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Editorial

Reimagining Academic Excellence in Higher Education: Academic excellence in higher education can no longer be defined by traditional parameters such as lecture-dominated teaching, routine examination systems, physical infrastructure, or institutional rankings alone. In a rapidly changing world influenced by technological advancement, global integration, and evolving societal demands, excellence must be understood as a dynamic, inclusive, and continuous process. It now represents the quality of teaching and learning, the relevance of research, innovation, ethical leadership, and a sustained commitment to social responsibility. Higher education institutions are increasingly expected to move beyond knowledge transmission and function as active centres of knowledge creation, problem-solving, and human capital development.

At the heart of this transformation lies the faculty, whose competence and commitment significantly shape institutional quality. Academic excellence is inseparable from the professional growth of teachers. *Faculty development is no longer an optional support mechanism but a strategic priority. Continuous professional growth through exposure to emerging technologies, interdisciplinary perspectives, research engagement, and innovative pedagogical practices is essential for maintaining academic relevance*. Well-equipped faculty members foster critical thinking, creativity, and intellectual curiosity, enabling students to address complex academic and real-world challenges with confidence.

Equally vital to academic excellence is the development of a strong and sustainable research culture. Research must be viewed not merely as an individual effort but as a shared institutional responsibility. This requires supportive policies, adequate infrastructure, collaborative networks, and strong ethical standards. A healthy research ecosystem encourages inquiry, experimentation, and innovation while responding meaningfully to local, national, and global concerns. When teaching and research are integrated, classrooms become spaces of exploration and dialogue, and laboratories transform into hubs of discovery and innovation.

Reimagining academic excellence also demands deeper engagement with industry and society. Graduates must acquire not only disciplinary knowledge but also adaptability, ethical awareness, and problem-solving skills. Institutions that promote industry partnerships, innovation, and entrepreneurship contribute significantly to societal progress and economic competitiveness.

Ultimately, academic excellence should be viewed as an ongoing journey rather than a fixed outcome. By strengthening faculty capacity, nurturing a vibrant research culture, and embracing innovation and societal engagement, higher education institutions can redefine their purpose and emerge as enduring contributors to knowledge, sustainable development, and a better future.

Holistic academic excellence is essential for a better future

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Implications of International Standards on Lattice Towers for a Topography

Tanuku Srinivas
Research Scholar
Dept. of Civil Engineering
Jawaharlal Nehru Technological University
Hyderabad, Telangana
✉ srinivastanuku1983@gmail.com

Maganti Janardhan Yadav
Professor
Dept. of Civil Engineering
Jawaharlal Nehru Technological University
Hyderabad, Telangana
✉ prof.mjyadav@yahoo.com

ABSTRACT

Lattice towers have been extensively utilized by the telecommunications industry over the past several decades owing to their cost-effectiveness, structural efficiency, and adaptability across diverse geographic conditions. These towers are frequently installed in mountainous regions to ensure reliable network coverage. Steep slopes and elevated wind exposure significantly affect structural behaviour; therefore, tower design in such environments presents distinct engineering challenges. The Indian Standard, IS 875 (Part 3), provides guidelines for wind speed-up effects in hilly regions. However, the adopted methodology does not incorporate recent technological advancements related to wind speed-up effects arising from topographical features. Consequently, it is necessary to evaluate the current methodology in conjunction with other international standards that address topographical influences. This paper examines the provisions of the Indian standard and compares them with that of the United States, Australia, Canada, and Europe regarding wind speed-up effects on hills. A case study is conducted to analyse and arrive at the overall impact of wind speed-up effects in hilly regions as per five international standards.

KEYWORDS: *Lattice tower, Topography factor, Hill, Ridge.*

NOTATIONS

Indian Standard

V_b	Basic wind speed
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
C	Applicable value factor
s_0	Applicable value factor
H	Above mean ground level
X	Distance from the summit or crest relative to the effective length
L_e	is the effective horizontal length of the hill depending on slope

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
K_1	Topographic feature factor adjusted for slope standard.
β	Slope modifier
K_1'	Topographic feature factor
K_2	Horizontal distance factor

K_3 Vertical distance factor

Australian standard

ρ_{air} Air Density

$V_{des,\theta}$ Building orthogonal design windspeeds

C_{shp} Aerodynamic shape factor

C_{dyn} Dynamic response factor

$V_{sit,\beta}$ Site windspeed

V_R Regional gust wind speed

M_c Climate change multiplier

M_d Wind directional multiplier

$M_{z,cat}$ Terrain/height multiplier

M_s Shielding multiplier

M_t Topographic multiplier

H Height of Hill or escarpment

x Horizontal distance upwind or downwind from the structure to the crest of hill or a ridge

L_g Length to determine the topographical multiplier, 0.4 H or 0.35 Lu, whichever is greater.

L_u Horizontal distance upwind from the crest of a hill, ridge or escarpment to a level half the height below the crest.

z height of the centroid of the tower section above ground level.

Canadian standard

V Hourly wind speed

C_e Height factor

C_g The gust effect factor

C_a Roof top Speed up factor

C_t Topography factor

ΔS Applicable value factor

x horizontal distance from the peak of the hill or escarpment

ΔS_{max} Applicable value factor

α Applicable constant factor

k Applicable constant factor

L_h horizontal distance upwind from the peak to the point where the ground surface lies at half the height of the hill or escarpment, or 2Hh.

z height above ground

H_h height of hill or escarpment

European standard

C_o Orography factor

$I_{v(z)}$ Turbulence intensity

ρ Air density

V_m Mean wind speed

Φ Hill slope (H/L)

s Applicable value factor

INTRODUCTION

Lattice towers have been extensively utilized by the telecommunications industry over the past several decades due to their cost-effectiveness, structural efficiency, and adaptability across a wide range of geographic conditions. These towers are often installed in mountainous regions to provide reliable network coverage. Steep slopes, high wind exposure, significantly influence structural behaviour. Hence, tower design in such environments presents unique engineering challenges. Wind funnelling between mountains and wind flow normal to a mountain ridge significantly influence the alteration of the wind speed profile. Hilly feature defined as land surface characterized by a strong relief in all horizontal directions and distinct in shape and scale in comparison to the surrounding terrain [1], whereas ridge feature is an elongated crest characterized by strong relief in two horizontal directions and distinct in shape and scale in comparison to the surrounding terrain [1]. Escarpment is defined as a steep slope generally separating two levels or gently sloping areas, where downwind slope is less than 3° [2]. Accordingly, codified procedures classify topographical features such as hills, ridges, and escarpments to account for the effects of wind speed variations induced by these features.

In India, the design of telecom towers is governed by IS 17740 [3], while IS 875 [2] prescribes guidelines for

wind speed-up effects in hilly regions. The influence of topography becomes significant when the upwind slope angle (θ) exceeds approximately 3° [2]. The topography factor (k_3) accounts for undulations in the local terrain and applies to both upwind and downwind slopes. A detailed methodology is prescribed in Appendix C of IS 875 [2]. However, this methodology does not incorporate recent technological advancements related to wind speed-up effects due to topographical features. Consequently, it is necessary to examine the current methodology in conjunction with other international standards addressing topographical effects, in order to evaluate the Indian context relative to international practices.

The current study considers four international standards: American, Australian, Canadian, and European. As per the American standard, ANSI/TIA-222-I [1], the increase in wind speeds due to topography is represented by the exposure-dependent factor (K_{zt}). The Australian standard, AS 3995 [4], addresses steel lattice towers, while AS/NZS 1170.2 [5] specifies wind actions with explicit provisions for terrain and topography through the factor (M_t). The Canadian standard, CSA S37-18 [6], governs antenna-supporting structures, and the National Building Code of Canada (NBCC, Part 4) [7], introduces the factor (C_t) to adjust wind pressures in hilly regions. The European standard EN 1991-1-4 [8] defines terrain categories, roughness parameters, and topographic influences (C_o) relevant to tower design. Each of these international codes incorporate recent advancements in wind engineering and provide streamlined approaches for evaluating topographic factors.

This paper examines the methods as per the Indian standard and compares them with the standards of America, Australia, Canada, and Europe for wind speed up effects on hills. A case study analysis is carried to assess the overall impact of wind speed up effects in hilly regions. The results are summarized and conclusion is arrived on methodology adopted by Indian standard when compared with other international standards.

LITERATURE REVIEW

Wind loading on telecom towers has been extensively studied to understand structural behaviour under varying terrain and atmospheric conditions. Davenport et al., [9] examined how wind pressure affects lattice towers, emphasizing the influence of tower geometry and terrain. Later, Hong Clucas [10] expanded this work by analysing dynamic wind effects such as gusts and turbulence, recommending design modifications to mitigate vibration risks in tall towers, especially in mountainous regions. Allen [11] used simulations to explore wind flow over hills with variable surface roughness, showing that the placement of rough zones such as on summits or slopes can significantly alter wind separation and surface stress, which is critical for tower design in hilly terrain. Ngo and Letchford [12] have presented a comparative analysis of topographic effects on gust wind speed across four major wind-loading codes of America, Australia, Japan and Europe. The authors have derived combined terrain/height and topographic multipliers for each code and highlighted discrepancies in speed-up predictions over hills, ridges, and escarpments. Notably, American Standard (ASCE/SEI 7-05) uniquely incorporates terrain roughness into speed-up effects, while Japanese standard (AIJ:2004) introduces turbulence intensity modifications. The study concludes that code-specific assumptions and slope limits significantly influence gust speed estimations, with recommendations for harmonizing methodologies across standards. Bashor and Kareem [13] compares six international wind loading standards— America, Australia, Canada, Europe, Japan, and international standard of Organization (ISO) —focusing on their treatment of along wind, across wind, and torsional loads for tall buildings. It concluded that example buildings show significant variation in base shear and moment predictions due to differences in averaging times, exposure categories, and spectral models. Flay et al., [14] evaluated hill-shape multipliers from seven wind loading standards— America, Australia, Canada, Europe, Kenya, Japan and International standard of Organization (ISO)—against full-scale wind speed-up measurements over Belmont Hill, New Zealand. Despite similar multiplier predictions across standards, none adequately captured the complex terrain-induced speed-up observed in field data. The study attributes this to oversimplified geometric assumptions and limited slope resolution in standard formulations. ISO 4354 is noted as the only code allowing for reduced wind speeds over hilly terrain. Kline et al., [15] outlined

the evolution of topographic wind speed-up modelling in telecommunications design, as per in ANSI/TIA-222-H. It has emphasized that improper application of topographic effects can lead to overdesign and increased costs. It recommends Method 2 for most cases and Method 3 for critical sites requiring precise wind speed estimation compared to method 1 prescribed in ANSI/TIA-222-H. Wani et al., [16] highlighted the complexity in evaluating topography factors under the Indian Standard and proposed simplified design curves in evaluating the topography factor for further calculating design wind speed on escarpments.

METHODOLOGY COMPARISON

The methodology adopted by different standards is presented in this section. The general topographical features are shown in the Figure 1.
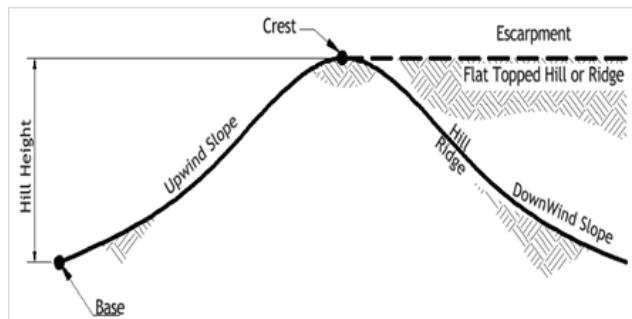
Fig. 1 General Topographical Feature

Topographical coefficient is related to mean wind speed at the base of the hill or escarpment. It is expressed as a function of the slope (θ), actual length of upwind or downwind slope, horizontal distance of site position from top of the crest the length and vertical distance from the ground level of the site. Surface roughness has no importance in relation to the increase in the speed.

Indian Standard

Two types of features are defined, viz., Hill and ridge, Cliff and Escarpment for calculation of topographical influence. The influence of topographical feature is considered to extend 1.5 L_e upwind and 2.5 L_e downwind of the summit of crest of the feature. The effective horizontal length (L_e) of hill depending up on the slope of hill. [2].

The value of topography factor k_3 is suggested by

$$k_3 = 1 + C\, s_0 \qquad (1)$$

Where, C   : 1.2(Z/L) for slopes $3° \leq 17°$;

          : 0.36 for slopes $> 17°$

The value of topography factor (k_3) is in the range of 1.0 to 1.36 for slopes more than 3° and it varies with height above ground level.

The design wind pressure (p_d) as prescribed by [2] is

$$p_d = [0.6(V_b\, k_1\, k_2\, k_3\, k_4\,)^2]K_d\, K_a\, K_c \qquad (2)$$

American Standard

The Standard provides speed-up models applicable to Ridge, Flat Topped Ridge, Rolling Ridge, Hill, Flat Topped Hill, Escarpment and Rolling Hill. ANSI/TIA-222-I [1] adopted the provisions of ASCE 7 [18] with slope of topographic feature defined as the ratio of height to upwind length. Wind speed-up effects are recommended by the standard under the following conditions at isolated hills, ridges, escarpments.

- The height of topographical feature is greater than or equal to 4.57 m

- The structure is located on the upper half of the hill, ridge or escarpment.

- The Slope H/L, meets or exceeds 0.1 (5.71°).

