4% in the 25–35 years category, indicating that middle-aged travelers form the primary customer base.

Table 3: Purpose of Stay

Purpose	Frequency	Percentage
Business	155	44.3
Leisure	110	31.4
Medical Tourism	50	14.3
Family Functions	35	10.0
Total	350	100.0

Interpretation

Business travellers represent the largest segment (44.3%), highlighting Chennai's importance as a commercial and corporate destination.

Table 4: Satisfaction with Room Quality

Response	Frequency	Percentage
Highly Satisfied	150	42.9
Satisfied	130	37.1
Neutral	40	11.4
Dissatisfied	20	5.7
Highly Dissatisfied	10	2.9
Total	350	100.0

Interpretation

A significant majority (80%) of respondents are satisfied or highly satisfied with room quality, indicating strong performance in accommodation services.

Table 5: Satisfaction with Staff Behaviour

Response	Frequency	Percentage
Highly Satisfied	135	38.6
Satisfied	140	40.0
Neutral	45	12.9

Dissatisfied	20	5.7
Highly Dissatisfied	10	2.8
Total	350	100.0

Interpretation

Approximately 78.6% of respondents express satisfaction with staff behavior, suggesting that employee professionalism contributes significantly to guest experiences.

Table 6: Satisfaction with Food and Beverage Services

Response	Frequency	Percentage
Highly Satisfied	120	34.3
Satisfied	145	41.4
Neutral	50	14.3
Dissatisfied	25	7.1
Highly Dissatisfied	10	2.9
Total	350	100.0

Interpretation

About 75.7% of guests are satisfied with food and beverage services, reflecting the importance of quality dining experiences in luxury hotels.

Table 7: Satisfaction with Technological Facilities

Response	Frequency	Percentage
Highly Satisfied	115	32.9
Satisfied	145	41.4
Neutral	55	15.7
Dissatisfied	25	7.1
Highly Dissatisfied	10	2.9
Total	350	100.0

Interpretation

More than 74% of respondents are satisfied with technological facilities such as Wi-Fi, online booking systems, and digital services.

SUGGESTIVE RECOMMENDATIONS

Based on the results of the study, the following suggestions are made to improve customer satisfaction in premium and luxury hotels located in Chennai:

Enhance Personalized Services

Hotels ought to prioritize delivering personalized guest experiences by comprehending customer preferences, special requests, and the purposes of their travel. Tailored services can greatly enhance guest satisfaction and foster loyalty.

Strengthen Employee Training Programs

Ongoing training and development initiatives should be implemented for hotel staff to enhance their communication skills, service efficiency, cultural awareness, and problem-solving capabilities. Well-trained personnel positively influence guest experiences.

Adopt Advanced Hospitality Technologies

Luxury hotels should allocate resources towards smart technologies such as mobile check-in/check-out, AI-driven concierge services, digital room controls, and contactless payment systems to align with changing customer expectations.

Improve Food and Beverage Offerings

Hotels should broaden their menu selections, highlight local and regional cuisines, and uphold high standards of food quality and hygiene. Offering special dietary and wellness-oriented menus can further elevate customer satisfaction.

Focus on Sustainability Practices

Premium and luxury hotels should implement eco-friendly initiatives, including energy-efficient systems, waste management strategies, plastic reduction programs, and sustainable sourcing. Environmentally responsible practices enhance brand reputation and customer perception.

Enhance Customer Feedback Mechanisms

Hotels should consistently gather customer feedback through surveys, online reviews, and digital platforms. Prompt responses to guest concerns can enhance service quality and improve customer retention.

FURTHER RESEARCH DIRECTIONS

This study offers significant insights into customer satisfaction within premium and luxury hotels in Chennai. Nonetheless, future researchers might consider exploring the following areas:

Comparative Analyses

Subsequent studies could compare customer satisfaction levels among luxury, premium, mid-scale, and budget hotels in various cities.

Technology's Influence on Customer Experience

Investigations may focus on how artificial intelligence, robotics, virtual reality, and smart hospitality technologies affect guest satisfaction and loyalty.

Sustainable Practices in Hospitality

Further research could analyze the connection between sustainability initiatives and customer satisfaction among eco-conscious travelers.

Customer Loyalty and Retention Factors

Future studies might examine the elements that impact customer loyalty, repeat visits, and brand advocacy within the luxury hospitality sector.

Cross-Cultural Perspectives on Customer Satisfaction

Comparative research involving both domestic and international tourists could yield deeper insights into differing customer expectations and service preferences.

Trends in Hospitality Post-Pandemic

Researchers may investigate how evolving health, safety, and wellness expectations affect customer satisfaction in luxury hotels.

The Impact of Social Media and Online Reviews

Future studies could evaluate the influence of social media platforms and online review systems on customer perceptions and hotel performance.

CONCLUDING OBSERVATIONS

The hospitality sector has increasingly shifted towards a customer-centric approach, with guest satisfaction recognized as a vital measure of organizational success and competitive edge. This research assessed customer satisfaction within premium and luxury hotels in Chennai City by analyzing various service dimensions, such as room quality, staff conduct, food and beverage offerings, technological amenities, and overall guest experiences. The results indicate that a significant number of customers express satisfaction with the services provided by premium and luxury hotels in Chennai. Service quality has emerged as a crucial factor influencing customer satisfaction, with staff professionalism, accommodation standards, personalized service, and technological convenience playing a significant role in shaping guest perceptions. Additionally, the study underscores the rising significance of digital innovation, sustainable practices, and enhanced safety protocols in addressing the changing expectations of customers. The analysis affirms that customer satisfaction is closely linked to service excellence and has a positive effect on customer loyalty, repeat visits, and favorable word-of-mouth referrals. In a highly competitive hospitality landscape, hotels must consistently innovate, uphold high service standards, and prioritize customer needs to achieve long-term success. In summary, premium and luxury hotels in Chennai have shown a strong dedication to providing exceptional guest experiences. By concentrating on improving service quality, advancing technology, implementing sustainability initiatives, and adopting customer-focused strategies, hotels can further enhance their market position and support the ongoing growth of Chennai's hospitality industry. The study concludes that customer satisfaction is an essential strategic asset for attaining sustainable competitiveness and excellence in the luxury hotel sector.

REFERENCES

1. Ahmed, S., Khan, R., & Ali, M. (2023). Sustainability initiatives and customer satisfaction in luxury hospitality. International Journal of Hospitality Management, 112, 103498. https://doi.org/10.1016/j.ijhm.2023.103498
2. Ali, F., Hussain, K., & Omar, R. (2019). Building customer loyalty through perceived service quality and customer satisfaction in the hotel industry. Journal of Tourism Futures, 5(1), 1–15.
3. Baker, D. A., & Crompton, J. L. (2000). Quality, satisfaction and behavioral intentions. Annals of Tourism Research, 27(3), 785–804.
4. Barsky, J., & Nash, L. (2003). Customer satisfaction: Applying concepts to industry-wide measures. Cornell Hotel and Restaurant Administration Quarterly, 44(5–6), 173–183.
5. Chen, Y., Wang, X., & Li, H. (2024). Smart hospitality

technologies and customer satisfaction in luxury hotels. Tourism Management Perspectives, 49, 101158.

6. Choi, T. Y., & Chu, R. (2001). Determinants of hotel guests' satisfaction and repeat patronage in the Hong Kong hotel industry. International Journal of Hospitality Management, 20(3), 277–297.
7. Cronin, J. J., & Taylor, S. A. (1992). Measuring service quality: A reexamination and extension. Journal of Marketing, 56(3), 55–68.
8. Dominici, G., & Guzzo, R. (2010). Customer satisfaction in the hotel industry: A case study from Sicily. International Journal of Marketing Studies, 2(2), 3–12.
9. Gallarza, M. G., & Saura, I. G. (2006). Value dimensions, perceived value, satisfaction and loyalty: An investigation of university students' travel behavior. Tourism Management, 27(3), 437–452.
10. Kim, J., & Lee, S. (2022). Digital transformation and customer satisfaction in luxury hotels. Journal of Hospitality and Tourism Technology, 13(4), 615–631.
11. Kotler, P., Bowen, J. T., & Makens, J. C. (2022). Marketing for hospitality and tourism (8th ed.). Pearson Education.
12. Kumar, V., & Bhatia, S. (2025). Customer loyalty and experiential hospitality in luxury hotels. International Journal of Hospitality and Tourism Systems, 18(1), 22–36.
13. Nair, A., & Joseph, M. (2024). Customer expectations and satisfaction in premium hotels: Evidence from India. South Asian Journal of Tourism and Hospitality, 9(2), 45–59.
14. Oliver, R. L. (2015). Satisfaction: A behavioral perspective on the consumer (2nd ed.). Routledge.
15. Parasuraman, A., Zeithaml, V. A., & Berry, L. L. (1988). SERVQUAL: A multiple-item scale for measuring consumer perceptions of service quality. Journal of Retailing, 64(1), 12–40.

Assessing the Role of Foreign Direct Investment in the Indian Hotel and Tourism Sector and Its Contribution to Economic Growth

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ABSTRACT

The Hospitality and Tourism sector is recognized as one of the most vibrant and swiftly growing industries on a global scale. India, as a developing country, possesses a rich array of tourism resources that establish it as a potential premier destination for travelers from around the world. Tourism has consistently been a crucial contributor to the nation's GDP, creating jobs, encouraging infrastructure development, and fostering international solidarity. It acts as a reliable pathway for sustainable development within the nation. The hotel industry has emerged as a vital pillar, offering a steady and dependable source of revenue and investment. In India, the hotel and tourism sector represents roughly 10% of the overall GDP, rendering it an essential element of the national economy. The tourism industry in India not only signifies a promising avenue for economic advancement but also serves as a significant source of foreign exchange and income for local and neighboring communities. India's tourism offerings are characterized by their beauty, distinctiveness, luxurious lifestyle, and rich historical background. The country has been actively involved in promoting tourism on both domestic and international fronts. The rise in tourist arrivals in recent years has greatly enhanced India's economic framework. Factors such as increasing profit margins, evolving living standards, improvements in various tourism services, and favorable regulatory measures from the government play a crucial role in shaping the travel and tourism industry in India. This study examines the influence of Foreign Direct Investment on the economic landscape of India, with a particular focus on the Indian Hotel and Tourism sector.

KEYWORDS: *FDI, GDP, FEE, Hospitality industry, Tourism industry, Tourism Economy.*

INTRODUCTION

The Hospitality and Tourism sector is among the most dynamic and rapidly expanding industries globally. India, as a developing nation, boasts a rich heritage of tourism resources that position it to become a premier global tourism destination. Tourism has consistently been a significant contributor to the nation's GDP, a generator of employment, a catalyst for infrastructure development, and a means of fostering international unity. It has the potential to serve as a dependable source of sustainable development for the country. The hotel industry has undeniably been a robust pillar, providing a consistent and reliable source of revenue and capital. The Hotel and Tourism sector is a key contributor to the Indian economy, accounting for up to 10% of the total GDP. The tourism industry in India represents a bright spot for the economy, serving as a major source of foreign exchange and income for both host and neighbouring communities. India's tourism offerings are remarkable for their beauty, uniqueness, luxurious lifestyle, and historical significance. The country has been actively engaged in promoting tourism both domestically and internationally. With a rise in tourist numbers in recent years, tourism has made a substantial contribution to India's economic framework. Increasing

profit margins, changing living standards, enhancements in various tourism services, and supportive regulatory and legislative measures from the government are all critical factors influencing the tour and travel industry in the nation. This study primarily investigates the impact of Foreign Direct Investment on the economic landscape of India, specifically within the context of the Indian Hotel and Tourism Industry.

OBJECTIVES OF THE STUDY

The research is designed to accomplish the following objectives:

1. To explore the patterns of foreign direct investment (FDI) in the Indian Hotel and Tourism industry.
2. To assess the performance and present contributions of the Hotel and Tourism industry to the broader Indian economy.
3. To examine the current FDI Policy pertaining to the Indian Hotel and Tourism industry.
4. To analyze the yearly and sector-specific trends of FDI inflows within the Indian Hotel and Tourism industry.

RESEARCH QUESTIONS

1. What is the present trend of Foreign Direct Investment (FDI) within the Indian hotel and tourism sector?
2. In what ways has FDI impacted the growth and advancement of the hotel and tourism industry in India?
3. How do FDI inflows correlate with India's economic growth, especially regarding GDP, job creation, and foreign exchange earnings?
4. What key factors are drawing Foreign Direct Investment into the Indian hotel and tourism sector?
5. What obstacles and challenges hinder Foreign Direct Investment in India's hotel and tourism industry?

RESEARCH METHODOLOGY

Research Design: This study incorporates both descriptive and analytical components.

Types of Data and Data Collection: The research is based on secondary data obtained from multiple sources, including annual reports from the Ministry of Tourism, documentation from the Department of Industrial Policy and Promotion (DIPP) of the Government of India, SIA Newsletters, reports from the World Travel and Tourism Council, and the Confederation of Indian Industry. Additionally, published literature, academic journals, articles, newspapers, and various online resources have been reviewed.

Tools Used: A range of statistical tools, including mean, percentage, Compound Annual Growth Rate (CAGR), trend analysis, as well as tables and graphs, have been employed to fulfill the objectives of the study. The research encompasses a ten-year period, from 2013 to 2022.

Contribution Indian Hotel and Tourism Industry to the Economy

The tourism sector in India is acknowledged as one of the fastest-growing segments of the economy. It is vital for creating job opportunities and promoting regional development, while simultaneously improving the performance of related industries through a multiplier effect. As indicated by the data in Table 1, the contribution of travel and tourism to the GDP increased from 172.91 billion dollars in 2013 to 190 billion dollars in 2022. However, the annual growth rate showed variations during the study period, including a downturn in 2019 and 2020.

REVIEW OF LITERATURE

The World Bank (2025) evaluated the macroeconomic impact of Foreign Direct Investment (FDI) on developing nations. In the context of India, the report noted that FDI in the tourism and hospitality sectors has fostered capital formation, job creation, regional development, and increased export revenues through international tourism. Additionally, the report highlighted that enhancements in the ease of doing business and investments in infrastructure would persist in attracting global investors.

Singh and Verma (2026) investigated the correlation between FDI, tourism competitiveness, and economic

growth within India. Through panel data analysis encompassing key tourism states, the researchers identified a positive correlation between FDI inflows and various indicators of tourism competitiveness, such as hotel standards, visitor satisfaction, tourism revenue, and employment levels. The study advocated for the enhancement of investment facilitation mechanisms and the promotion of sustainable tourism investment strategies.

UN Tourism (2026) indicated that international investments in tourism are increasingly directed towards digital innovation, sustainable tourism practices, destination resilience, and environmentally friendly hospitality infrastructure. India has emerged as a favored investment location due to its growing tourism demand, governmental support, skilled labor force, and substantial domestic market. The report concluded that FDI will continue to play a vital role in fostering inclusive and sustainable economic growth.

Discussion and Analysis

Table 1: Contribution of Travel and Tourism to GDP& Employment

Year	Contribution to GDP (US$ Billion)	Annual Growth Rate (AGR %)	Contribution to Employment (Million Jobs)	Annual Growth Rate (AGR %)
2013	172.91	–	67.20	–
2014	185.63	7.36	69.75	3.79
2015	201.43	8.51	72.26	3.60
2016	219.72	9.08	75.34	4.26
2017	232.01	5.59	72.26	-4.09
2018	247.37	6.62	75.34	4.26
2019	191.30	-22.67	72.69	-3.52
2020	121.90	-36.65	75.85	4.17
2021	178.00	47.11	79.86	5.33
2022	190.00	6.74	40.09	-49.37
CAGR (in%)	0.95	-	-5.03	-

The analysis of Table 1 revealed that the contribution of travel and tourism to employment increased from 67.20 million in 2013 to 79.86 million in 2021, before experiencing a significant drop to 40.09 million in 2022.

Performance Indian Hotel and Tourism Industry

The Hotel and Tourism sector represents a crucial and essential component of the Indian economy. The performance of Indian tourism, as indicated by tourist arrivals and foreign exchange earnings, is illustrated in Table 2.

Table 2: Foreign Exchange Earnings from Tourism in India from 2013-2022

Sl. No.	Year	Foreign Tourist Arrivals (in nos)	Percenta ge Change over Previous year	Foreign Exchange Earnings (Rs. Crore)	Percentage Change over previous year	Foreign Exchange Earnings (Million US$)	Percentage Change over previous year
1.	2013	6967601	5.9	107563	12.51	18396	2.36
2.	2014	7679099	10.2	120366	11.90	19699	7.08
3.	2015	8027133	4.6	134843	12.03	21012	6.67
4.	2016	8804411	9.6	150750	11.80	22428	6.74
5.	2017	10035803	14.1	178189	18.20	27365	22.01
6.	2018	10557976	5.2	195312	9.61	28565	4.40
7.	2019	10930355	3.5	216467	10.83	30721	7.54
8.	2020	2744766	-74.9	50136	-76.84	6958	-77.35
9.	2021	1527114	-44.5	65070	29.79	8797	26.43
10.	2022	6437467	321.5	139935	115.05	17611	100.19
CAGR (in%)	-0.79	-	2.67	-	-	-	

The analysis of Table 2 reveals that Foreign Tourist Arrivals (FTA) increased from 6.96 Lakhs in 2013 to 64.37 Lakhs in 2022. The emergence of the Coronavirus pandemic in March 2020 has posed significant challenges for economies and the global tourism industry. Between 2013 and 2019, FTA saw a growth of 63.74 percent; however, this upward trend was interrupted by the pandemic, leading to a decline of 398.22 percent in 2020 and 179.73 percent in 2021. A slight recovery was noted from 2021 to 2022, with an increase of 23.72 percent. Furthermore, Foreign Exchange Earnings (FEEs) from tourism experienced a considerable rise from Rs. 107,563 crore in 2013 to Rs. 216,467 crore in 2019, achieving an impressive growth rate of 201.24 percent in 2019. Nonetheless, the annual growth rate of FEEs has fluctuated in the following years due to the pandemic's effects. Chart 1 depicts the trend of Foreign Tourist Arrivals in India from 2013 to 2024.