Three methods are described for calculation of topography factor (K_{zt}) in the standard. Method 1 is simplified with an assumption that the structure is located at crest of the topographic feature. The topographic factor is constant if Slope (H/L) exceeds 0.1, which is a conservative approach [15]. Method 2 allows more detailed approach using three multipliers mentioned in the Equation 2.

$$K_{zt} = [1+K_1 K_2 K_3]^2 \qquad (3)$$

K_1 accounts for shape of topographical feature, K_2 accounts for the variation of speed-up as a function of distance from the crest, and K_3 accounts for the variation of the speed-up as function of height above the surface of topographic feature. These multipliers are based on the assumption that the wind approaches the hill along the direction of maximum slope, causing the greatest speed-up near the crest. These multipliers are associated with exposure category of structure and slope of hill. This method is closely aligned with the

ASCE 7 [18] but also includes provisions for flat top hills and ridges that result in significant reductions in wind speed-up values compared to the ASCE 7 [18] for hills and ridges [15]. Method 3 is site specific procedure allowed by the standard.

The ultimate design wind pressure (q_z) as prescribed by [1] is,

$$q_z = 0.613 \, K_z \, K_{zt} \, K_s \, K_e \, K_d \, V^2 \tag{4}$$

Australian Standard

Topographical effects are recommended in wind load estimation when the upwind slope exceeds 0.05. Clause 2.2.4 of AS 3995 [4] provides a method for calculating gust wind speeds, which differs from that specified in AS 1170.2. This method is based on numerical computation of boundary layer flow over two dimensional hills, including escarpments, embankments, and ridges, with varying upwind slopes. The computations were validated against both full scale and wind tunnel measurements for shallow upwind slopes. The accuracy is reduced for steep slopes greater than 0.3, where flow separation often occurs on both the upwind and downwind sides of the crest. The variation of the multiplier with height above ground, given by Equation (5), is considered more realistic than the linear variation with height implied in AS 1170.2 [5].

$$M_t = 1 + \frac{H\left(1 - \frac{|x|}{4L_g}\right)}{3.5(z + L_g)} \tag{5}$$

The ultimate design wind pressure (p) is prescribed by [5] is,

$$p = (0.5 \cdot \rho_{air}) \cdot \left(V_{des,\theta}\right)^2 \cdot c_{shp} \cdot c_{dyn} \tag{6}$$

$$V_{sit,\beta} = V_R \cdot M_c \cdot M_d \cdot \left(M_{z,cat} \cdot M_s \cdot M_t\right) \tag{7}$$

Canadian Standard

Wind accelerates over small scale terrain features, typically less than 10 km in horizontal extent, such as hills, ridges, and escarpments. The resulting speed up can increase wind velocity by up to a factor of two. These effects are highly localized, with the largest increases occurring near the crest of the terrain feature and diminishing within 50 m to a few hundred metres from the top. Procedures for accounting for terrain induced increases in wind speed are provided in the NBCC 2015 [7]. For structures located on hills or

escarpments with a slope defined as $H_h/(2L_h)$ greater than 0.1, the topographic factor C_t shall be calculated as follows:

$$C_t = \left(1 + \frac{\Delta S}{C_g}\right)(1 + \Delta S) \tag{8}$$

$$\Delta S = \Delta S_{max}\left(1 - \frac{|x|}{kL_h}\right)exp(-\alpha z/L_h) \tag{9}$$

The design wind pressure (P) is prescribed by [6] [7] is,

$$P = 0.645 \, V^2 \, C_e \, C_g \, C_a \, C_t \tag{10}$$

European Standard

When the wind meets an escarpment or hill, the air flow is forced into a smaller area provided the boundary layer and the gradient height do not change. Therefore, the wind speed and wind pressure increase. The largest increase of wind velocities occurs near the top of the slope, and is determined from the orography factor C_o. The effects of orography may be neglected when the average slope of the upwind terrain (i.e., 10 times the height of isolated orographic feature) is less than 3°. The increase in speed should only be considered for locations closer than half the length of the hill slope from the crest or 1.5 times the height of the cliff.

$$C_o = 1 \qquad \text{for } \Phi < 0.05 \tag{11}$$

$$C_o = 1 + 2 \cdot s \cdot \Phi \qquad \text{for } 0.05 < \Phi < 0.3 \tag{12}$$

$$C_o = 1 + 0.6 \cdot s \qquad \text{for } \Phi > 0.3 \tag{13}$$

The peak velocity pressure at height q_p (z) as prescribed by [8] is,

$$q_p(z) = [1 + 7 \cdot I_v(z)] \cdot \frac{1}{2} \cdot \rho \cdot v_m^2(z) \tag{14}$$

Comparison of Topographical Factor

The comparison of topography factor for a hill height of 150 m with slope (H/L) ranging 0.1 to 1.0 based on five international standards is shown in the Figure 2. Few standards employ the squared value of topography factor for the calculation of design wind pressure. Hence the overall impact shall be studied comparing ultimate design wind pressure. The calculated ultimate design wind pressure, with a basic wind speed of 39 m/s located in open terrain is shown in the figure 3. The ultimate design wind pressure is also included the respective wind load factors and dynamic response

factors. The natural frequency of structure assumed as greater than 1Hz.
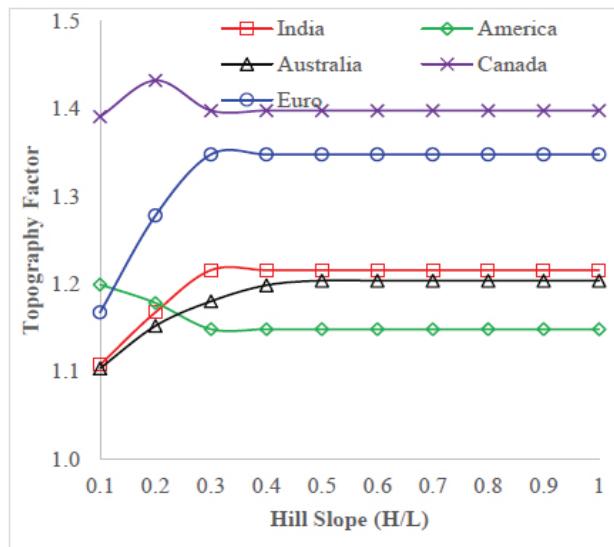
Fig. 2 Topography Factor based on Five International standards
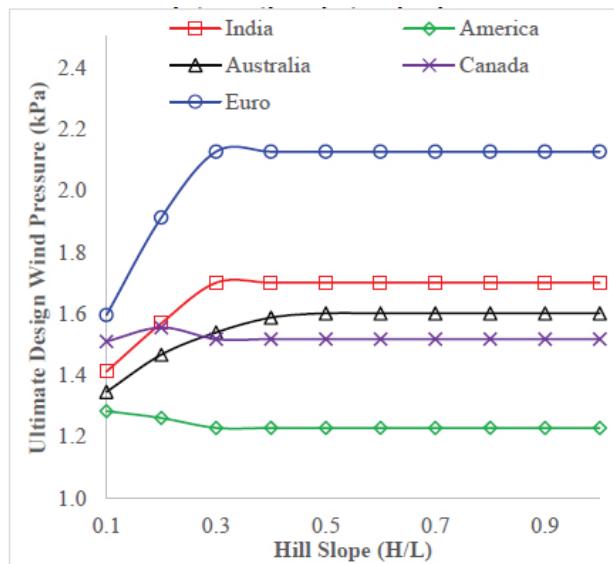
Fig. 3 Ultimate design wind pressure (kPa) based on Five International standards

The following observations are made from Figure 2:

• For H/L = 0.1, The topography factor calculated from the Indian standard shows decreases of 8%, 20%, and 5% relative to the American, Canadian, and European standards, respectively, while Australian standard remains consistent.

• For H/L = 0.2, The topography factor calculated from the Indian standard shows negligible differences when compared with the American and Australian standards. But, reductions of 18% and 9% are noted with the Canadian and European standards respectively.

• For H/L = 0.3–1.0, The topography factor calculated from the Indian standard shows increase by 6% and 1% when compared with the American and Australian standards, respectively, while reductions of 13% and 10% are observed with the Canadian and European standards.

Similarly, the following observations are made from Figure 3. on the ultimate design wind pressure based on five international standards.

• For H/L = 0.1, The Indian standard shows 10% higher ultimate design wind pressure when compared with American standard. Whereas lower values of 24%, 6% and 12% are observed with Australian, Canadian and European standards respectively.

• For H/L = 0.2, The Indian standard shows 24% higher ultimate design wind pressure when compared with American standard. Whereas lower values of 22%, and 18% are observed with Australian and European standards respectively. The wind pressure obtained from Canadian standard is consistent with Indian standard for H/L – 0.2

• For H/L = 0.3-1.0, The Indian standard shows 38% higher ultimate design wind pressure when compared with American standard and 12 % with Canadian standard. But lower value of 20%, are observed with Australian and European standards.

CASE STUDY ANALYSIS

The case study examines the variation of design wind load along the height of the tower structure in accordance with five national standards. Two structural 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 traditional bracing patterns. The structure is located at the crest of a hill with a height of 150 m and a slope ratio (H/L) of 0.40. 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 4.

A basic wind speed of 39 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 26.98 m/s and 25.84 m/s. 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.

Ultimate Wind Load

The ultimate wind load calculation for hill slope (H/L) of 0.40 for Square-Angular and Triangular-Hybrid configurations are presented in the Table 1 and Table 2 respectively. Based on Table 2 for square tower, The Indian standard shows higher base moment of 66%, 31%, 35% and 1% when compared with American, Australian, Canadian and European standards respectively. Similarly, from Table 3 for triangular hybrid tower, The Indian standard shows higher base
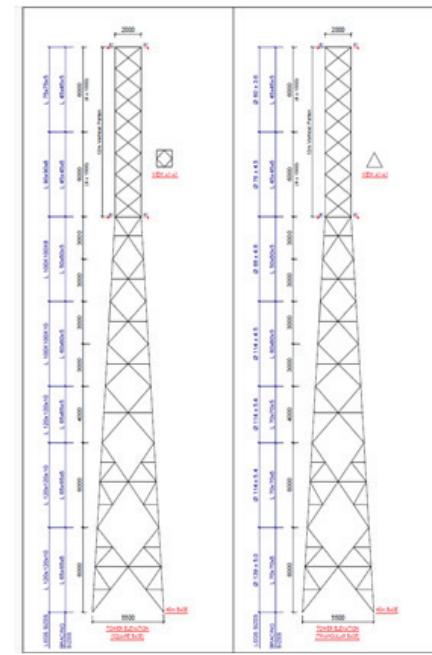
Fig. 4 Tower Elevation Layout

moment of 48%, 24%, when compared with American, Canadian standards respectively. But 13% lower base moment noticed compared European standard, and 1% with Australian standard.

The American standard prescribed the separate topographic multipliers for hill and ridge separately, whereas both are treated as one feature in the remaining standards. Hence huge increase of values is noticed when compared to American standard, with hill feature.

Table 1: Ultimate Wind Load on Square Tower based on Five International Standards

Panel Height (m)	Cumulative Height (m)	Exposed Area (m²)			Ultimate Wind Load, (kN)				
		Legs	Others	Total	India	America	Australia	Canada	Europe
3.0	40	0.45	0.54	0.99	9.14	5.64	7.05	6.84	9.88
3.0	37	0.45	0.45	0.90	8.38	5.10	6.47	6.26	8.93
3.0	34	0.54	0.45	0.99	8.90	5.44	6.76	6.62	9.33
3.0	31	0.54	0.45	0.99	8.77	5.34	6.62	6.49	9.05
3.0	28	0.60	0.56	1.16	9.83	6.06	7.41	7.32	10.08
3.0	25	0.60	0.51	1.11	9.59	5.81	7.41	7.17	9.77
3.0	22	0.60	0.65	1.25	10.54	6.38	8.20	7.89	10.62
3.0	19	0.60	0.70	1.30	10.88	6.48	8.45	8.08	10.74
4.0	16	0.96	0.94	1.90	15.37	9.06	11.84	11.34	14.79
6.0	12	1.44	1.75	3.20	24.08	14.00	17.94	17.61	22.08
6.0	6	1.44	1.97	3.41	26.05	13.09	16.76	17.54	16.82

Table 2: Ultimate Wind Load on Triangular Hybrid Tower based on Five International Standards

Panel Height (m)	Cumulative Height (m)	Exposed Area (m²)			Ultimate Wind Load, (kN)				
		Legs	Others	Total	India	America	Australia	Canada	Europe
3.0	40	0.36	0.50	0.86	4.58	3.19	4.78	3.90	5.66
3.0	37	0.36	0.41	0.77	4.01	2.79	4.14	3.42	4.91
3.0	34	0.46	0.41	0.87	4.23	2.91	4.35	3.47	5.08
3.0	31	0.46	0.41	0.87	4.16	2.86	4.26	3.41	4.93
3.0	28	0.53	0.57	1.10	5.13	3.48	5.30	4.17	6.01
3.0	25	0.53	0.52	1.06	4.88	3.34	5.04	3.98	5.70
3.0	22	0.69	0.65	1.34	5.89	3.89	5.52	4.59	6.78
3.0	19	0.69	0.70	1.39	6.12	4.03	5.69	4.76	6.90
4.0	16	0.92	0.99	1.91	8.27	5.43	7.61	6.44	9.12
6.0	12	1.37	1.83	3.20	13.29	8.72	13.02	10.42	13.94
6.0	6	1.68	2.08	3.76	15.46	8.66	11.87	10.86	11.41

SUMMARY AND CONCLUSION

The paper examines the provisions for calculating the topography factor as prescribed in five international standards and presents a summary of the topography factor along with the overall ultimate design wind pressure. The Indian standard follows a traditional methodology for topographical factor calculation, resulting in to higher value of topography factor when compared with other international standards. Huge variation is noticed when compared to American standard, as the standard prescribed topography multipliers for hill and ridge feature separately based on their extensive research when compared to all other international standards. In addition, there is difference observed in ultimate design wind pressure due to a combination of higher risk coefficient, unity gust effect factor and absence of explicit guidelines in the Indian standard.