Table 3: International Tourist Arrivals in World and India, 2013-2022

Sl. No.	Year	World		India		Percentage Share of India	Rank of India
		Number (in million)	% Change	Number (in million)	% Change		
1.	2013	1087	4.6	7	5.9	0.64	41st
2.	2014	1137	4.6	13.1	87.1	1.15	24th
3.	2015	1195	5.1	13.8	5	1.15	24th
4.	2016	1241	3.8	15	9.1	1.21	26th
5.	2017	1332	7.3	16.8	11.8	1.26	26th
6.	2018	1413	6.1	17.4	3.7	1.23	23rd
7.	2019	1464	3.6	17.9	2.8	1.22	24th
8.	2020	407	-72.2	6.3	-64.8	1.55	19th
9.	2021	458	12.5	7.0	11.1	1.53	18th
10.	2022	969	111.6	14.32	104.6	1.48	-
CAGR(in %)	-1.14	-	7.42	-	-	-	

Table 3 indicates that in 2021, India held the 18th position globally regarding International Tourist Arrivals, a ranking that was notably lower when compared to 2013. The following chart 3 showing Percentage Change in Foreign Tourist Arrivals in India over Previous Year.

Table 4: International Tourism receipts and India's rank and share, 20013-2022

Sl. No.	Year	World		India		Percentage Share of India	World Rank of India
		Growth rate	Receipts (US$ billion)	Growth rate	Receipts (US$ billion)		
1.	2013	1198	7.3	18.4	2.3	1.54	16th
2.	2014	1252	4.5	19.7	7.1	1.57	15th
3.	2015	1217	-2.8	21.0	6.6	1.73	14th
4.	2016	1247	2.5	22.9	9.1	1.84	13th
5.	2017	1349	8.2	27.3	19.1	1.84	13th
6.	2018	1439	6.7	28.6	4.7	1.99	13th
7.	2019	1486	3.3	30.7	7.3	2.07	14th
8.	2020	554	-62.7	13.0	-57.7	2.35	13th
9.	2021	632	14.1	8.7	-33.1	1.38	23rd

10.	2022	1109	75.5	21.4	146.0	1.93	14th
CAGR(in%)	-0.77	-	1.52	-	-	-	

An examination of Table 4 reveals a notable enhancement in the performance of the tourism sector in India, particularly regarding International Tourism Receipts. India has achieved a ranking of fourteenth globally.

FDI Policy of Indian Hotel and Tourism sector

The Foreign Direct Investment (FDI) policy in India establishes the framework for foreign investments. This policy allows investments through the automatic route, which does not require prior government approval, while other types of investments require government consent in advance. The Department of Industrial Policy and Promotion (DIPP) is tasked with developing and executing strategies to enhance the industrial sector. Given its significance, the hotel and tourism sector is subject to government regulation. The current FDI policy for the hotel and tourism sector is outlined as follows:

a. To promote foreign investment in the tourism sector, 100% foreign direct investment (FDI) is permitted through the automatic route. Since April 2000, this sector has attracted a total of US$ 17.1 billion in FDI. Importantly, in the last four fiscal years (2020-23), it has garnered over 25% of this investment, totaling US$ 4.36 billion.

b.100% FDI is allowed in tourism-related construction projects, which include the development of hotels, resorts, and recreational facilities.

Table 5: Financial Yearwise Foriegn Direct Investment in Indian Hotel and Tourism

Sl. No.	Year (Apr-Mar)	Total FDI		FDI in Hotel & Tourism		%age of Total Inflows	Change over previous years (US $)	Trend Analysis (Base year=201 3)
		In Rs. In Crores	US$ million	In Rs. In Crores	US$ million			
1.	2013	121907	22423	17777	3259	14.54	-	100%
2.	2014	147518	24299	2949	486	2.00	-85.08	14.91%
3.	2015	189107	30931	4740	777	2.51	59.87	23.84%
4.	2016	262322	40001	8761	1333	3.33	71.55	40.90%
5.	2017	288889	44857	7279	1132	2.52	-15.07	34.73%
6.	2018	309867	44867	7590	1076	2.40	-4.94	33.02%
7.	2019	353558	49977	21060	2938	5.88	173.04	90.15%
8.	2020	442569	59636	2761	359	0.60	-87.78	11.01%
9.	2021	437188	58773	2805	369	0.62	2.78	11.32%
10.	2022	367435	46034	3642	440	0.96	19.24	13.50%
CAGR(in %)	11.66	-	-14.66	-	-	-	-	-

Table 5 illustrates that Foreign Direct Investment (FDI) in India's hotel and tourism sector has shown growth over the study period, albeit inconsistently. In 2013, the sector received FDI totaling US $ 3,259 million, representing the highest influx recorded in any year. Furthermore, the data indicates that negative growth rates were noted in the years 2014, 2017, 2018, and 2020.

SUMMARY OF FINDINGS

The principal findings from the research are summarized as follows:

- ❖ The influence of tourism on GDP has shown a notable upward trend throughout the study period.
- ❖ Simultaneously, the contribution of tourism to employment has experienced a consistent rise, although there were some variations in certain years.
- ❖ A marked increase in the total number of Foreign Tourist Arrivals (FTA) in India was noted, particularly in 2019.

- ❖ Foreign exchange earnings derived from tourism experienced a significant boost during the study timeframe, despite a downturn in 2020.
- ❖ The performance of the tourism sector in India, as reflected by International Tourist Arrivals, demonstrated exceptional growth in 2017, 2018, and 2019 when compared to other years.
- ❖ The Foreign Exchange Earnings (FEE) peaked in 2019 relative to the other years analyzed.
- ❖ In terms of International Tourism Receipts, there has been a notable enhancement in the performance of the Indian tourism sector, although negative growth rates were recorded in 2020 and 2021 due to the COVID-19 pandemic.
- ❖ The current study indicates that the Hotel and Restaurant sector attracted the largest share of total Foreign Direct Investment (FDI) in the Indian Hotel and Tourism industry during the study period.
- ❖ Despite some variations, a consistent increase in the share of FDI within the Hotel sector has been documented.
- ❖ The Foreign Direct Investment (FDI) in the Indian Hotel and Tourism sector has exhibited a positive trend, with the exception of the years 2020, 2021, and 2022.

SUGGESTIONS

- The government must take effective steps to improve India's standing in the global hotel and tourism sector.
- It is vital for the government to implement suitable strategies that ensure consistent growth in the Indian hotel and tourism industry, thereby aiding the country's economic progress.
- The government ought to undertake significant measures to create additional employment opportunities by fostering a variety of tourism-related activities.
- Focusing on enhanced security, increased investment, and the establishment of world-class infrastructure is essential. Furthermore, it is important to elevate the quality of services in hotels, airports, railway stations, and similar facilities.
- ❖ There is a necessity to develop and invest in research and development projects to stay attuned to consumer demands and preferences.

CONCLUSION

The importance of Tourism and Hospitality in the economic development of any nation is undeniable. The Indian Hospitality Sector, in particular, plays a crucial role in generating significant foreign exchange and contributing to the overall economic growth of the country. Nevertheless, it is essential to tackle the urgent challenges facing this industry, including insufficient infrastructure, complicated taxation systems, a lack of adequately trained staff, security issues, and licensing obstacles. Although the potential for expansion is immense, achieving this potential requires a cooperative effort between key stakeholders in the private sector and relevant government authorities to genuinely enhance the Indian hospitality landscape in the coming years. The study's findings indicate a considerable opportunity for improvement within the Indian Hotel and Tourism sector. It is vital for the government to implement strategic initiatives aimed at improving India's position in the global hospitality and tourism market. Over the years, the government's initiatives have produced encouraging growth indicators, successfully attracting foreign direct investment through various channels. To maintain this progress, it is crucial for the government to adopt effective strategies that guarantee a steady influx of FDI into the Indian Hotel and Tourism sector. Furthermore, focused efforts should be made to draw significant foreign investment in tourism and its various sub-sectors, extending beyond just hotels and restaurants.