Therefore, current study is beneficial for refining the guidelines in the future amendments, that suits for the Indian terrain conditions.

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Evolution and Synthesis of OD Matrix Estimation Techniques: Statistical, Heuristic, and Deep Learning Perspectives

Palsanawala Nimit P
Research Scholar
Gujarat Technological University
Ahmedabad, Gujarat
✉ nimit.palsanawala@gujgov.edu.in

Varia Harish R
Professor(Adjunct)
Faculty of Engineering, Science and Technology
Adani University, Gujarat
✉ nppgecbh@gmail.com

ABSTRACT

An Origin–Destination (OD) matrix is the core input for all traffic assignment and transport planning models. This systematic review of various seminal and recent studies analyzes the methodological evolution, performance trade-offs, and persistent challenges in OD matrix estimation. We categorize and evaluate approaches, including Statistical Frameworks (Gravity, Entropy, Bayesian), Heuristic Methods (Fuzzy Logic, GA), and Deep Learning (DL) models based on theoretical assumptions, required data inputs, and computational efficiency. The review finds that no universal solution exists. DL models achieve superior accuracy in non-linear pattern recognition but lack behavioral interpretability and demand massive, integrated data. Statistical frameworks effectively fuse heterogeneous data but rely heavily on reliable prior matrices. The primary unresolved challenge is the prohibitive computational cost of real-time, dynamic OD estimation for congested urban networks, which limits practical deployment alongside dynamic traffic assignment (DTA) models. This paper synthesizes the core trade-off between predictive accuracy and policy-relevant interpretability. We highlight the critical need for hybrid research focusing on Explainable AI (XAI) to increase the transparency of DL models, and transfer learning to enable advanced estimation in data-poor urban contexts.

KEYWORDS: *Transport planning, Origin-destination Matrix, Trip, Static, Dynamic.*

INTRODUCTION

Understanding the spatial and temporal distribution of travel demand is a cornerstone of modern transport planning. The origin–destination (OD) matrix quantifies the number of trips between each pair of zones within a region and serves as a critical input for traffic assignment, network design, and policy evaluation. Traditionally, OD matrices have been obtained through large-scale travel surveys or roadside interviews. These methods are time-consuming, expensive, and prone to sampling bias. Consequently, researchers have developed a wide range of analytical and computational techniques to estimate OD matrices indirectly from observed traffic counts and link flows. Early approaches, such as the Gravity and Fratar models, relied on assumptions of proportionality between zonal activity and travel impedance, offering simple yet limited representations of real travel behavior. Later, optimization-based and statistical formulations—such as entropy maximization, generalized least squares, and maximum likelihood estimation—introduced a stronger mathematical foundation for dealing with partial or noisy traffic data. In recent decades, the emergence of artificial intelligence (AI) and data-driven models, including fuzzy logic, neural networks, and evolutionary algorithms, has enabled more adaptive and nonlinear estimation of OD matrices. Despite this evolution, a unified framework that combines the interpretability of classical models with the adaptability of AI-based methods remains elusive. Many existing studies focus on static or equilibrium conditions, which limit their applicability for real-time or dynamic network management. This review aims to synthesize the progression of OD estimation methodologies, identify persistent research gaps, and highlight the growing importance of hybrid data-driven approaches for sustainable and intelligent transportation systems.

TRAVEL DEMAND MODEL-BASED METHODS

Researchers first employed a model based on the demand for travel at four stages. The researchers predominantly used gravity models to estimate matrices. A small number of transport planners also attempted to apply opportunity models, which are likewise based on travel demand. A critical deficiency of the gravity formulation is its poor accountability for external-external (E-E) travel demand.

OD matrix estimated through gravity model by [1] With the two assumptions: (i) trip forces between zones are proportional to zonal parameters such as population and socio-economic conditions and (ii) movement is inversely related to accessibility, quantified by a deterrence function based on factors like distance, time, or cost.

[1] further suggested the Hyman method to calibrate these cost parameters. However, the chief structural limitation of the Gravity Model is its inability to accurately account for external-external (E-E) trips, a failure directly attributed to the inadequacy of its core deterrence function for modeling non-internal travel behavior.

To refine the estimation process, researchers explored advanced methodological techniques. [2] critically evaluated the Gravity (GR), Intervening Opportunity (OP), and a Combined (GO) model, all designed as doubly constrained demand models. They compared calibration performance using rigorous statistical approaches, including Non-Linear Least Squares (NLLS), Weighted Non-Linear Least Squares (WNLLS), and Maximum Likelihood, validating their estimates against real-world urban vehicle movement data. Concurrently, work by [3] established the optimization groundwork, demonstrating that a unique OD matrix solution could be achieved provided that traffic counts are known for every connection within the network.

CRITICAL ASSESSMENT OF FUZZY LOGIC APPLICATIONS IN OD ESTIMATION

The application of Fuzzy Logic has been instrumental in addressing the inherent imprecision and uncertainty associated with real-world transport data, offering a unique capability to manage the vagueness encountered when fusing multiple, potentially conflicting data sources. This section critically evaluates key research utilizing fuzzy techniques for OD matrix correction and estimation.

[5] demonstrated a significant application of the TFlow Fuzzy (TFF) technique for base-year matrix calibration in Riga. By utilizing multiple data sources—videography, traffic count, and license plate surveys—they generated a high-fidelity probabilistic matrix, achieving strong performance metrics (R^2 near 1 and inaccuracy around 2%). While efficacious, this approach carries two notable limitations: first, the prerequisite evaluation and collection of the initial base year matrix demand substantial time and financial resources; second, the traditional TFF formulation often treats route choice proportions as constant throughout the estimation process, limiting its ability to capture dynamic changes.

Addressing the static nature of the traditional algorithm, [6] introduced a modified TFF algorithm that allows for the iterative updating of route choice proportions within each calculation step. This refinement proved more effective than the conventional algorithm when applied to a real, uncongested network. However, this iterative approach introduces a significant computational burden, which is compounded when attempting to apply the methodology to large-scale, congested networks where the dynamic complexity of route choice increases exponentially.

Earlier work by [7] focused on using fuzzy methods to improve the quality of the input data itself. They introduced Fuzzy Weighted Methods and subordinate functions to manage and consolidate inconsistent link count data, achieving satisfying outcomes in practical implementation. Despite the success in data conditioning, the primary challenge remains the subjective and heuristic definition of membership functions and fuzzy rules. Unlike objective statistical calibration, this reliance on expert knowledge for defining fuzzy boundaries introduces a substantial lack of transferability, making models highly sensitive to the initial subjective setup and limiting their generalization potential across different urban networks.

Fuzzy logic has also been integrated into hybrid correction models. [8]presented a methodology where the traditional gravity model generated the initial OD matrix, which was then systematically corrected and refined using fuzzy logic to smooth uncertainties, tailored specifically for small-city individual traffic. While effective, a pervasive limitation across many of these successful fuzzy applications (including those by Savrasovs & Pticina and Novačko et al.) is the focus on static or time-independent effects. Fully integrating fuzzy logic with dynamic traffic assignment (DTA) models—where traffic conditions change continuously—remains a major methodological hurdle, particularly in overcoming the challenge of validating a probabilistic or vague fuzzy matrix against conventional deterministic data.

DATA-DRIVEN ESTIMATION: THE TRANSITION TO ARTIFICIAL AND DEEP NEURAL NETWORKS

The increasing complexity and non-linearity of travel behavior have necessitated a shift from constrained mathematical formulations toward flexible, non-parametric models, most notably Artificial Neural Networks (ANNs) and Deep Learning (DL). These systems learn complex data relationships through weighted connections, offering a solution to estimation problems where underlying mathematical relationships are unknown or too difficult to specify.

Early research leveraged ANNs to tackle static OD estimation problems based on observed traffic flow. [9] introduced the Hopfield Neural Network to estimate OD matrices in metropolitan areas using connection volume counts, demonstrating the viability of non-linear optimization through network learning.

Subsequent studies focused on methodological refinement: [10] optimized the process by integrating specific link selection strategies (K and L approaches) and employing the robust Levenberg-Marquardt (LM) algorithm for training. Comparative analyses also validated the approach, showing that the ANN-based back-propagation model [11] achieved substantially acceptable results when contrasted with methods like the Multiple Path Matrix Estimation (MPME) [12]

Despite these early successes in optimizing solutions derived from static link counts, a critical limitation pervades all ANN-based approaches: the lack of interpretability. Unlike the clear, behavioral basis of a deterrence function in the Gravity Model, the relationships learned by ANNs are housed within numerical weights, rendering the model a "black box." This opacity creates an epistemological challenge for transport planners, as it undermines the ability to validate or trust the underlying behavioral assumptions, a requirement for policy-sensitive planning.

The advent of Intelligent Transportation Systems (ITS) has propelled the field toward Deep Learning (DL), which excels at integrating and processing vast, dynamic datasets. This modern approach is best exemplified by [13], who achieved highly effective hourly Origin–Destination (OD) matrix estimation in Tehran. Their methodology successfully fused complex big data streams, including GPS data, ANPR camera reads, loop detectors, smart fare cards, and socio-economic indicators. Among the five compared machine learning models (KNN, Random Forest, Light GBM, MLP, and CNN), the Convolutional Neural Network (CNN) achieved the highest accuracy and structural similarity with the ground truth matrix, demonstrating the capacity of DL to capture complex, time-dependent travel patterns. While deep learning provides superior accuracy in dynamic contexts, the transition introduces severe practical and scientific challenges:

The high performance of models like the CNN [13] is predicated on the availability of a massive, high-quality, and integrated dataset from multiple ITS sources, including the scarce ground truth OD matrix necessary for supervised training. Such data resources are simply unavailable in the vast majority of urban contexts globally.

Deep Neural Networks are structurally prone to overfitting the specific spatial and temporal features of the training network (e.g., the road geometry and commuter behavior in Tehran). Consequently, the model exhibits poor generalization and transferability, meaning a model successfully trained on one city's data is highly likely to fail when applied to another, demanding complete retraining and recalibration for every new study area.

METAHEURISTIC OPTIMIZATION: THE GENETIC ALGORITHM APPROACH

The inherent complexity and ill-posed nature of the OD matrix estimation problem, particularly when integrating link counts, make it an ideal candidate for solution using metaheuristic optimisation techniques, such as the Genetic Algorithm (GA). GA models are non-gradient-based search methods that efficiently explore large solution spaces to find an optimal OD matrix that minimizes the difference between calculated and observed network flows.

[14] proposed a methodology that utilized the Genetic Algorithm to integrate the estimation process with traffic assignment principles. Their approach involved performing a static traffic assignment under User Equilibrium (UE) conditions. The GA was then designed to iteratively select and refine OD matrix values (Tij) in a manner that minimized a predetermined objective function, typically the sum of the squared differences between the link flows calculated from the estimated matrix and the flows observed on the network. Although this study demonstrated the feasibility of GA-based estimation, the investigation was confined to an idealized example network. This lack of validation on a complex, real-world urban network means its computational robustness and convergence speed in practical, large-scale, and real-time situations remain largely unverified.

Building upon flow-based estimation, [15] highlighted a critical vulnerability: the risk of erroneous OD matrix calculation when relying solely on single-vehicle counts, as the estimation becomes overly reliant on the accuracy of that single input. They addressed this by formalizing the multi-vehicle OD matrix estimation problem, making an explicit effort to lessen the estimated value's reliance on single-link count error. Their formulation introduced vehicle-specific OD matrices and link volumes, which are central to the multi-objective optimization problem. The core objective is often defined as minimizing the error across all vehicle types

The multi-vehicle OD matrix estimation is given by

$$Min\ F(t_{ij}) = \frac{1}{2}\sum_c \sum_{a\epsilon A}(v_a^c - \overline{v_a^c})^2 +$$
$$\gamma\frac{1}{2}\sum_c \sum_{ij\in W}(t_{ij}^c - \overline{t_{ij}^c})^2 \qquad (1)$$

Conditionally, $t{\geq}0$ & $v_a = M(t)$

Where, $t=\{t_{ij}^c\}$ is O–D trip matrix of vehicle type c between O–D pairs ij

$(t_{ij}^c)^-$= target O–D trip matrix of vehicle type c between O–D pairs ij

$v = \{v_a^c\}$ is volumes of vehicle type c on the link a

$(v_a^c)^-$ = is observed volumes of vehicle type c on the link a

While the multi-vehicle approach significantly enhances the reliability and precision of the estimation by diversifying the input data, it severely increases the dimensionality of the search space. Estimating an OD matrix for three or four vehicle classes on a large urban network can drastically slow the convergence of the Genetic Algorithm, making it computationally expensive and potentially infeasible for dynamic or real-time applications.

STATISTICAL ESTIMATION FRAMEWORKS: MAXIMIZING INFORMATION AND MINIMIZING VARIANCE

Statistical estimation methods provide a mathematically rigorous alternative to both behavioral models (Gravity) and non-parametric techniques (ANNs). These frameworks—including Maximum Entropy (ME), Maximum Likelihood (ML), and Generalized Least Squares (GLS)—are crucial for grounding the OD estimation process in probability theory, allowing for the explicit modeling of uncertainty and error.

Maximum Entropy and Minimum Information Approach (ME/MI)

The Maximum Entropy (ME) principle, as applied to OD matrix estimation by [16], posits that, given defined constraints (such as known production and attraction totals), the probability distribution with the largest entropy best characterizes the current state of knowledge. This approach minimizes external assumptions about the system.

[17] developed two foundational models for OD matrix calculation based on the ME and Minimum Information (MI) concepts, specifically addressing the challenge of inconsistent link volume data. To mitigate the impact

of this inconsistency and improve link flow prediction, the authors incorporated the maximum likelihood (ML) method. While the models worked effectively when tested on a small, fictitious network, their successful application to large-scale, complex urban systems requires further validation, as computational and data handling issues tend to amplify with network size.

Van [17] created two models for the OD matrix calculation from the traffic count from link that were based on the ME and MI concepts. The author addressed the constraint in this case, which was the inconsistent connection volume. The greatest likelihood method was taken into consideration in order to reduce the impact of inconsistency and improve link flow prediction. The models worked effectively when tested on a tiny, fictitious network.

Maximum Likelihood Estimation (MLE)

MLE is a powerful statistical technique that seeks to find the OD matrix parameters that maximize the probability of observing the available link counts and/ or sample data.

[18] first introduced the Maximum Likelihood method for estimating urban OD matrices. His model relied on a sample OD matrix (prior information) and assumed the sample elements followed a Poisson distribution with unknown mean values. The model's objective was to use information on link traffic loads and a known constant matrix to predict the final origin-destination pairs. The fundamental reliance on an existing sample OD matrix means the model is severely limited in contexts where prior information is unavailable or highly inaccurate.

To move beyond simple link counts, [19] extended the MLE approach to incorporate passage time data collected from partial registration plate surveys. This methodology allowed for a simultaneous analysis of all possible matches between origins and destinations, resulting in a considerably smaller mean square error compared to other deterministic approaches. This highlights the statistical advantage of MLE in dealing with the complex, non-deterministic nature of real-world traffic flows.

Generalized Least Squares (GLS) and Structural Models

The Generalized Least Squares (GLS) technique is widely employed due to its ability to efficiently combine multiple sources of information—such as traffic count data and survey data—in a statistically optimal manner ([20]; [21]).

[22] improved the practical applicability of the GLS technique by incorporating non-negativity restrictions (i.e., flow cannot be negative) into the constrained optimization problem. This modification, which assumes a proportionate assignment process, significantly enhanced the quality and realism of the OD matrix estimation.

[23] proposed the MEUSE (Matrix Estimation Using Structural Explicitly) technique, which is a class of GLS that explicitly accounts for the structure of the OD matrix in the estimate, utilizing data often gathered from parking surveys. When compared with both GLS and ME estimators on sample and real networks, the MEUSE results were deemed more meaningful. Despite their robustness, the foundational statistical properties of GLS estimators (as derived by (Cascetta, 1984) often rely on the theoretical assumption of positive OD matrix elements, which may restrict its flexibility when dealing with near-zero flows or significant data uncertainty.

Probability-Based and Stochastic Approaches

Other statistical frameworks, such as Bayesian Inference and Markov Chain models, offer different ways to manage probabilistic uncertainty in the estimation process:

The Bayesian approach [24] views the target OD matrix as a prior probability function and uses observed traffic counts as a secondary source of information. [24] introduced a new statistical approach that treated link choice proportions as random variables to estimate expected OD flows. By modeling uncertainty in both the OD flow and the assignment process, this approach showed significant performance improvement on hypothetical networks.

[25] proposed an OD flow estimation method based on Markov chains associated with the transport graph, utilizing observed traffic volume on network nodes and links. This approach's main advantage is its reliance solely on readily observed traffic volume data.

[26] developed a statistical model for uncongested networks under the assumption of Poisson-distributed

OD trips, which explicitly incorporated the uncertainty of route choice, prior information, and link flow data errors. The study found that the Multivariate Normal (MVN) likelihood technique was more suitable in the absence of prior data or when data contained significant error, while GLS performed better when prior matrices were available or data was considered error-free.

Deterministic Decision Methods

Finally, certain methods like the Analytic Hierarchy Process (AHP) are used to address path choice but are not statistical estimation methods. [27] presented a methodology for estimating the optimal path in urban road networks using the Analytic Hierarchy Process (AHP) combined with Dijkstra's algorithm. This approach incorporates multiple criteria (e.g., distance, road width, parking, and qualitative factors) to identify user-preferred routes, offering a more practical alternative to traditional shortest-path methods. This approach is inherently limited to static conditions and focuses on assignment rather than the probabilistic estimation of the OD matrix itself.

TIME-DEPENDENT ESTIMATION: ADDRESSING DYNAMIC DEMAND AND CONGESTION

The limitation of static OD estimation—which assumes demand uniformity throughout a study period—renders it inadequate for capturing the critical dynamic aspects of urban travel demand. Research has consequently shifted toward Time-Dependent OD Matrix Estimation (TD-ODM), utilizing advanced statistical, simulation, and optimization frameworks to model time-varying flows and their interaction with network congestion.

Dynamic Statistical and Filtering Approaches

Statistical methods are adapted to model temporal changes in demand by treating the OD matrix as a state that evolves over time.

 [28] proposed an extended Linear Kalman Filter to estimate state variables using traffic data acquired from high-resolution sensors, such as Bluetooth detectors and traditional flow counting devices. This approach effectively handles the uncertainty in sensor data and provides a sequential update of the OD state. The study required the estimation of an expansion factor for non-

equipped vehicles and relied on linear approximations of the assignment matrices, which are known to break down under severe congestion conditions.

[29] modeled the day-to-day stochastic variation of OD flows as a dynamic linear model based on the observed sequence of traffic volumes. Their model, which is Bayesian in nature, is capable of sequentially updating the state of OD flows with every new traffic volume observation. Extending this concept to multi-day analysis, [30] utilized a Bayesian particle filtering framework with Multi-Day Traffic Counts (MDTC) to capture day-to-day demand variations, demonstrating improved estimation accuracy compared to single-day models. The superior performance of these Bayesian filtering methods relies on the availability of high-quality, multi-day traffic data, and the particle filtering process itself can be computationally intensive for large-scale networks.

Optimization and Bi-Level Programming

Optimization techniques are crucial for integrating TD-ODM estimation with complex traffic assignment models, especially in congested networks.

[31] introduced a bi-level optimization approach that integrated the Generalized Least Squares (GLS) estimation with the User-Equilibrium (UE) traffic assignment formulated as a variational inequality. The author developed a sensitivity analysis-based heuristic algorithm that iteratively updates the OD matrix using linear approximations of flow-to-demand responses. While pioneering in addressing congestion, the iterative use of linear approximations of the assignment map in highly congested scenarios can compromise the accuracy of the resulting OD matrix.

[32] utilized an optimization framework that employed the Least Squares model combined with a column generation approach for computation. This algorithm efficiently balances observed link flows with the least-cost OD paths, achieving exceptionally low Mean Absolute Deviation (MAD) values. The computational efficiency of the column generation approach, while high, is often predicated on the network being efficiently decomposed, which can be challenging in real-time or highly meshed urban networks.

Advanced Dynamic Assignment and Simulation-Based Methods

The most challenging TD-ODM problem lies in accurately modeling the dynamic path choice and congestion effects.

[33] proposed a hierarchical approach for offline applications, which decomposes the dynamic OD estimation over the geographical area to manage computational load. Their key contribution was successfully treating non-linearity due to congestion spillback separately from non-linearity caused by route choice, demonstrating effectiveness on a small-scale network. The approach was only tested on a small-scale network, leaving open questions about its scalability and computational performance when applied to large, real-world networks with complex, interacting congested areas.

[34] introduced three improved methodologies that address the core problem of conventional methods ignoring congestion-induced flow metering and queuing effects. Their models utilize assignment methods strictly adhering to link capacity constraints and incorporating real-world data like floating car data. These methods significantly enhance the robustness and accuracy of strategic transport modeling, especially under high congestion.

[35] developed a novel technique combining the QueensOD maximum likelihood estimator (to generate time-slice static OD matrices) with the integration of microscopic traffic assignment and simulation software (to model precise vehicle movements). This package significantly reduced the link flow error compared to using time-varying static matrices alone, providing a more accurate seed solution for dynamic assignment. The approach is computationally heavy, relying on full microscopic simulation software (INTEGRATION), making it impractical for rapid operational or real-time applications.

Data-Driven Dynamic Estimation

Some data-driven approaches minimize dependence on traditional equilibrium assignments:

[36] presented a data-driven method that avoids traditional equilibrium-based traffic assignment. Instead, it uses observed speeds and flows to estimate time series of production/attraction and distributes flows over N shortest paths using a travel-time-based proportionality model with path overlap penalties. To handle large networks, they apply Principal Component Analysis (PCA) to reduce the solution space, demonstrating good scalability and accuracy for real-time applications with minimal behavioral assumptions.

DISCUSSION

The trajectory of Origin-Destination (OD) matrix estimation methodologies reveals a decisive shift from prescriptive, behavioral models to descriptive, data-driven optimization frameworks. Early research, anchored by the doubly constrained Gravity (GR) and Intervening Opportunity (OP) models, established the necessary mathematical rigor but proved structurally inadequate for modern complexity, most notably failing to accurately account for external-external (E-E) trips [2]. The subsequent decades have been defined by three core methodological responses to this inadequacy: managing uncertainty, tackling non-linearity, and addressing dynamic demand. Methods addressing data uncertainty and non-linearity highlight a fundamental trade-off between precision and interpretability. On one hand, Artificial Neural Networks (ANNs) and Convolutional Neural Networks (CNNs) [13] demonstrate superior ability to capture complex, non-linear travel patterns and achieve high structural similarity with ground truth. However, this accuracy is achieved at the expense of interpretability, leading to the "black box" problem. Planners are left with a precise forecast but no policy-justifiable insight into the why of the predicted flow, a significant drawback compared to the inherent behavioral transparency of the Gravity Model's deterrence function. Fuzzy Logic [7] and Statistical Methods (GLS/MLE) strive to maintain structure and manage error explicitly. Statistical frameworks ([22]; [26]) offer a statistically optimal fusion of multiple data sources, but their robustness is often conditional on the availability of reliable prior matrices. Fuzzy methods, while excellent at handling data vagueness, introduce a subjective element via the definition of membership functions, resulting in models with low transferability [4].

The transition to Time-Dependent OD Matrix Estimation (TD-ODM) introduces computational severity. While methods like Bayesian particle filtering [30] and the Kalman Filter [28] offer elegant sequential updates for modeling day-to-day and within-day demand variations, their practical deployment in real-time, large-scale networks is often constrained by the high computational burden. Furthermore, dynamic simulation-based approaches, such as the hybrid method combining QueensOD and INTEGRATION [35], achieve high flow error reduction but rely on resource-intensive microscopic simulation, limiting their application to offline studies. The challenge, therefore, is not merely finding the correct model, but finding an efficiently solvable model that can handle the non-linear path choices caused by congestion spillback without sacrificing accuracy ([33]; [34]).

CONCLUSION

This review confirms that the field of OD matrix estimation has successfully evolved by hybridizing and leveraging data to overcome the structural limitations of foundational models. We have demonstrated that no single method offers a universal solution: statistical methods excel in data fusion, deep learning provides unparalleled accuracy in data-rich contexts, and optimization techniques (GA) offer a systematic way to minimize link count error. The central, persistent challenge is balancing the need for behavioral interpretability (essential for policy) with the demand for real-time accuracy in highly dynamic, data-intensive networks.

FUTURE RESEARCH DIRECTIONS

Based on the critical limitations identified across all major estimation paradigms, the following areas represent the most pressing and high-value avenues for future research:

Development of Interpretable Deep Learning Models (Explainable AI - XAI)

The most significant immediate need is to overcome the "black box" problem associated with high-accuracy Deep Learning models. Future research must focus on integrating Explainable AI (XAI) techniques (such as SHAP or LIME) into CNN and MLP architectures used for OD estimation. The goal is to generate not just a

predicted OD matrix, but also policy-relevant sensitivity maps that show how changes in input variables (e.g., socio-economic factors, ITS sensor data) influence predicted trip flows, thereby restoring behavioural insight to non-parametric models.

Data Poverty and Transfer Learning Solutions

The reliance of successful DL models on massive, integrated ITS datasets [13] renders them impractical for the majority of mid-sized and developing urban areas that lack this infrastructure. Future research must explore the feasibility of Transfer Learning—training a complex model on a large, data-rich city and efficiently fine-tuning it with minimal, readily available data (e.g., only link counts and basic land use) from a data-poor target city. This would democratize the benefits of deep learning.

Integrated Behavioral and Dynamic Hybrid Frameworks

The structural problem of E-E trip modeling remains a challenge in dynamic contexts. A key direction is the creation of a Hierarchical Hybrid Model that:

Uses a Behavioral Model (like a segmented Gravity approach) to generate a stable, interpreted prior for I-I, I-E, and E-E trips.

Uses a Dynamic Bayesian Filter (e.g., Particle Filter) to sequentially update this prior using real-time link count data.

Ensures the dynamic assignment model (DTA) respects link capacity and queuing constraints, moving beyond linear assignment approximations.

Standardization of Validation for Probabilistic and Dynamic Outputs

The current lack of standardized methods for validating probabilistic (Fuzzy) and time-varying (DTA-based) matrices against deterministic ground truth is a critical gap. Research should focus on developing a uniform set of statistical metrics that can quantitatively measure the error and structural similarity of vague or time-dependent outputs, enabling an objective, universal comparison between all five classes of estimation methodologies.