REFERENCES

1. Azizbek A, Alexander P, Iddrisu Md (2021), "Government commitment to tourism and hospitality sector during COVID-19 pandemic," Emerald Publishing Limited, Vol. 2 No. 2, Pp. 153-169.
2. Navjeet Kaur, (2017), "Analysis of the contribution of Hospitality Sector in the development of the Indian Economy," International Journal of science and Technology Management, Vol-6, Issue-1, Pp-91-100
3. Niranjana. C and Vimya K.P (2013), "Foreign Direct Investment: An Exploration of Opportunities in Indian

Tourism", International Journal of Management and Development Studies, Vol- 2, Issue-12, Pp.27-33.

4. Sandeep Naik and Deepali Garge (2023), "A Study of Government Ingenuities: A Case Study of Tourism a.nd Hospitality Industry in Maharashtra Post Covid-19," The Online Journal of Distance Education and e-Learning, Vol.11, Issue.1, Pp-1-8

5. Sudha, Selvam, and Saroja Devi (2023), Tourism & Hospitality Industry: Problems and Prospects of India," World Wide Journal of Multidisciplinary Research and Development, vol-9,issue 9, Pp-32-36.

6. Vijay Kumbhar and Kolekar, (2020), "Recent Trends and Issues in Indian Hotel Industry," Our Heritage, Vol-68-Issue-33, Pp-443-448

7. Navjeet Kaur, (2017), "Analysis of the contribution of Hospitality Sector in the development of the Indian Economy," International Journal of science and Technology Management, Vol-6, Issue-1, Pp-91-100

8. Sandeep Naik and Deepali Garge (2023), "A Study of Government Ingenuities: A Case Study of Tourism a.nd Hospitality Industry in Maharashtra Post Covid-19," The Online Journal of Distance Education and e-Learning, Vol.11, Issue.1, Pp-1-8

9. Vijay Kumbhar and Kolekar, (2020), "Recent Trends and Issues in Indian Hotel Industry," Our Heritage, Vol-68-Issue-33, Pp-443-448

10. Sudha, Selvam, and Saroja Devi (2023), Tourism & Hospitality Industry: Problems and Prospects of India," World Wide Journal of Multidisciplinary Research and Development, vol-9,issue 9, Pp-32-36.

Strategic Role of the Hotel Industry and Room Division Management in Enhancing Indian Tourism and Generating National Revenue

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ABSTRACT

The hotel industry serves as a crucial foundation of the tourism and hospitality sector, significantly contributing to economic development, job creation, infrastructure enhancement, and foreign exchange revenue. In India, the swift growth of both domestic and international tourism has led to an increased demand for high-quality accommodations and effective hotel services. The room division department is crucial among the various hotel departments, as it ensures guest satisfaction through effective management of front office operations, housekeeping, reservations, guest relations, and revenue optimization. Proper management of the room division not only enhances service quality and occupancy rates but also cultivates customer loyalty and operational efficiency, thereby strengthening the competitive advantage of hotels in the global tourism sector. The hotel industry significantly contributes to India's Gross Domestic Product (GDP) both directly and indirectly by generating employment opportunities, attracting international visitors, supporting local businesses, and encouraging investments in hospitality infrastructure. Government initiatives such as Dekho Apna Desh, Swadesh Darshan, the PRASHAD Scheme, the Incredible India Campaign, and Digital India have further stimulated tourism growth, creating new opportunities for hotels in urban centers and emerging tourist destinations. Technological advancements, including artificial intelligence, online booking systems, contactless services, and revenue management tools, have revolutionized room division operations, enhancing customer experiences and maximizing hotel profitability. Despite significant growth, the industry still encounters challenges including seasonal demand variations, shortages of skilled labor, escalating operational expenses, sustainability issues, and heightened competition from alternative lodging providers. Tackling these challenges through strategic management of room divisions, technological advancements, employee training, and sustainable hospitality practices is crucial for preserving India's status as a premier global tourism destination. This study emphasizes the strategic significance of the hotel sector and room division management in fostering tourism development while boosting national revenue and ensuring long-term economic sustainability.

KEYWORDS: *Hotel Industry-Room Division Management-Indian Tourism-National Revenue-Hospitality Management.*

INTRODUCTION

The hotel industry is a fundamental component of the tourism and hospitality sector, acting as a major driver of economic growth for nations. The success of tourism is heavily reliant on the presence of safe, comfortable, and high-quality accommodation options that cater to the varied needs of both domestic and international travellers. Hotels not only provide lodging but also extend food and beverage services, recreational amenities, business facilities, transportation support, and tailored guest experiences that collectively enhance tourist satisfaction. In India, the hotel industry has rapidly evolved into a significant service sector,

propelled by rising disposable incomes, urbanization, globalization, enhanced transportation infrastructure, digital advancements, and proactive government policies aimed at boosting tourism. India is globally acknowledged for its rich cultural heritage, historical landmarks, spiritual sites, diverse landscapes, wildlife reserves, medical tourism, wellness tourism, culinary diversity, and business travel prospects. These attractions have led to a notable increase in tourist arrivals over the last decade, resulting in a heightened demand for quality accommodation across various segments, including luxury, mid-scale, budget, boutique, heritage, eco-friendly, and homestay options. As reported by the World Travel and Tourism Council (WTTC), the travel and tourism sector makes a substantial contribution to India's Gross Domestic Product (GDP) and provides millions of direct and indirect job opportunities across multiple industries. The hotel industry is crucial in maintaining this contribution by offering high-quality hospitality services that promote repeat visits and foster positive destination branding. Within the operational sectors of hotels, the room division department is considered the primary revenue-generating entity, as accommodation revenue constitutes a significant portion of the overall hotel income. This department includes the front office, reservations, housekeeping, guest relations, concierge services, uniform services, and night audit functions. These interrelated units collaborate to provide a seamless experience for guests from the moment of reservation until check-out. The efficiency of room division management has a direct impact on guest satisfaction, occupancy rates, average daily rate (ADR), revenue per available room (RevPAR), online reviews, customer loyalty, and overall profitability. The front office operations serve as the initial point of contact between guests and the hotel. Professional reception services, effective reservation management, precise billing systems, swift complaint resolution, and personalized communication with guests create favorable first impressions that shape customer perceptions. Housekeeping, another vital aspect of room division management, guarantees the cleanliness, hygiene, safety, and upkeep of guest rooms and public spaces. Maintaining high standards in housekeeping is crucial for customer satisfaction, particularly in the post-pandemic hospitality landscape, where cleanliness has emerged as a key factor in hotel selection. Recent years have witnessed a significant transformation in room division management due to technological advancements. Hotels are increasingly adopting Property Management Systems (PMS), Customer Relationship Management (CRM) software, Artificial Intelligence (AI), cloud-based reservation systems, mobile check-in and check-out options, contactless payment technologies, digital concierge services, Internet of Things (IoT) devices, and revenue management software to enhance operational efficiency and elevate guest experiences. These technologies enable real-time management of room inventory, dynamic pricing strategies, demand forecasting, personalized marketing, and effective customer engagement, allowing hotels to optimize occupancy rates and profitability. Moreover, the hotel industry plays a crucial role in driving national economic development through various avenues. It creates millions of jobs across sectors such as hospitality, transportation, travel agencies, food production, handicrafts, entertainment, event management, and local supply chains. Hotels source goods and services from a wide array of local businesses, thereby fostering regional economic growth and supporting small and medium enterprises (SMEs). Additionally, international tourism contributes significantly to foreign exchange earnings, bolsters India's balance of payments, and enhances the nation's global standing as a favored travel destination. Government policies have significantly contributed to the rapid expansion of India's hotel sector. Initiatives like Incredible India, Swadesh Darshan, PRASHAD (Pilgrimage Rejuvenation and Spiritual Heritage Augmentation Drive), Dekho Apna Desh, Digital India, e-Visa facilities, UDAN (Ude Desh Ka Aam Nagrik), and investments in tourism infrastructure have enhanced accessibility, fostered destination development, and boosted tourist arrivals. Public-private partnerships have stimulated investments in hotel infrastructure, especially in emerging tourism hotspots and Tier-II and Tier-III cities.

The COVID-19 pandemic posed unprecedented challenges for the global hospitality sector. Travel restrictions, lockdowns, health concerns, and a drop in tourist arrivals severely impacted hotel occupancy rates, revenue generation, and employment levels.

Nevertheless, the industry exhibited remarkable resilience by implementing enhanced hygiene protocols, contactless technologies, flexible booking policies, digital marketing strategies, and diversified service offerings. Domestic tourism emerged as a crucial driver of recovery, while wellness tourism, medical tourism, staycations, and work-from-hotel concepts opened new business avenues for hotel operators. Sustainability has increasingly become a vital consideration in hotel management. Contemporary hotels are adopting environmentally responsible practices such as energy conservation, water management, waste reduction, renewable energy utilization, plastic-free operations, green building certifications, and community engagement initiatives. Sustainable room division management not only lowers operational costs but also improves brand reputation and attracts environmentally conscious travelers.