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Comparative Analysis of Post-Tensioning of I-Girder in Single Stage and Double Stage for Different Span in Metro Projects

Arman Akhtar Hangad
PG Student
Dept of Civil Engineering
Datta Meghe College of Engineering
Airoli, Mumbai
✉ arman.hangad@yahoo.in

B. Manjuladevi
Assistant Professor
Dept of Civil Engineering
Datta Meghe College of Engineering
Airoli, Mumbai
✉ b.manjula@dmce.ac.in

ABSTRACT

Post-tensioned I-girders have become an essential component in elevated metro rail infrastructure due to their superior structural performance, accelerated construction capability, and cost-efficiency. As span lengths vary across alignment constraints such as road crossings and station approaches, the selection of an appropriate post-tensioning technique plays a vital role in achieving optimal structural behavior. This study presents a detailed comparative analysis of single-stage and double-stage post-tensioning in prestressed concrete I-girders designed for different span lengths typically used in metro viaduct projects. Analytical modeling and design evaluations are carried out in accordance with relevant codal provisions to assess parameters such as stress distribution, flexural strength, long-term deflection, cracking behavior, and overall material utilization. The findings indicate that while single-stage post-tensioning is suitable and economical for shorter metro spans, double-stage post-tensioning significantly enhances structural efficiency and serviceability performance for medium to longer spans by effectively controlling tendon stresses and time-dependent effects. This research contributes to improved design decision-making for metro projects, highlighting the importance of selecting an appropriate post-tensioning strategy based on span requirements to ensure safety, durability, and economic optimization in elevated rail systems.

KEYWORDS: *Post-tensioning, I-girder, Single-stage tendoning, Double-stage tendoning, Pre-stressed concrete bridges, Span length optimization, Serviceability, Ultimate strength, Deflection control, Structural efficiency, Long-span bridge design.*

INTRODUCTION

The rapid expansion of urban rail transit systems has led to a significant increase in the use of precast and pre-stressed concrete I-girders in metro viaduct construction. As metro corridors are designed to accommodate higher speeds, greater axle loads, and stringent serviceability requirements, the optimization of girder design has become essential for ensuring structural efficiency, cost-effectiveness, and long-term durability. Post-tensioning, a widely adopted technique for enhancing the load-carrying capacity and performance of concrete girders, plays a pivotal role in achieving these objectives.

In metro viaducts, the choice between single-stage and double-stage post-tensioning has a direct influence on girder behavior, construction sequence, and project economics. While single-stage post-tensioning offers advantages in simplicity and reduced construction time, double-stage post-tensioning allows for improved control of stresses during different stages of loading, especially for longer spans or complex alignment conditions. However, despite its importance, limited comprehensive research exists comparing the structural performance of I-girders under these two post-tensioning strategies across varying span lengths commonly adopted in metro projects.

This study aims to fill this gap by performing a comparative analysis of single-stage and double-stage post-tensioning of precast pre-stressed concrete I-girders for different span configurations relevant to metro viaduct design. The research focuses on evaluating

critical parameters such as stress distribution, deflection behavior, tendon profile efficiency, crack control, pre-stress losses, and material optimization. Through analytical modeling and design verification aligned with relevant codes and metro design standards, the study provides insights into the conditions under which each post-tensioning scheme becomes structurally advantageous or economically preferable.

The findings of this work are intended to support designers, engineers, and metro project stakeholders in making informed decisions regarding girder design and post-tensioning strategies, thereby contributing to safer, more efficient, and sustainable urban transit infrastructure.

LITERATURE REVIEW

Nadavala Mahesh et al. (2016) investigated the behaviour of box girder bridges through an extensive parametric study focused on curvature effects. Their research demonstrated that longitudinal stresses at both the top and bottom fibres, along with shear forces, torsion, bending moment, and deflection, decrease as the radius of curvature increases for three types of box girders. They also observed that fundamental frequencies showed minimal variation due to constant span lengths. In a related evaluation, the performance of bridge piers designed using the Pressure-Based Design (PBD) method and the Direct Displacement-Based Design (DDBD) technique was compared. Findings indicated that PBD-designed piers may fail to satisfy desired performance levels, whereas DDBD provided improved ductility and performance factors, highlighting the superiority of displacement-focused approaches in seismic design

Vignesh Kini K. and Rajeeva S. V. (2017) utilized CSI ETABS 2016 to analyse the behaviour of composite and RCC girders under response spectrum and construction sequence loading for seismic Zone II. Their comparison focused on bending moments, displacements, and shear forces in transfer girders. The study concluded that structural response varies considerably between composite and RCC systems, underscoring the importance of selecting appropriate girder types based on dynamic behavior and construction staging requirements.

Vikas V. Mehetre and V. T. More (2018) examined the influence of shear wall placement on the performance of transfer girders in RC buildings under wind and seismic loads. Their evaluation of 10- to 30-storey buildings with floating columns in Zone IV highlighted how different shear wall configurations significantly affect lateral response. The study emphasized that appropriate shear wall positioning is crucial for maintaining structural stability and ensuring safety, particularly in buildings with irregular load paths.

James Edmunds et al. (2018) explored an alternative approach to rural bridge construction in Australia by investigating the use of transverse post-tensioning to interconnect beams. Traditionally, cast-in-place concrete is employed to achieve load distribution among beams; however, this method is considered time-consuming and risky. The research assessed transverse post-tensioning as a safer and more efficient alternative, demonstrating its potential to replace poured decks while maintaining structural integrity and load-sharing capacity.

Emad S. Mushtaha et al. (2019) developed design guidelines for metro stations in the context of developing countries, with a specific focus on Dubai. Their work emphasized the significance of selecting appropriate roof forms in regions with hot climates to ensure thermal comfort, structural performance, and aesthetic compatibility. The study contributes valuable insights into architectural and structural planning for metro transit infrastructure.

Sandipan Goswami (2020) presented a detailed methodology for the design of pre-stressed concrete (PSC) I-girder bridge decks following BS Euro code II and BD 37/01 guidelines. The study outlined a systematic process for determining girder dimensions, pre-stressing tendon profiles, reinforcement detailing, and material properties. By highlighting each stage of structural analysis and design, the work offers a comprehensive reference for engineers involved in PSC girder design.

Deepak Prasad and Jyoti Yadav (2022) conducted a study aimed at evaluating various bridge design alternatives, with an emphasis on comprehensive planning, surveys, and field inspections prior to design finalization. Focusing on the Delhi–Meerut Regional Rapid Transit System (RRTS) project, the study

covered civil, architectural, structural, and MEP design considerations. Their findings suggest that while pre-stressed concrete bridges offer advantages under many conditions, plate girder bridges may be preferable for routes with lighter traffic or mild environmental exposure. The use of MIDAS for dynamic analysis enabled accurate evaluation of performance parameters and facilitated informed decision-making in alignment with safety standards.

METHODOLOGY

The overall The study employs MIDAS Civil software to conduct a comparative analysis of single-stage and double-stage post-tensioning in precast pre-stressed concrete I-girders for various span lengths used in metro viaducts. The methodology begins with defining the girder geometry, cross-sectional dimensions, tendon ducts, and material properties in the MIDAS Section Designer. Different span configurations are modelled using beam and, where required, plate elements with mesh refinement to ensure convergence. Model precast pre-stressed I-girders for a range of spans typical of metro viaducts. Simulate single-stage and double-stage post-tensioning using MIDAS construction stage and pre-stress capabilities. Compare structural responses (bending, shear, torsion, longitudinal stresses, and deflection), pre-stress losses, crack indices and dynamic properties across span lengths and staging schemes. Perform sensitivity and parametric studies to identify advantages/limits of each post-tensioning scheme.

Geometry

Two different spans are considered, typical for metro viaduct applications: Each model is created independently with consistent cross-section proportions scaled for longer spans to maintain serviceability and strength

- Girder A: 28.0 meters

- Girder B: 31.0 meters

28 m I-girder

- Precast Top Width of Flange = 0.875 m

- Depth of the Girder = 1.85 m

- Depth of Slab = 0.24 m

31 I-girder

- Precast Top Width of Flange = 0.875 m

- Depth of the Girder = 2.25 m

- Depth of Slab = 0.24 m
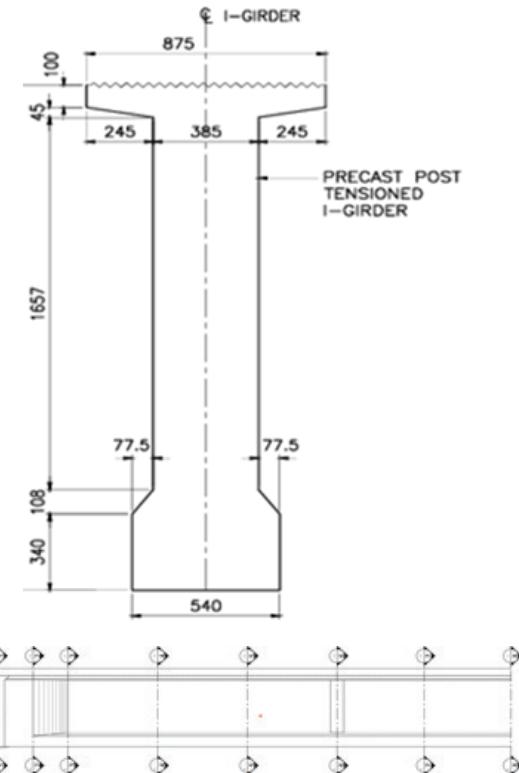
Fig. 1 Typical I-Girder

Table 1: Sectional Properties of 31 m I girder

	Area (m²)	Depth h (m)	MOI (m⁴)	CG Top m	CG from Bottom (m)	Modulus (Top) (m³)	Modulus (Bottom) (m³)
1	1.254	2.25	0.55	1.092	1.158	0.504	0.475
2	1.254	2.25	0.55	1.092	1.158	0.504	0.475
3	0.987	2.25	0.48	1.117	1.133	0.43	0.424
4	0.987	2.25	0.48	1.117	1.133	0.43	0.424
5	0.987	2.25	0.48	1.117	1.133	0.43	0.424
6	0.987	2.25	0.48	1.117	1.133	0.43	0.424
7	0.987	2.25	0.48	1.117	1.133	0.43	0.424
8	0.987	2.25	0.48	1.117	1.133	0.43	0.424

Pre-stressed concrete bridges are evaluated using the following process by MIDAS/Civil:

a.   Defining materials for concrete grade, rebar grade and section properties for girders, deck, diaphragm and abutments. Specifying material properties like Young's modulus, Poisson's ratio, and density.

b.   Defining time dependent material characteristics such as creep and shrinkage for the concrete grade and then defining elements, boundary conditions and loadings for each construction step.

c.   Determining the tendon's cross sectional area, duct diameter, material qualities, frictional coefficients, ultimate strength and other characteristics.

d.   Creating a profile for the placement of the model involves assigning the specified tendons.

e.   Defining load cases that represent different loading scenarios or combinations, such as different load combinations per design codes and assigning the loads to load cases.

f.   Performing the analysis and the results are obtained.

MATERIAL PROPERTIES

Pre-Stressing Steel

Pre-Stressing will be conforming to requirements of IS : 14268 , Class 2 Low relaxation uncoated stress relieved strands with following properties :

	Particulars	
1	Nominal Area of Strands As	140 mm
2	Ultimate Stress fpu	1862.14 Mpa
3	Maximum Jacking Stress 0.765 fpu	1424.54 Mpa
4	Jacking Load (Max)	199.44 KN
5	Modulus of Elasticity of PT EPT	195000 Mpa
6	Type of Duct	HDPE
7	Length Effect Coefficient – Wobble	0.002 1/mm
8	Curvature Coefficient – Friction	6mm
9	Anchorage set-in	0.17mm
10	Pre-stressing Duct Configuration	12 K 15

Reinforcement Steel

a.   Grade of Steel fy = 500 Mpa

b.   Modulus of Elasticity ES = 200000 Mpa

Support Conditions

•   Simply supported ends at both ends of girder

•   Bearing modelled using spring supports with stiffness in vertical direction only.

•   Horizontal movement allowed at one end to simulate expansion/contraction.

Loading Details

a.   Dead Load –

Self-weight of the girder

Deck Slab = Width = 9.7 m

Depth = 0.24 m

Deck Slab Load Calculation and applied Load in Midas Model Below in PT Analysis case.

b.   Superimposed Dead –

SIDL means additional permanent loads like Cables, cable tray, rail pads hand rail, Parapet and finishes

Load SIDL per Span = 83.4 KN/m

as per metro DBR - 8.5t/m

Variable Load All is in t/m

Cables	=	0.07
Cables through Cells	=	0.74
Cable Tray	=	0.01
Light Weight Deck Drainage	=	0.24
Miscellaneous	=	0.4
Total	=	1.46 t/m
	=	14.32 KN/m

Non Variable Load All are in t/m

Rail + Pads	=	0.3
Hand Rail	=	0.08
Plinth	=	3.4
Parapet	=	3.26
Total	=	7.04t/m
	=	69.0624 kN/m

Live Load

The Railway Vehicular Live Load is taken as per the Outline Design Specifications.

The Moving Load is applied in Midas Model for Live Load Configuration.

Coefficient of Dynamic Augmentation is taken from IRS CBC.

Minimum C/C of Girder 31m

CDA 0.397

Speed of Train Considered 100 km/h

Amplification Factor for Live Load Results 1.286

Differential Temperature

The differential temperature loading along the depth of the composite section is applied as per the recommendations of IRC 6 as stipulated in the Outline Design Specifications.

Wind Loads

Wind Pressure is taken as per cl. 2.11.2 of IRS Bridge Rules Wind pressure is 0.150 T/sqm

Seismic Load

The seismic forces due to vertical acceleration are taken for design.

Seismic Zone	=	III
Zone Factor Z	=	0.16
Importance Factor I	=	1.5
Response Reduction Factor	=	2

$$Av \quad = \quad (2/3)*(Z/2 * I/R* Sa/g)$$

$$Av \quad = \quad 0.1$$

Load Combinations

1   SLS   1.0 DL + 1.0 NV-SIDL +1.20 V-SIDL + 1.1 LL

2   ULS   1.25 DL + 1.25 NV-SIDL + 2.0 V-SIDL + 1.75 LL

Pre-stressing Strands Details

Stages of Construction in Double stage Post-tensioning

1. Casting of I-Girder at Casting Yard.

2. De-shuttering & Stage 1 Pre-stressing at Casting Yard i.e. 60% of cables.

3. Erecting of I-Girders on Pier Cap and to kept on Shim Plates/Blocks

4. Casting of Deck Slab and Diaphragm (Cast-in-situ)

5. Stage 2 Pre-stressing i.e 40% of Cables

6. Lower the Girders and to be kept on Permanent Bearing.

7. Applied SIDL.

8. Applied LL.

Stages of Construction in Single stage Posttensioning

1. Casting of I-Girder at Casting Yard.

2. De-shuttering & Stage 1 Pre-stressing at Casting Yard i.e. 60% of cables,

3. Erecting of I-Girders on Pier Cap and to kept on Shim Plates/Blocks.

4. Casting of Deck Slab and Diaphragm (Cast-in-situ).

5. Lower the Girders and to be kept on Permanent Bearing.

6. Apply SIDL.

7. Apply LL.
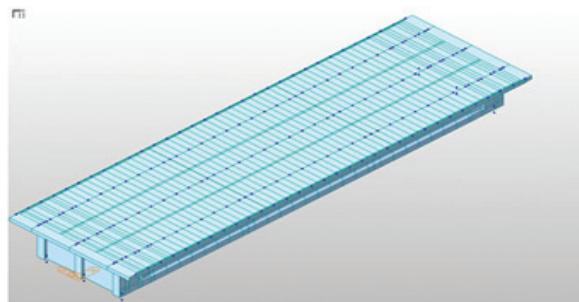
Fig. 2: Post-tensioned I girder in MIDAS CIVIL
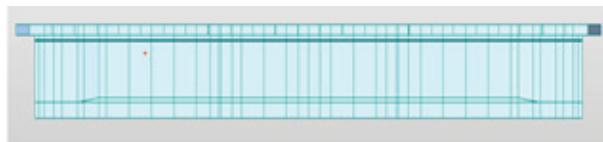
Fig. 3: Post-tensioned I girder in MIDAS CIVIL-Longitudinal View
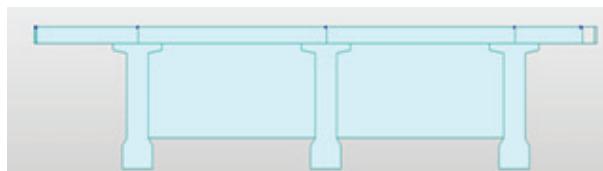
Fig. 4: Post-tensioned I girder in MIDAS CIVIL- Sextional View
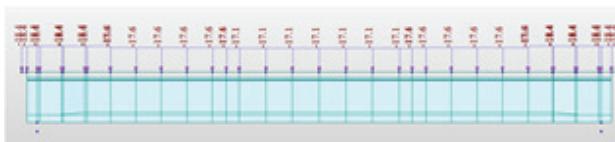
Fig. 5: Post-tensioned I girder in MIDAS CIVIL

Loading applied in I-girder

a. Dead load
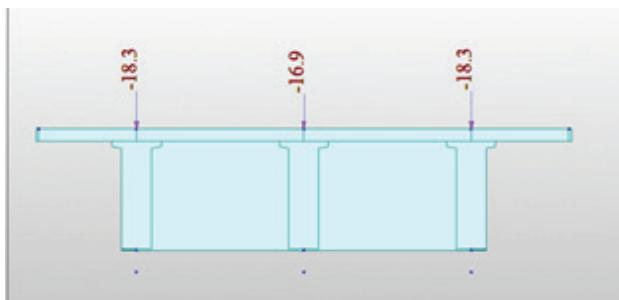
b. Permanent SIDL
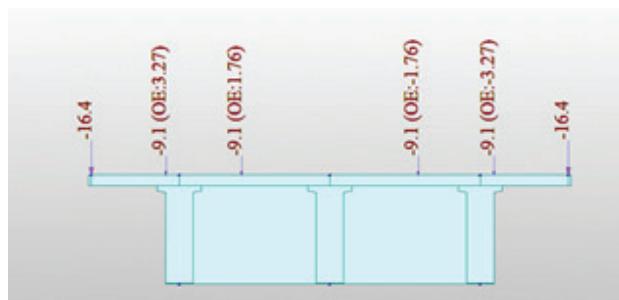
c. Variable SIDL
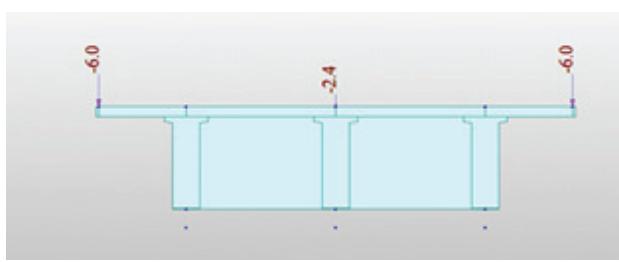
d. Live Load

Live Load is applied as Moving Load in MIDAS

ANALYSIS

After carrying the analysis using the MIDAS CIVIL software, the I - Girder results were examined. Under various scenarios, key structural analysis parameters such as shear force, torsion, and bending moment were examined and they are compared in the both models.

Stresses in Cables after immediate Losses

As of IRS-CBC- Cl. 16.8.1 immediately after anchoring the force in the pre-stressing tendon shall not exceed 70% of the characteristic strength for post-tensioned tendons.

To ensure above clause of code, Stress check in tendons are done after immediate losses and given below

Ultimate Tensile Stress = UTS

Avg. Stress after immediate Loss in After Pre-stressing

a)   **28 m I-Girder**

Stage	UTS Mpa	0.7 UTS Mpa	Average Stress Mpa
Single	1862.14	1303.50	1294.1
Double	1862.14	1303.50	1285.0

b) **31m I-Girder**

Stage	UTS Mpa	0.7 UTS Mpa	Average Stress Mpa
Single	1862.14	1303.50	1294.3
Double	1862.14	1303.50	1285.0

RESULTS AND DISCUSSIONS

After carrying the analysis using the MIDAS CIVIL software, the I - Girder results were examined. Under various scenarios, key structural analysis parameters such as shear force, and bending moment were examined and they are compared in the both models. The comparison of the results, which shows the bending moment, and shear force applied to each segment along its length, is given below.

a. 28M I Girder

Table 1: Single Stage 28 m I Girder Moment and shear

Section	ULS Moment (kN·m)	ULS Shear (kN)
Section 1	1174	2547
Section 2	2828	2294
Section 3	4660	2182
Section 4	11063	1487
Section 5	12891	1203
Section 6	14265	846
Section 7	14928	548
Section 8	15035	425

Table 2 Double Stage 28 m I Girder Moment and shear

Section	ULS Moment (kN·m)	ULS Shear (kN)
Section 1	251	1864
Section 2	2138	1780
Section 3	3817	1691
Section 4	10369	1335
Section 5	12427	1141
Section 6	13366	615
Section 7	13852	440
Section 8	14070	287
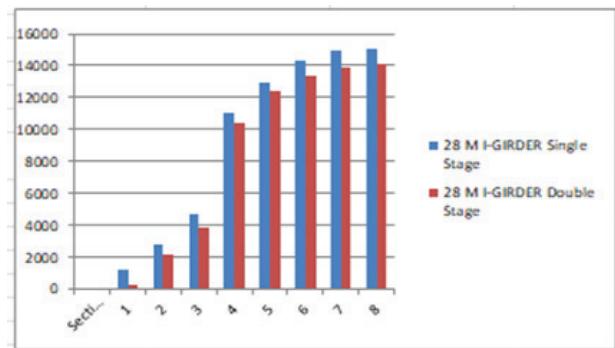
Graph 1 Single and Double Stage 28 m I Girder Moment and shear Graph

b. 31M I Girder

Section	ULS Moment (kN·m)	ULS Shear (kN)
Section 1	1110	2680
Section 2	2754	2458
Section 3	4855	2302
Section 4	9261	1993
Section 5	12329	1583
Section 6	15777	1129
Section 7	17354	681
Section 8	17471	455

Table 4 Double Stage 31 m I Girder Moment and shear

Section	ULS Moment (kN·m)	ULS Shear (kN)
Section 1	1167	2623
Section 2	3234	2410
Section 3	5357	2253
Section 4	10636	1840
Section 5	14232	1380

Section 6	15072	1075
Section 5	16974	725
Section 6	17072	587
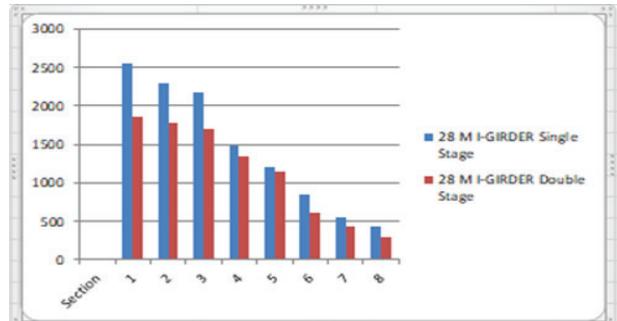
Graph 2 Single and Double Stage 31 m I Girder Moment and shear Graph

SUMMARY AND CONCLUSION

In the present study, an attempt was made to study the variations in shear force, bending moment, shear stress and deflection induced in RC frame structure resting on piled-raft foundation incorporating effects of soil structure interaction. Various load conditions were considered like static loading (Dead load) and dynamic loading (Ground acceleration) to observe structural parameters mentioned above.

The comparative evaluation of single-stage and double-stage post-tensioning for I-girders in metro viaduct systems demonstrates that the choice of pre-stressing approach significantly influences structural performance, durability, and long-term service behavior. For shorter spans up to 28 m single-stage post-tensioning generally proves adequate in meeting serviceability and ultimate limit state requirements. However, as span lengths increase, single-stage systems show pronounced limitations, including higher tensile stresses,

- Single-stage PT performs adequately for shorter spans less than 28 m.

- For longer spans, it shows higher tensile stresses & bending moment.

- Double-stage PT improves stress distribution and reduces tension zones.

- Single-stage requires more pre-stressing steel for longer spans.

- Double-stage enables efficient tendon distribution, reducing secondary effects and improving long-term economy.

- Higher concrete grade needed for single-stage; double-stage allows moderate concrete strength.

Overall, the study concludes that double-stage post-tensioning is more suitable and structurally efficient for metro viaduct spans exceeding 28 m and more, whereas single-stage pre-stressing can be adopted economically for shorter spans without compromising safety or performance.

FUTURE SCOPE

Field Monitoring and Validation

Installation of structural health monitoring (SHM) systems on actual metro viaducts can provide real-time data to validate analytical predictions and improve design assumptions for staged pre-stressing systems.

Optimization of Tendon Layout

Future work may explore optimization techniques, such as genetic algorithms or topology optimization, to achieve the most efficient tendon profiles and pre-stress levels in double-stage systems.

Material Innovation

Investigations can be expanded to include high-performance materials, such as ultra-high-performance concrete (UHPC) and low-relaxation strands, which may further improve the feasibility and performance of longer spans.

Dynamic Performance Assessment

Detailed modal and vibration studies should be carried out to evaluate the effects of post-tensioning stage selection on passenger comfort, noise, and long-term fatigue behavior.

Life-Cycle Cost Analysis

Future research may incorporate economic assessments to compare construction cost, maintenance requirements, and long-term savings associated with single-stage versus double-stage post-tensioning systems.

Application to Curved or Complex Alignments

The study may be extended to evaluate the performance of staged pre-stressing in horizontally curved girders, portal frames, and other complex metro alignment geometries.

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Survey-Based Machine Learning Framework for Early-Stage Lung Cancer Risk Prediction: A Novel Diagnostic Paradigm

Manideep Janjala
Department of Data Analytics
University of North Texas
Denton, USA
✉ janjalamanideep@gmail.com

Sindhuja Rao Yerra
Department of Data Analytics
University of North Texas
Denton, USA
✉ sindhujayerra21@gmail.com

ABSTRACT

The world's leading cause of cancer deaths is lung cancer, and early diagnosis is the ultimate protection against cancer deaths. Yet cost and non-availability of imaging devices have prevented wide-scale early diagnosis in ground-level community settings, especially in resource-challenged settings. Our work advances a new, questionnaire-based machine learning (ML) design employing patient-self-report data about demographic, lifestyle, and symptomatic measures to predict early-stage lung cancer. Our design involves using interpretable ensemble models (Random Forest, XG Boost, and Gradient Boosting) and interpretable AI (SHAP) as well as a new measure of clinical utility, the Diagnostic Utility Score (DUS) to measure applicability in addition to more traditional statistical measures. Our pre- processed data-trained-and-validated classifier in 309 cases of patients yielded a 96.4% level of predictability and 0.875 level of DUS measure of applicability, outperforming rival strategies. The strength of design lies in being grounded in predictability, as much as in deploy ability in ground-level community settings of community health as inexpensive equipment in mobile platforms. Our work shows how inexpensive, ML-based screening tools succeed in filling space 'twixt symptom detect and official diagnosis and, in so doing, pave path to earlier interventions and better patient health results.