LOGICAL BACKGROUND OF THE STUDY

The hotel industry serves as a crucial element of the tourism sector, significantly contributing to the enhancement of destination appeal, visitor satisfaction, and economic growth. With the ongoing expansion of tourism activities throughout India, there has been a marked increase in the demand for high-quality accommodations and effective hospitality services. Among the various departments within hotels, the room division department is regarded as the operational nucleus, as it directly oversees guest services, reservations, front office functions, housekeeping, and occupancy management. Efficient management of the room division leads to improved guest satisfaction, higher occupancy rates, enhanced online reputation, and increased revenue generation. Technological innovations, such as property management systems, artificial intelligence, online booking platforms, and revenue management tools, have further bolstered operational efficiency and customer service. Concurrently, government initiatives aimed at promoting tourism and developing infrastructure have expedited the growth of the hotel industry. Therefore, comprehending the strategic interplay between hotel operations, room division management, tourism development, and national revenue is vital for achieving sustainable growth and enhancing India's competitiveness in the global tourism arena.

The hotel sector has emerged as a vital contributor to India's tourism industry and national economy. Despite the swift increase in tourist arrivals and growing investments in hospitality infrastructure, numerous hotels still encounter operational difficulties that hinder service quality, customer satisfaction, and revenue generation. The room division department, encompassing front office, reservations, housekeeping, and guest services, is essential in influencing hotel performance, as accommodation revenue represents the largest portion of hotel income. Nonetheless, challenges such as ineffective room allocation, workforce shortages, inconsistent service standards, insufficient employee training, difficulties in technological adaptation, seasonal demand variations, and rising competition from alternative accommodation providers continue to affect operational efficiency.

Furthermore, changing customer expectations, digital transformation, sustainability demands, and intensified competition necessitate that hotels implement strategic room division management practices to optimize occupancy, enhance guest experiences, and boost profitability. Although the hotel industry's role in tourism and economic development is well acknowledged, there is a lack of comprehensive research exploring the strategic connection between room division management, tourism growth, and national revenue generation within the Indian context. Consequently, this study aims to investigate how efficient hotel operations and room division management contribute to tourism development, improve customer satisfaction, increase hotel revenues, create employment opportunities, and promote India's overall economic growth.

REVIEW OF LITERATURE

Rao and Srinivasan (2025) conducted a study on revenue management practices within Indian hotels. Their findings indicated that effective forecasting, dynamic pricing, demand analytics, and strategic management of room inventory led to significant increases in Average Daily Rate (ADR), Revenue per Available Room (RevPAR), and overall hotel profitability. They suggested a stronger integration of predictive analytics into the management of room divisions.

Hospitality Industry Report (2025) The report highlighted that sustainability, digitalization, personalized guest experiences, and operational excellence have emerged as crucial competitive advantages in the hospitality sector. Hotels that invested in smart technologies and sustainable room operations reported higher guest satisfaction ratings and enhanced financial outcomes.

Joshi and Verma (2026) investigated the impact of artificial intelligence on room division management. Their research revealed that AI-driven forecasting, automated room assignments, chatbot-assisted customer service, and predictive maintenance significantly enhanced operational efficiency and lowered costs. The researchers concluded that adopting technology-driven approaches in room division management is vital for sustaining competitiveness in the rapidly changing hospitality industry.

OBJECTIVES OF THE STUDY

- To assess the critical role of room division management in improving guest satisfaction, operational effectiveness, and hotel profitability.
- To evaluate the hotel industry's contribution to India's national revenue through job creation, foreign exchange earnings, tax income, and Gross Domestic Product (GDP).
- To propose strategic initiatives aimed at enhancing the hotel industry and room division management to boost India's tourism competitiveness and economic progress.

RESEARCH QUESTIONS

1. In what ways does the hotel sector facilitate the expansion and progress of tourism in India?
2. What significance does room division management hold in enhancing guest satisfaction and the operational efficiency of hotels?
3. How does the hotel industry play a role in generating national revenue through avenues such as employment, taxation, foreign exchange earnings, and contributions to GDP?
4. What effects do technological innovations and digital transformation exert on room division management within Indian hotels?
5. What strategies can be implemented to improve the efficiency of room division management, thereby bolstering tourism development and contributing to national economic growth?

The hotel sector has rapidly become one of the most dynamic components of the global economy, acting as a fundamental element in the development of tourism, job creation, and economic advancement. Hotels offer vital accommodation and hospitality services that support both leisure and business travel. The effective management of hotel operations, especially in room division management, plays a crucial role in enhancing customer satisfaction, occupancy levels, and overall profitability. As a result, the hotel industry makes a significant contribution to national income, foreign exchange earnings, and regional development in numerous countries.

DATA ANALYSIS AND INTERPRETATION

Table 1: Demographic Profile of Respondents by Gender

Gender	Frequency	Percentage (%)
Male	118	59.0
Female	82	41.0
Total	200	100.0

Interpretation

The data reveals that 59% of the participants are male, whereas 41% are female. This implies that both genders are adequately represented in the study, with a slightly greater participation from males.

Table 2: Age of Respondents

Age Group (Years)	Frequency	Percentage (%)
Below 25	34	17.0
26–35	72	36.0
36–45	51	25.5
46–55	29	14.5
Above 55	14	7.0
Total	200	100.0

Interpretation

A significant portion of respondents (36%) falls within the 26–35 years age range, suggesting that young professionals make up the largest group of participants.

Table 3: Type of Hotel

Hotel Category	Frequency	Percentage (%)
Luxury Hotel	56	28.0
Business Hotel	44	22.0
Budget Hotel	48	24.0
Resort	30	15.0
Heritage Hotel	22	11.0
Total	200	100.0

Interpretation

Luxury hotels account for the largest share (28%), followed by budget hotels at 24% and business hotels at 22%, reflecting a varied representation within the hotel sector.

Table 4: Importance of Room Division Management

Opinion	Frequency	Percentage (%)
Highly Important	96	48.0
Important	72	36.0
Neutral	18	9.0
Less Important	10	5.0
Not Important	4	2.0
Total	200	100.0

Interpretation

Almost 84% of respondents view room division management as either highly important or important, underscoring its essential function in hotel operations.

Table 5: Room Division Management Improves Guest Satisfaction

Response	Frequency	Percentage (%)
Strongly Agree	88	44.0
Agree	70	35.0
Neutral	22	11.0
Disagree	14	7.0
Strongly Disagree	6	3.0
Total	200	100.0

Interpretation

A total of 79% of respondents agree that effective room division management significantly improves guest satisfaction.

Table 6: Hotel Industry Contributes to National Revenue

Response	Frequency	Percentage (%)
Strongly Agree	94	47.0
Agree	69	34.5
Neutral	19	9.5
Disagree	12	6.0
Strongly Disagree	6	3.0
Total	200	100.0

Interpretation

More than four-fifths (81.5%) of respondents believe that the hotel industry makes a significant contribution to India's national revenue.

SUGGESTIONS

1. Enhance Employee Training and Skill Development: Hotels ought to offer ongoing training in customer service, communication, digital technologies, foreign languages, and crisis management to elevate service quality and operational efficiency.
2. Embrace Advanced Technologies: Hotel management should allocate resources towards Property Management Systems (PMS), Artificial Intelligence (AI), cloud-based reservation systems, mobile check-in/check-out, contactless payment solutions, and revenue management software to enrich guest experiences and optimize profitability.
3. Improve Room Division Management: The front office, housekeeping, reservations, and guest relations departments should collaborate closely to ensure smooth service delivery, minimize operational errors, and enhance customer satisfaction.
4. Fortify Government–Industry Collaboration: The government should persist in supporting the hospitality sector through tourism promotion campaigns, infrastructure development, tax incentives, skill development programs, and streamlined regulatory processes to stimulate further investment.
5. Enhance Digital Marketing Strategies: Hotels should utilize social media platforms, online travel agencies (OTAs), search engine optimization

(SEO), influencer marketing, and customer relationship management (CRM) tools to draw in both domestic and international tourists.

RECOMMENDATIONS

1. The Ministry of Tourism ought to develop long-term policies that promote sustainable hotel development and the technological modernization of all hotel categories.
2. Hotel management should implement ongoing professional development programs for room division staff to uphold international hospitality standards.
3. Hospitality educational institutions need to update their curricula to incorporate Artificial Intelligence, revenue management, digital hospitality, sustainability, and customer experience management.
4. Hotels should consistently assess guest satisfaction through online reviews, customer feedback systems, and service quality evaluations to pinpoint areas that need enhancement.
5. Government agencies should promote investment in eco-friendly hotels by offering financial incentives, subsidies, and recognition programs.