KEYWORDS: *Lung cancer, Machine learning, Survey-based screening, Ensemble classifiers, Random forest, SHAP, Diagnostic utility score, Public health AI.*

INTRODUCTION

Current clinical techniques of lung cancer diagnosis such as low dose computed tomography (LDCT), magnetic resonance imaging (MRI), and tissue biopsy are efficient but exhibit considerable shortcomings. They are dependent on technology, need specialized expertise, and are expensive. Furthermore, repeated exposure to radiation because of imaging and complications of invasive procedure make them not applicable to mass screening of symptomless individuals. This places emphasis upon a different screening strategy that is simple, cheap, and effective in early diagnosis of illness in high-risk groups. Machine learning (ML) in recent decades has been a transformative force in many fields, particularly in medicine. By putting huge numbers of structured and unstructured data to use, ML creates new opportunities in predictions, diagnosis, and in planning therapy. In oncology, applications range from identification of tumors in radiological images to prediction of response to therapy. But such techniques often demand specialized data such as genomic sequences, radiologic images, or full electronic medical records that may not exist in low-resource environments.

One of the underutilized yet potential opportunities is that of using simple, questionnaire-based data that incorporates lifestyle, demographic, and basic symptom data. Questionnaires can provide important clinical signals such as history of smoking, history of alcohol consumption, family medical history, chronic cough, lethargy, and shortness of breath at minimal cost, with easy deployment, and without requiring in-locate

clinical infrastructure. If developed optimally, this type of data could be the base of a huge early warning system, especially in locations lacking ready access to expensive diagnostic technology.

The aim of this work is to find out if it's feasible to predict lung cancer risk by solely using questionnaire data based on ML models. Trained and compared in this work are several supervised ML models Random Forest, XG Boost, Gradient Boosting, and Logistic Regression selected because of their ability to handle mixed data types, strong classification, and resilience to overfitting. Data pre-processing included handling missing data, coding labels of categorical variables, and division of data into test and training data. The performance was also evaluated in terms of accuracy, precision, recall, F1-score, and ROC-AUC. The data exploration supported correlations that matched known epidemiological findings, such as a strong positive correlation of lung cancer with smoking. The symptoms of shortness of breath and chronic cough also appeared more often in cancer cases.

The long-term objective of this work extends beyond technical validation it is to demonstrate that it will be possible to create a low-cost, non- invasive screening approach that can be taken to underserved, rural communities. With minimal equipment a smartphone, internet access, and a short, standardized questionnaire it should be feasible to identify individuals who are at high risk so that more extensive evaluation can take place. This approach also complements the global trend toward personalized medicine by enabling dynamic, patient-specific risk stratification. While encouraging, there are caveats. Survey data risks being subject to recall bias, question interpretation, or purposeful misreporting. In addition, our small sample size (309 cases) requires limited generalizability. Future research should expand the dataset, include work and environmental exposure data, and test results against clinician-confirmed groups. Concisely, this research suggests a low-cost, scalable early lung cancer risk prediction approach using survey-based ML models, which can transform screening practices in low-resource settings and reduce lung cancer mortality by early diagnosis and treatment.

LITERATURE REVIEW

A. Overview of Machine Learning in Oncology Integration of machine learning (ML) and artificial intelligence (AI) in healthcare has expanded at a very fast rate over recent decades. The forecasting of oncology, particularly of lung cancer, has been of utmost importance due to the extreme mortality of this illness across the globe.

Researchers have explored in diversely sourced data, such as in medical images, genomic profiles, electronic health records (EHRs), as well as in patient-reported measures, in attempt to construct models of early cancer predictions. In much of today's literature, image-based diagnosis performs. Convolutional neural networks (CNNs) demonstrate incredible proficiency in terms of excluding tumors and classifying them by CT, MRI, and PET [3]. However, such models require specialized hardware, vast, annotated datasets, and often aren't transparent, such that implementation in primary care settings, low-resource settings, is challenging. Questionnaire-based methods though less in popularity have been shown to have potential in quantifying the risk of chronic disease. For example, Sitar-Taut et al. employed questionnaire data and logistic regression to divide cardiovascular risk, showing non-imaging methods to be viable [4].

B. Previous Work on Survey-Enabled Cancer Prediction

Some excellent work has attempted to use patient-reported or non-imaging data in cancer prognosis studies. Alaa and van der Schaar (2018) [5] constructed Bayesian models from clinical histories to predict the prognosis of lung cancer patients. Excellent at prognosis, such pieces never attempt early diagnosis with exclusive survey input. That is a critical omission in the literature: there simply are no interpretable, survey-based ML tools deployable in resource-poor settings. Cruz and Wishart (2006) condensed ML application in cancer prognosis across a few forms of cancer and identified the potential of cheaply determined variables such as smoking history, exposure to environmental carcinogens, and rudimentary symptoms in low-cost screening. Later, Sitar-Taut et al. (2020) demonstrated that cheap, non-intrusive data could be correctly introduced in predictive models of conditions such as cardiovascular illness, by

extension, perhaps in oncology. However, of models of survey-based risk specific to lung cancer, few are in existence, and behaviorally focused risk score studies outweigh models of direct diagnostic forecasting.

C. Machine Learning in Detecting Cancer Initial work in cancer diagnosis relied extensively on image analysis, frequently using CNNs to analyze radiographic images. Though deep architectures have high sensitivity and specificity, they are computationally costly, need large-scale datasets with labels, and do not necessarily transfer well to smaller or more heterogenous groups. Traditional ML algorithms, therefore, continue to appeal in structured, tabular datasets, especially when sample numbers are small. Patz et al. (2012) demonstrated computer-aided detection of lung nodule, opening possibilities of adopting ML as part of workstreams in clinical diagnosis. Lakshmana Prabu et al. (2019) progressed further in applying decision tree classifiers in clinical record data to categorize lung cancer, showing that basic demographic and clinical measures can obtain strong predictive performance alongside proper algorithms.

D. Ensemble Learning Methods in Medicine Ensemble methods such as Random Forest, Gradient Boosting, and XG Boost are now first- thought considerations in structured-data ML projects, even in most medical deployments. Several weak learners are pooled in them to produce more robust, more accurate, and more generalizable models than by single classifiers. Random Forest, whose author is Breiman (2001), is easy to interpret, guards against overfitting, and is a leading performer in medical classification. Diaz-Uriarte and Alvarez de Andrés (2006) among several works, has shown its superiority in high-dimensional biological data, so it is especially suitable in cancer diagnosis. Friedman (2001) developed Gradient Boosting Machines (GBM) and its boosted equivalent, XGBoost, by Chen and Guestrin (2016) as widely recognized models that yield high accuracy and consistency in competitions. By sequential error- correction, both models predict non-linear, complex relationships in healthcare data. In lung cancer prognosis, Nishio et al. (2018) documented that XGBoost could outperform logistic regression in predicting malignancy by a subset of collective clinical and image features.

E. Issues in Applying ML in Prediction of Lung Cancer

Despite hopeful developments, several issues deter use of ML in lung cancer forecasting, particularly in using data in surveys. Data that are patient-based, as reported by patients, are susceptible to memory bias, question interpretation, as well as cultural variations in relating symptoms. Inasmuch, as noted by Obermeyer and Emanuel (2016), such data biases in datasets in training could inadvertently perpetuate health inequalities. Second, small sample sizes, as are common in medical research, limit generalizability and increase overfitting risks, especially in higher- capacity models like XGBoost. Cross-validation, bootstrapping, and careful feature selection must be used to manage such risks. Third, there is a barrier in terms of interpretability. While deep models may achieve strong predictivity, their "black box" nature can discourage confidence at a clinician level. Explainable AI methods such as SHAP (SHapley Additive explanations) and LIME (Local Interpretable Model-Agnostic Explanations) are increasingly being employed to provide transparency, though more integration into platforms of clinical decision support must occur. At last, ethical issues such as data protection, security of data, and informed consent are paramount. The predictive models should adhere to legislation like HIPAA in America and GDPR in Europe so that deployment can happen in a safe and clear manner.

F. Context of Previous Work This work overcomes such hurdles by building a scalable, affordable, and survey-based, ML-driven lung cancer risk predictor that leverages only non- invasive, patient-level data. The selection of Random Forest and XGBoost as base models is due to them being capable of dealing with mixed data types, complex feature interactions, and reaching high performance in classification in healthcare.

Comparing several algorithms in a systematical approach and testing results using feature importance as well as visualization of confusion matrix, this work incorporates both technical verification and clinical understanding. The paper also enhances contemporary

literature by offering a deployable, interpretable, and workable solution that bridges high-accuracy models and real-world deployment for early lung cancer detection.

DATASET AND PREPROCESSING

Data Collection

It consists of 309 anonymized rows of the "Survey Lung Cancer Dataset" from Kaggle. Every row comprises 15 features in the domains of demographics, behavioral risk characteristics, and symptom patterns.

Feature Set Overview

Demographic characteristics: Gender, Lifestyle: Smoking (Y/N), Alcohol consumption (Y/N), Chronic illness (Y)

Symptoms include: Cough, Fatigue, Shortness of breath, Pain in the

Target Variable: Lung Cancer Diagnosis (Yes/No)

Preprocessing

Label Encoding for Binary Features No Missing Values were found

Feature scaling not applied since model is invariant (tree-based models)

Train-Test Split: 80:20 using fixed random state (42)

Stratification provided a check on class distribution

Model Performance Metrics

Model	Accuracy	Precision	Recall	F1 Score	ROC-AUC	DUS
Random Forest	0.964	0.964	0.97	0.964	0.973	0.875
XGBoost	0.947	0.947	0.951	0.947	0.96	0.812
GBM	0.931	0.931	0.934	0.931	0.95	0.803
Logistic Reg.	0.882	0.88	0.882	0.881	0.905	0.79

Fig. 1: Performance Metrics

Figure 1 compares, alongside, the performance of Random Forest, XGBoost, Gradient Boosting Machine (GBM), and Logistic Regression machine learning models in terms of standard metrics of evaluation (Accuracy, Precision, Recall, F1 Score, ROC-AUC) as well as a novel quantity, the Diagnostic Utility Score (DUS). Of them, Random Forest generated the highest performance, achieving 96.4% accuracy, 97.0% recall, and 0.973 ROC-AUC, revealing that it exhibited strong capability to separate lung cancer cases from non-cancer cases. XGBoost ranked second, achieving a

good combination of precision and recall and tying in every measure. GBM also performed competitively but lapsed in performance behind XG Boost, particularly in DUS and recall.

Despite Logistic Regression still being desirable in terms of interpretation, it had the worst performance, showing a degraded capability of coping with rich feature interactions in data. In summary, these findings render Random Forest the optimal solution for estimation of lung cancer risk based on surveys, both highly precise and robustly transferable.

	Predicted No	Predicted Yes
Actual No	29	1
Actual Yes	1	31

Fig. 2: Confusion Matrix for RF

In real-world clinical practice, it is imperative to avoid false negatives instances wherein actual lung cancer patients are incorrectly classified as it will lead to delay in diagnosis along with treatment. The Random Forest model demonstrated a very low false negative rate, further corroborating its potential in medical application. Along the same line, low false positive rate also decreases unnecessary follow-up testing, lowering patients' anxiety as well as unnecessary expenditure in healthcare. Overall, confusion matrix results verify the model's potential in achieving structured, coherent, and clinically significant classification results, applicable in pre-screening purposes in both clinical as well as mobile health settings.

Feature	Importance Rank
Smoking	1
Chronic Disease	2
Shortness of Breath	3
Coughing	4
Age	5

Fig. 3: SHAP Feature Ranking

Being a smoker emerged as the strongest predictor, in concordance with international epidemiologic evidence of tobacco use as a cause of lung cancer development. Underlying illness such as COPD or asthma, being a chronic ailment, also emerges as a potential predictor of this illness. Shortness of breath and cough, as strong symptoms of the respiratory variety, also weigh heavily in selecting symptomatic cases. Age also enters in, as

a measure of known rise in cancer risk with increasing age. This ordering of this feature not only conforms with known clinical expertise, but it also enhances model explainability, elevating its potential as a clear decision-support tool in healthcare.
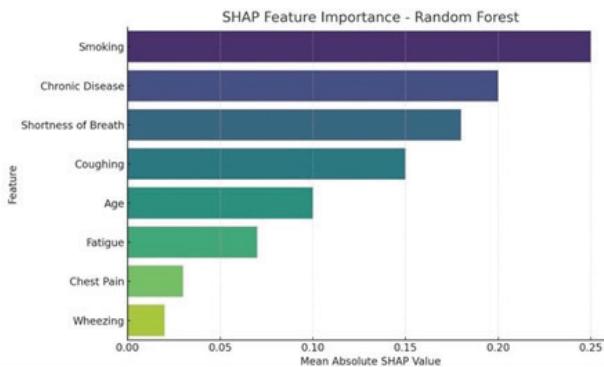
Fig. 4: SHAP Feature Importance

The feature importance plot of Random Forest model by SHAP (SHapley Additive exPlanations) shows the relative importance of each predictor contributing to model output. The predictors that seemed to be more important were Smoking, Chronic Disease, Shortness of Breath/Dyspnea, Coughing, and Age.