CONCLUSION

The hotel sector is an essential element of India's tourism framework and acts as a crucial catalyst for the nation's economic advancement. It plays a direct role in contributing to the GDP, generating employment, earning foreign exchange, collecting tax revenues, developing infrastructure, and fostering regional economic growth. As tourism continues to flourish throughout India, the need for high-quality lodging and professional hospitality services has significantly risen, positioning the hotel industry as one of the most vibrant service sectors in the country. Among the various operational departments, the management of room divisions is pivotal in determining the success of hotel operations. The effective administration of front office services, housekeeping, reservations, guest relations, and revenue management directly impacts guest satisfaction, occupancy levels, online reputation, and financial outcomes. The incorporation of advanced technologies such as Artificial Intelligence, Property Management Systems, mobile applications, cloud computing, and data analytics has revolutionized room division operations by enhancing efficiency, lowering operational expenses, and providing tailored guest experiences.

The research also indicates that government initiatives including Incredible India, Dekho Apna Desh, Swadesh Darshan, PRASHAD, and the enhancement of tourism infrastructure have considerably bolstered the growth of the hotel sector. Concurrently, challenges such as workforce shortages, escalating operational costs, evolving consumer expectations, sustainability demands, and intensifying market competition necessitate ongoing innovation and strategic management.

In summary, the enduring success of the Indian hotel industry hinges on proficient room division management, technological progress, employee skill development, sustainable hospitality practices, and robust collaboration between the government and the private sector.

REFERENCES

1. Deloitte India. (2023). Hospitality industry outlook: India.
2. Ernst & Young India. (2024). Indian hospitality sector outlook 2024.
3. Joshi, A., & Verma, P. (2026). Artificial intelligence in room division management: Emerging trends in Indian hospitality. Journal of Hospitality and Tourism Management, 58, 112–126.
4. KPMG India. (2023). Digital transformation in the Indian hospitality industry.
5. Kumar, R., & Nair, S. (2024). Employee competency and room division performance in Indian hotels. International Journal of Hospitality Management, 118, 103678.
6. Ministry of Tourism, Government of India. (2022). India tourism statistics 2022.
7. Ministry of Tourism, Government of India. (2025). India tourism statistics 2025.
8. Patel, H., & Mehta, D. (2024). Technology adoption and front office performance in luxury hotels. Journal of Tourism and Hospitality Research, 19(2), 75–91.

9. Rao, V., & Srinivasan, K. (2025). Revenue management strategies and hotel profitability in India. Asia Pacific Journal of Tourism Research, 30(1), 44–61.

10. Sharma, P., & Gupta, R. (2021). Hotel industry recovery strategies in post-pandemic India. International Journal of Hospitality Studies, 15(3), 85–101.

11. Singh, M., & Kaur, H. (2022). Room division management and guest satisfaction in Indian premium hotels. Journal of Hospitality Management and Tourism, 13(4), 210–223.

12. UN Tourism. (2023). World Tourism Barometer.

13. World Travel & Tourism Council. (2022). Economic impact report: India.

Decolorization of High Iron Transparent Soda Lime Silicate Float Glass and Assessment of their Effect on Optical Properties

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ABSTRACT

The objective of the study is to overcome the green ting problem (green appearance) of transparent soda lime silicate float glass by decolorization and subsequently improve the aesthetics. Green tinge in transparent soda lime float glass has emerged as a major challenge and has affected some applications of transparent float glass to achieve their desired results. Major aesthetic issues are faced in the application of facades, tableware, back painted glass and some laminated safety glass combinations.

The target is taken to decolorize soda lime silicate glass having high iron content (0.10% wt Fe_2O_3). Soda–lime–silicate glass containing 0.10 wt% Fe_2O_3 was synthesized using high-iron silica sand and dolomite as the principal raw materials. The batch composition also included soda ash, salt cake (Na_2SO_4), slag, and blue dust (iron oxide) to achieve the desired glass composition and iron oxide content

Iron oxide in soda–lime glass exists predominantly in two oxidation states: ferrous iron (Fe^{2+}), which imparts a blue coloration, and ferric iron (Fe^{3+}), which contributes a yellow coloration to the glass.

In the present study, transparent soda–lime–silicate glass was decolorized using two distinct approaches: physical decolorization and chemical decolorization.

Physical decolorization of clear glass involves masking the color caused by impurities like iron with other colouring agents. Chemical decolorization of clear glass involves masking the color caused by impurities like iron by changing its oxidation state. This is often achieved by oxidizing or reducing the iron state. In chemical decolorization decolorizer is used to transform one iron oxide form into another by changing the redox profile and achieving the required color tone (color/tinge).

This study investigates the decolorization of soda-lime silicate glass using five different agents, manganese oxide (MnO2), tin oxide (SnO2), neodymium oxide (Nd2O3), cobalt oxide (CoO) and carbon(C). The glass is melted and formed three times in a pilot furnace using a platinum dish and the optical properties are examined using a UV-Vis spectrophotometer, lambda, windows, and optics software.

The colour results obtained using the CIE L*a*b* system indicate that chemical decolouration method by adding carbon as reducing agent is more effective and the glass containing 0.04 wt% carbon exhibited excellent clarity and appeared visually transparent.

The decolorization reactions in glasses containing carbon, manganese (Mn), and tin (Sn) proceed through a chemical decolorization mechanism. However, the extent of these reactions is limited and is governed primarily by the redox equilibrium established within the glass melt.

The reactions were described by the following equation,

$$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO \quad (1)$$

OR

$$Fe_3+ + C \rightarrow Fe_2+ + C+ \quad T\uparrow \quad (2)$$

$$Mn_3+ + Fe_2+ \rightarrow Mn_2++ Fe3+ \quad T\downarrow \quad (3)$$

$$Mn_3+ + Fe_2+ \leftarrow Mn_2++ Fe_3+ \quad T\uparrow \quad (4)$$

$$Sn_5+ + Fe_2+ \rightarrow Sn_4++ Fe_2+ \quad T\downarrow \quad (5)$$

$$Sn_5+ + Fe_2+ \rightarrow Sn_4++ Fe_2+ \quad T\uparrow \quad (6)$$

For Nd_2O_3 and CoO, decolorization occurs through a physical decolorization mechanism, as the colors imparted by these oxides remain stable in the molten glass and can directly counteract the coloration caused by Fe_2O_3. Therefore, this approach can be applied to the production of transparent soda–lime silicate float glass using high-iron-content silica sand.

KEYWORDS: *Decolorization, transparent soda-lime silicate float glass, colorants, reducing agent, dolomite, silica sand, CIE L*a*b* system.*

INTRODUCTION

The main source of this high iron content in soda lime silicate glass is mainly from basic mine raw materials such as silica sand and dolomite. Silica sand and dolomite with mainly iron content are not suitable for manufacturing transparent float glass. Since silica sand and dolomite occupy the major portion of the batch and contribute to the high iron presence in the glass.

Consequently, the production of transparent float glass necessitates the use of high-purity silica sand and dolomite to maintain the iron oxide concentration at a minimum level. Typically, transparent float glass contains only 0.09–0.10 weight% Fe_2O_3 to mitigate the coloring effect of iron impurities, which imparts a green tint to the glass. Using high purity (low iron oxide) silica sand and dolomite is a bit challenging due to high cost and no practical feasibility.

By seeing low cost and economic viability it is worth using decolorization technique (physical and chemical) to overcome green ting problem of soda lime silicate float glass by using suitable decolorizing agents to achieve indented appearance and aesthetic.

There are two major ways to enable discoloration process, namely physical and chemical decolorization.

In chemical decolorization method, specially oxides of transition metals and rare earth metals are used as decolorizing agents, few of most common decolorizing agents are Cobalt oxide(CoO), Nickel oxide(NiO), Selenium(Se), Copper oxide(CuO), Arsenic oxide(As2O5), and Antimony oxide (Sb2O5), Manganese oxide (MnO2), Tin oxide (SnO2), Neodymium oxide (Nd2O3) and Titanium oxide (TiO2).

The objective is to seek suitable descolorizing agent to overcome green ting problem of soda lime silicate glass so that the end application problem of customers can be resolved without compromising with requirements.

MATERIALS AND EXPERIMENTAL

Materials

Silica sand (Earth Industries, Avadh Minerals), dolomite (Orsang Minerals, Babji Minerals), limestone (Shri Laxmi Industries), slag (D.R Slag), saltcake (Birla Cellulose) and soda ash (Tata Chemicals) were used to prepare a homogenous batch through appropriate in-house mixing procedures at Asahi India Glass Limited, India.

The composition of the raw material is given in the table 1.

Table 1 presents the chemical composition of the raw materials used for the preparation of a homogeneous glass batch.

S. No	Parameter	Silica Sand	Dolomite	Limestone	Slag	Salt Cake	Soda Ash	Iron Oxide
1	SiO2(%)	98.69	2.32	1.51	32.92	NA	NA	NA
2	Al2O3(%)	0.66	0.12	0.30	15.89	NA	NA	NA
3	Fe2O3(%)	0.05	0.201	0.102	0.31	NA	NA	NA
4	TiO2(%)	0.05	Tr	Tr	0.72	NA	NA	NA
5	CaO (%)	Tr	28.94	52.65	33.35	NA	NA	NA
6	MgO (%)	Tr	21.09	0.32	6.40	NA	NA	NA
7	Na2O (%)	Tr	Tr	Tr	0.11	Purity 99.2% (Na2SO4)	Purity 99.2% (Na2CO3)	Purity 93% (Fe2O3)
8	K2O (%)	Tr	Tr	Tr	0.56	NA	NA	NA
9	SO3(%)	Tr	Tr	Tr	0.76	NA	NA	NA

Experimental-Batch Preparation and Melting in Pilot Furnace

After analysing and confirming the chemical composition of each raw material, ten batches (300 g each) were prepared using the same raw materials to ensure homogeneity for the subsequent addition of decolorizing agents to evaluate their effect.

The proportion(wt%) of raw materials in ten batches is given in the table 2.

Table 2. presents the batch composition of the basic raw materials along with the proportion of each constituent used in the glass preparation

Raw Material	Batch Samples (Wt gm)									
	1	2	3	4	5	6	7	8	9	10
Silica sand	174.22	174.15	174.11	174.23	174.12	174.20	174.21	174.19	174.10	174.15
Dolomite	45.29	45.30	45.24	45.30	45.30	45.34	45.44	45.42	45.31	45.32
Soda ash	55.47	55.45	55.44	55.45	55.48	55.49	55.45	55.47	55.47	55.44
Salt cake	2.60	2.60	2.62	2.61	2.60	2.63	2.66	2.61	2.61	2.60
Slag	9.31	9.30	9.33	9.37	9.31	9.33	9.32	9.32	9.31	9.36
Limestone	13.18	13.06	13.17	13.18	13.14	13.11	13.17	13.16	13.05	13.15
Total Wt (Gm)	300	300	300	300	300	300	300	300	300	300

The chemical composition of the prepared glass samples was analysed using WD-XRF (Zetium, PANalytical, The Netherlands), and the results are presented in table 3.

This analysis was performed to ensure that the targeted iron content (0.10%) was maintained in the glass samples selected for subsequent experiments to evaluate the effect of decolorizing agents.

Table 3. presents the glass basic composition (before adding decolorizing agent)

Parameter (%)	SiO2	Al2O3	Fe2O3	TiO2	CaO	MgO	Na2O	K2O	SO3	CoO	Se	Cr2O3	Nio
Result-Wt (%)	71.01	1.21	0.10	0.07	9.16	4.13	13.89	0.21	0.23	ND	ND	ND	ND

Batches with varying proportion of different decolorizing agents are prepared and get melted in pilot furnace (Naskar & Company) at 1450 °C for 90 minutes (as per standard operating procedure-) to prepare the glass targeted samples to check actual color tone (tinge).

The chemical composition of the prepared glass

samples was determined using wavelength-dispersive X-ray fluorescence (WD-XRF) spectroscopy (Zetium, PANalytical, Netherlands). The optical and energy-related properties of the glass samples were characterized using a UV–Vis–NIR spectrophotometer (Lambda 9, PerkinElmer, USA). Color measurements were quantified using the CIE L*a*b* color space and a HunterLab colorimeter (ColorQuest XE US Pro).

Table 4. Shows the batch composition basic raw material with varying concentration of decolorizing agents

Material	Batch adding decolorizing agent (Qty- gm)									
	1	2	3	4	5	6	7	8	9	10
Fe_2O_3*	0.083	0.082	0.075	0.074	0.075	0.077	0.079	0.077	0.075	0.076
MnO_2	1.507	1.501	….	1.501	….	….	….	….	….	….
SnO_2	1.504	….	….	….	1.501	….	….	….	….	….
Nd_2O_3	1.502	1.503	….	….	….	1.505	….	….	….	….
TiO_2	….	1.501	….	….	….	….	1.505	….	….	….
CoO	….	….	….	….	….	….	….	….	….	….
C	….	….	0.108	0.109	0.109	0.109	0.108	0.135	0.288	0.438

*Fe_2O_3 is added in batch to maintain iron content in the finished glass 0.10% for each sample for decolorization purpose...

10 numbers of batches with similar composition having same proportion of basic raw materials are prepared and then different decolorizing agents are added (as per table-4) to check decolorizing effects of selected different decolorizing agents.

Sample-1 with 0.5% MnO2, 0.5% SnO2, and 0.5% Nd2O3 shows greyish tinge, sample-2 with 0.5% MnO2, 0.5% Nd2O3 , and 0.5% TiO2 exhibits light greyish tinge, sample-3 with 0.036% C content shows some greenish tinge, Sample-4 with 0.5% MnO2 and 0.036% C content exhibits yellowish tinge, sample-5 with 0.5% SnO2 and 0.036% C content exhibits bluish tinge, sample-6 with 0.5% Nd2O3 and 0.036% C content exhibits green-blue tinge, sample-7 with 0.5% TiO2 and 0.036% C content exhibits yellowish tinge, sample-8 with 0.04% C shows clear with very light blueish tone(calm color), sample-9 with 0.10% C shows amber-yellow tinge, and sample-10 with 0.15% C exhibits dark amber tinge. Sample-2, 5, 6 and 8 were visually appealing and taken for further study to improve aesthetic (color tone).

RESULT AND DISCUSSION

The optical properties of the prepared glass samples were investigated using a UV–Vis–NIR spectrophotometer (Lambda 9, PerkinElmer, USA) to evaluate their transmittance and reflectance behavior. Colorimetric parameters (L, a, and b*) were determined using a HunterLab UltraScan PRO spectrocolorimeter, and the corresponding results are summarized in Table 5.

Table 5. Presents the glass transmittance and reflections data (Tr, RF and RG)

Hunterlab result of Batch Samples					
Parameter		Sample-2	Sample-5	Sample-6	Sample-8
Transmittance	L*(%)	89.12	93.24	90.99	94.04
	a*	-3.05	-3.71	-3.42	-2.22
	b*	-2.81	-1.48	-5	0.27
	Y (%)	74.41	83.51	78.46	85.37
Reflectance (RG)	L*(%)	30.34	32.13	31.26	32.04
	a*	-1.16	-1.3	-0.99	-0.86
	b*	-0.79	-1.32	-2.18	-0.53
	Y (%)	6.38	7.14	6.76	7.1
Reflectance (RF)	L*(%)	30.56	31.75	30.52	31.84
	a*	-1.21	-1.48	-0.19	-0.97
	b*	-1.02	-0.99	-1.43	-0.68
	Y (%)	6.47	6.98	6.45	7.02

The angular color performance of the prepared glass samples was evaluated using a gonio-spectrophotometer (Photo Research Inc., USA) over incidence angles ranging from 0° to 80°. Mechanical durability was assessed using a Taber abrasion tester (Model 5135

Abraser, Taber Industries, USA). Chemical durability was examined through salt spray and acid–base resistance tests conducted using equipment from Gautam Lab Equipment, India. The samples were exposed to salt spray for 21 days and to acid–base conditions for 24 hours, in accordance with EN 1096 standard procedures.

Figure 1 illustrates the a* and b* color values of Samples 2, 5, 6, and 8 obtained using the HunterLab spectrocolorimeter. Optical measurements, including transmittance (Tr), glass-side reflectance (Rg), and film-side reflectance (Rf), were performed using a UV–Vis–NIR spectrophotometer across the 250–2500 nm wavelength range.

The average visible light transmittance of the four samples was calculated over the 380–780 nm range.

Sample-8 (with carbon- 0.04%) shows very clear and higher visible light transmittance and basis of the hunter lab result (a* & b*) and higher transmittance (85.2%) the 0.04% carbon(C) added sample shows very good result and neutral color tone.

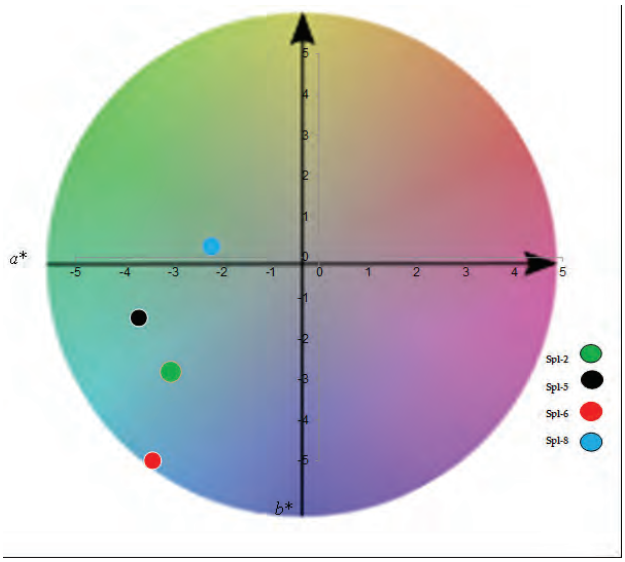

Fig. 1. Illustrates the CIE L,a,b color system and presents the a* and b* values of samples 2, 5, 6, and 8

The a* coordinate represents the red–green chromatic axis, while the b* coordinate corresponds to the yellow–blue chromatic axis.

Figure 2 presents the transmittance (Tr) spectra of the glass samples obtained using a UV–Vis–NIR spectrophotometer (Lambda 9, PerkinElmer, USA), covering the wavelength range of 250–2500 nm.

Sample 8A, which corresponds to the batch containing 0.04% carbon, was prepared to verify the repeatability and reproducibility of the results. This sample exhibited higher visible transmittance and reduced infrared (IR) transmittance, making it the most suitable among all the tested samples and enhancing the aesthetic appearance of the glass. The corresponding spectral characteristics are shown in figure 2.

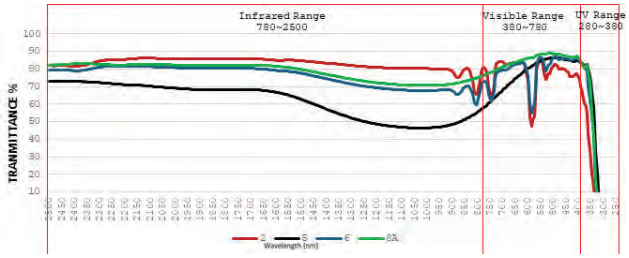

Fig. 2. Shows spectral distribution of sample-2, 5,6 and 8a*(transmission spectral distribution 250nm to 2500nm)

*8A sample is batch with 0.04% carbon to repeat the result (to check the repeatability and reproducibility).

CONCLUSION

Each decolorizing agent used for the study (Mn, Sn, Nd, Ti, and C) has different effect on the color tone of soda lime silicate glass. Sample-1 with 0.5% MnO2, 0.5% SnO2, and 0.5% Nd2O3 shows greyish tinge, sample-2 with 0.5% MnO2, 0.5% Nd2O3 , and 0.5% TiO2 exhibits light greyish tinge, sample-3 with 0.036% C content shows some greenish tinge, Sample-4 with 0.5% MnO2 and 0.036% C content exhibits yellowish tinge, sample-5 with 0.5% SnO2 and 0.036% C content exhibits bluish tinge, sample-6 with 0.5% Nd2O3 and 0.036% C content exhibits green-blue tinge, sample-7 with 0.5% TiO2 and 0.036% C content exhibits yellowish tinge, sample-8 with 0.04% C shows clear with very light blueish tone(calm color), sample-9 with 0.10% C shows amber-yellow tinge, and sample-10 with 0.15% C exhibits dark amber tinge. Sample-8 is visually appealing and shows very clear.

The redox reaction well described by the following reaction:

$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2$ or $Fe^{3+} + C \rightarrow Fe^{2+} + C+ \quad T\uparrow$

In above redox reaction carbon acts as reducing agent and changes ferric oxide(yellow-green) form to ferrous oxide(blue-green) and glass looks more neutral and calmer.

Study shows that the carbon is one of the best and economical decolorizing agents to decolorize soda lime silicate glass by chemical decolorization. Good results are achieved by adding 0.04% carbon in batch corresponding to 0.36~ 0.46 redox number.

REFERENCES

1. E. Meechoowas, S. Poosrisoma, P. Jampeeruang and T. Jitwatcharakomol, The effect of heat treatment on Fe2+/ Fe3+ ratio in Soda-lime silicate glass, Key Engineering Materials, 659 (2015), 194-198.
2. Meechoowas, P. Jampeeruang, K. Tapasa and T. Jitwatcharakomol The decolorizing of high iron containing Soda-lime silicate glass by annealing process, Key Engineering Materials, 702 (2016), 130-134.
3. F. V. Tooley, The handbook of glass manufacture 3rd, Ashlee Publishing Co., Inc. New York, 1984.
4. E. Meechoowas, Redox behavior of glasses doped with copper and arsenic, antimony or tin, Dissertation (2010), Friedrich-Schiller-Universität Jena, Jena, Germany.
5. C. Rüssel, Redox behaviour and electrochemical behavior of glass melts, in: L.D. Pye: Properties of glass forming melts. CRC Press, Boca Raton 2005, 27-56.
6. H. Schirmer, M. Müller and C. Rüssel, High-temperature spectroscopy study of redox reaction in iron and arsenic-doped melts. Glass. Sci. Technol. 76 (2003) 49-55.
7. L. Kido, M. Müller and C. Rüssel, Evidence of redox relaxation during thermal treatment of soda lime silica glasses doped with chromium and manganese, Chem. Mater. 17(2005) 39293934.
8. J. Kaufmann and C. Rüssel, Thermodynamic of Cu+/ Cu2+ redox equilibrium in soda-silicate and soda-lime silicate melts., J. Non-Cryst. Solids. 355(2009) 531-535.
9. E. Meechoowas, M. Müller and C. Rüssel, Redox relaxation in a sodium borosilicate glass doped with copper and arsenic, antimony, or tin, J. Non-Cryst. Solids. 356 (2010) 2528-2533.
10. M. Yamashita, T. Akai, R. Sawa, J. Abe and M. Matsumura, Effect of preparation procedure on redox states of iron in soda-lime silicate glass, J. Non-Cryst. Solids. 354 (2008) 4534-4538
11. G. Gravanis and C. Rüssel, Redox reactions in Fe2O3, As2O3 and Mn2O3 doped soda-limesilica glasses during cooling-a high-temperature EPR investigation, Glastech. Ber. 62(1989) 345-350.
12. N. Krishnamurthy and C. K. Gupta, Extractive metallurgy of rare earths 2nd, CRC Press., Florida, 2016.
13. A. A. Ramadan, Solarization behavior of manganese-containing glass: an experimental and analytical study, Meditterranean Archaeology and Archaeometry, 9 (2009) 37-53.
14. Ekarat Meechoowas1, Benjamon Petchareanmongkol1,Parida Jampeerung1, and Kanit Tapasa1,The Optical Properties of High Iron Contents Soda-Lime Silicate Glass, Key Engineering Materials, 2018 Trans Tech Publications, Switzerland
15. Nagendra Kumar, Pramod Kumar Awasthi, Vemuri S. R. S. Praveen Kumar. “Development of Heat Reflective Solar Control Coatings via Large-Area Magnetron Sputtering to Architectural Glass Facade Applications”, International Journal of Applied Glass Science, 2026
16. zh.scientific.net
17. www.biorxiv.org

GENERAL GUIDELINES FOR PREPARING AND SUBMITTING PAPERS

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Abstract

A single paragraph with a maximum of 200-250 words. Should comprise of important aims/objectives, results of the work and conclusions presented in the manuscript. Reader should easily understand and get a clear idea of what has been achieved and covered in the manuscript. Avoid the detailed information on the methodology followed.

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Acknowledgement

Authors can take the opportunity to acknowledge the persons who supported/encouraged in successfully completing the research work or survey and also the funding agencies.

References

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Journal Articles

Author 1 Name, Author 2 Name and Author 3 Name (Year), *Title of the* Article, Title of the *Journal Title in Italic*, Publisher Name, Publisher City Name, year. For example,

1. Bocky M Nat, Dolphin P Gem, Mcrath H. Sam (2021), "*Transforming Education Through Tech Age",* International Jour. of Sustainable Technologies, Vol. 47, No.03, Pp 56-65.
2. Bilroth N. Creen, Jingle M.S, Richy K. Mount (2023). *Embracing the Emerging Trends*, Int. Jour. of Engineering and Technologies 25(2): 35-42.

Conf. Proceedings

James F. Kennedy and Raj N. Cramp "*Studies on Recycling of Treated Waste from CETP for Green Belt Development"* at International Conference on "Special Conference on Water Quality" organized by the ABC College of Engineering & Technology, New Delhi, during 01-03 July2023.

Books

Author 1 Name, Author 2 Name and Author 3 Name, *Title of the Journal Title in Italic*, Publisher Name, Publisher City Name, year. For example,

Y. M. Bapu and S.M. Sastry, "*A Text Book on Machine Learning"*, Indian Society for Technical Education, New Delhi, 2023.

Theses

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Volume 49 • No 2 • April-June 2026
Periodicity: Quarterly • Subject: Multidiciplinary

ISSN 0971-3034

PUBLISHED BY
INDIAN SOCIETY FOR TECHNICAL EDUCATION
Near Katwaria Sarai, Shaheed Jeet Singh Marg,
New Delhi - 110 016

Printed at: Compuprint, Flat C, Aristo, 9, Second Street, Gopalapuram, Chennai 600 086.
Phone : +91 44 2811 6768 • www.compuprint.in