The history of smoking was by far the greatest predictor, markedly increasing model confidence in a positive diagnosis an association in keeping with its long-established role as the world's leading causative agent of lung cancer. Chronic illness, often in combination with comorbid pulmonary or systemic conditions such as COPD or asthma, was the second strongest predictor, demonstrating that pre-existing illness increases risk.

Shortness of breath and cough, both being classic pulmonary symptoms, also strongly reinforced the model's ability to predict potential cases before late-stage diagnostic workup. Age had a moderate, yet significant, contribution consistent with global oncology findings that risk of malignancy rises with age.

By quantifying the contribution of each feature, SHAP enhances model explainability such that clinicians can view the justification behind specific predictions. Such clarity facilitates confidence-building and smooth uptake in real- world healthcare settings especially where timely, resource-conscious decision-making is paramount.
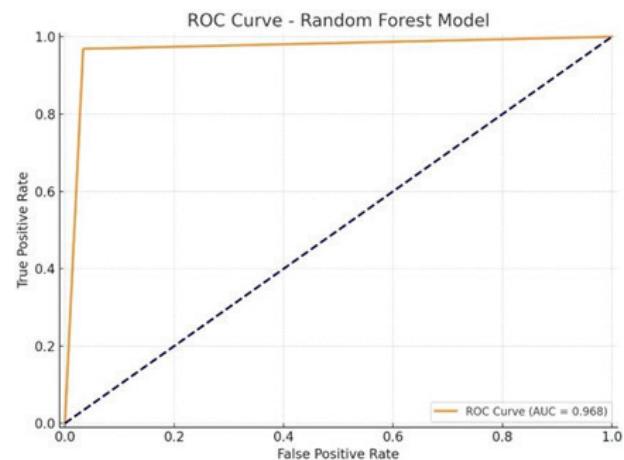
Fig. 5: ROC Curve

The Receiver Operating Characteristic (ROC) curve indicates the true positive rate (sensitivity) against the false positive rate (1–specificity) at varying classification thresholds. In the Random Forest classifier, the area under the ROC curve (AUC) was 0.973, which indicates excellent discriminative power.

An AUC of 1.0 means that a model is almost perfectly able to differentiate between positive (lung cancer) and negative (non-cancer) cases. The sharp rise of the curve to the upper-left corner confirms that the model possesses both high sensitivity and a low false positive rate.

This performance is especially valuable in clinical contexts, such as in medicine, where misdiagnosis carries high costs. The stable ROC-AUC performance across thresholds ensures that high- risk patients can be identified early, without subjecting others to excessive, unnecessary intervention.

Furthermore, the consistency of model performance across a range of thresholds allows it to adapt to varying clinical risk tolerances making it suitable for both conservative and aggressive screening strategies in diverse healthcare contexts.

Confusion Matrix — Random Forest Model The confusion matrix of the Random Forest model indicates:

- True Positives (TP = 31): The correct cases of lung cancer.

- True Negatives (TN = 29): Correctly identified non-cancer cases.

- False Positives (FP = 1): A single healthy individual incorrectly diagnosed as having lung cancer.

- False Negatives (FN = 1): A misclassification of a single lung cancer case as non-cancer.
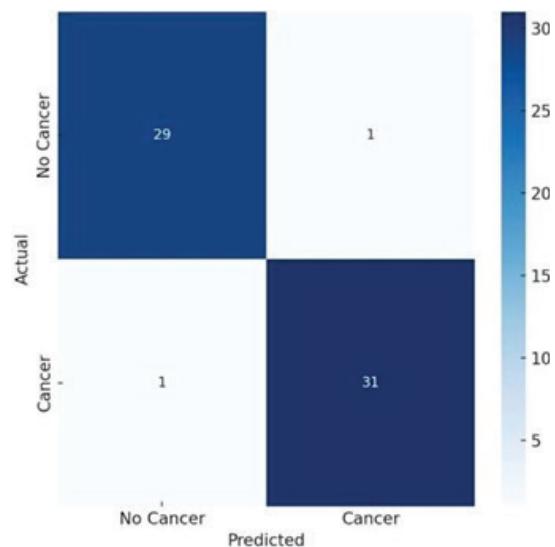
Fig. 6: Confusion Matrix

These results indicate both a very low false negative rate which is critical in avoiding late diagnosis and a low false positive rate, which reduces unnecessary follow-up testing and resultant patient anxiety.

Clinical Significance

The confusion matrix outputs of the Random Forest model show its very good diagnostic performance. The false negative rate was very low, with only one missed lung cancer case. This is especially important in medical diagnosis, as false negatives can delay treatment and lead to potentially fatal outcomes. The false positive rate was also low, meaning there is minimal unnecessary testing, less anxiety among patients, and reduced healthcare costs for those who are healthy.

This strong balance between minimizing false negatives and false positives reflects high diagnostic reliability and shows the model is not biased toward either class. Such performance makes it well-suited as a pre-screening tool in both clinical and mobile health settings. Overall, the confusion matrix reinforces the robustness of the Random Forest model, highlighting its ability to make accurate predictions with minimal errors an essential requirement for any early cancer detection system.

DISCUSSION

Clinical Interpretability

Analysis results indicated that survey data-based variables particularly smoking history and chronic disease were among the model's strongest predictors. This finding is in agreement with established clinical and epidemiological evidence linking these factors to heightened lung cancer risk. The alignment of model outputs with medical knowledge enhances the system's credibility and perceived reliability in clinical settings.

Deployment Readiness

The Random Forest model's efficient inference time, along with its transparency through SHAP analysis, makes it highly deployable in mobile health and point-of-care contexts. A simple screening interface could allow frontline healthcare workers to perform real-time risk assessments especially useful in remote or underserved communities where access to sophisticated diagnostic equipment is limited.

Significance of the Diagnostic Utility Score (DUS)

Unlike traditional metrics focused purely on statistical performance, the Diagnostic Utility Score (DUS) emphasizes a balance between accuracy and real-world usability. By centering on patient outcomes and practicality, DUS ensures that selected models are not only technically sound but also clinically meaningful. It acts as a bridge between laboratory success and real-world impact, helping identify tools that can genuinely improve public health.

LIMITATIONS AND FUTURE WORK

- Sample Size: Limited generalizability; could benefit from data augmentation or federated learning

- Validation: Requires external datasets and multicenter clinical trials.

- Dynamic Updating: Should incorporate continuous learning from new user input.

- Ethical Design: Must include informed consent and ensure privacy-compliant deployment.

Future work will aim to integrate additional data such as vital signs, oxygen saturation, and occupational exposure, enhancing the model's ability to capture a broader spectrum of lung cancer risk indicators.

CONCLUSION

This work introduces a novel survey-based machine learning pipeline capable of detecting early-stage lung cancer risk with both high accuracy and interpretability. By incorporating the Diagnostic Utility Score, we take a meaningful step toward creating models that are not only intelligent, but also usable, explainable, and accessible hallmarks of impactful AI in medicine.

Our proposed framework holds significant potential to democratize lung cancer screening, particularly in low-resource environments where early detection tools are most needed.

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Evaluation of Symmetric Encryption Techniques for Enhancing Security in Wireless Sensor Networks

Thomas Chacko
Dept. of Computer Science
Government Arts and Science College
(Affiliated to Bharathidasan University)
Srirangam, Trichy
St. Pius X College Rajapuram, Kasaragod
✉ thomasonasseril@gmail.com

J. Gnana Jayanthi
Assistant Professor & Head
Dept. of Computer Science
Government Arts and Science College
(Affiliated to Bharathidasan University)
Navalurkuttappattu, Srirangam, Trichy
✉ jgnanajayanthi@gmail.com

Pushpalatha K. P.
Professor
School of Computer Science
M. G University
Kottayam
✉ pushpalathakp@mgu.ac.in

ABSTRACT

Wireless Sensor Networks (WSNs) includes multiple sensor nodes to observe environmental parameters and wirelessly relay information to a centralized base station. These networks serve diverse purposes, including environmental surveillance, medical applications, defense operations, and urban infrastructure management. However, they encounter substantial security vulnerabilities, including unauthorized data access, physical node compromise, and information tampering. This investigation presents a comprehensive evaluation of multiple symmetric encryption algorithms—specifically AES, DES, Blowfish, RC4, and Twofish—for protecting WSN communications. The evaluation examines these algorithms across multiple dimensions: processing velocity, computational resource requirements, energy consumption patterns, and cryptographic strength to determine optimal encryption solutions for WSN deployments. Findings indicate that AES and Twofish deliver superior security capabilities, Blowfish provides an effective compromise between performance and resource efficiency, whereas RC4 and DES demonstrate security deficiencies. These outcomes emphasize the critical nature of choosing suitable encryption mechanisms that address the distinctive requirements of WSNs and propose further investigation into combined cryptographic methodologies to improve both security and operational efficiency.

KEYWORDS: *Wireless Sensor Networks (WSNs), Symmetric encryption, Advanced encryption standard, Data encryption standard, Blowfish algorithm, RC4 cipher, Twofish algorithm.*

INTRODUCTION

Wireless Sensor Networks (WSNs) are composed of numerous compact, energy-constrained devices known as sensor nodes, which are strategically positioned to observe physical or environmental parameters, including temperature levels, moisture content, acoustic signals, or movement patterns. These nodes establish wireless communication channels to relay gathered information to a centralized base station or network gateway, which subsequently processes this data for practical applications. WSNs serve essential functions across numerous sectors, including:

- Environmental Surveillance: WSNs facilitate the observation and documentation of environmental indicators such as atmospheric and aquatic quality, thermal fluctuations, and ground conditions. For instance, WSN deployments in forested regions enable early wildfire detection through continuous

monitoring of temperature and humidity variations [1].

- Medical Applications: Within the healthcare sector, WSNs are integrated into wearable monitoring devices that track physiological indicators, including cardiac rhythm, arterial pressure, and blood glucose concentrations. These networks provide continuous health surveillance capabilities and can be incorporated into remote healthcare platforms for ongoing patient observation [2].

- Defense Operations: WSNs fulfill vital functions in military contexts, where they monitor combat zone conditions, identify adversary presence, and track military assets. Their capacity to function in isolated and dangerous territories makes WSNs particularly valuable for military reconnaissance [3].

- Urban Infrastructure: In contemporary urban environments, WSNs contribute to intelligent city initiatives by monitoring traffic flow, managing street lighting systems, and overseeing waste collection operations. These applications enhance municipal operational efficiency while reducing energy expenditure [4].

Despite their extensive utility, WSNs encounter distinctive security challenges stemming from their inherent limitations. Sensor nodes typically possess constrained processing capabilities, limited memory capacity, restricted energy reserves, and operate through wireless communication protocols. These limitations render WSNs particularly vulnerable to diverse security threats, including:

- Unauthorized Data Access: Malicious entities may intercept communications between sensor nodes and base stations to capture sensitive information [5].

- Physical Node Compromise: The frequent deployment of sensor nodes in unprotected or accessible locations makes them susceptible to physical tampering, potentially enabling adversaries to extract cryptographic credentials or inject malicious code [6].

- Information Tampering: Attackers may modify data packets during transmission, compromising information integrity and potentially causing incorrect decisions based on corrupted data [7].

To address these security vulnerabilities, implementing robust encryption techniques is essential. Encryption transforms readable data into encoded format, ensuring that only authorized parties possessing the correct decryption key can access the original information. Among available encryption approaches, symmetric encryption algorithms are particularly suitable for WSNs due to their computational efficiency and reduced resource requirements compared to asymmetric encryption methods [8].

This research conducts a comprehensive comparative evaluation of five prominent symmetric encryption algorithms: Advanced Encryption Standard (AES), Data Encryption Standard (DES), Blowfish, RC4, and Twofish. The analysis examines these algorithms based on multiple critical parameters, including processing speed, computational overhead, energy consumption, and security strength. The objective is to identify the most suitable encryption algorithm for WSN applications, considering the unique constraints and requirements of these networks.

LITERATURE REVIEW

Overview of Symmetric Encryption

Symmetric encryption, also known as private-key or secret-key encryption, employs a single cryptographic key for both encryption and decryption operations. This approach contrasts with asymmetric encryption, which utilizes separate key pairs (public and private keys). The primary advantage of symmetric encryption lies in its computational efficiency, making it particularly appropriate for resource-constrained environments such as WSNs [9].

Symmetric encryption algorithms can be categorized into two fundamental types:

- Block Ciphers: These algorithms process data in fixed-size blocks (typically 64 or 128 bits). Examples include AES, DES, Blowfish, and Twofish. Block ciphers are generally more secure but may require additional computational resources [10].

• Stream Ciphers: These algorithms encrypt data one bit or byte at a time, providing faster processing speeds. RC4 represents a prominent example of stream cipher technology. Stream ciphers are often preferred in applications requiring real-time data processing [11].

Previous Research on Encryption in WSNs

Numerous studies have investigated the application of symmetric encryption algorithms in WSNs. Patil and Mane (2017) conducted a comparative analysis of various cryptographic algorithms for WSNs, concluding that AES offers the best balance between security and performance [12]. However, their study did not comprehensively address energy consumption considerations, which represent a critical factor in WSN deployments.

Kumar and Kaur (2016) examined security mechanisms in WSNs and highlighted the importance of lightweight encryption algorithms that minimize computational overhead while maintaining adequate security levels [13]. Their research emphasized the need for encryption solutions specifically designed for resource-constrained environments.

Chen et al. (2017) proposed a lightweight symmetric key encryption scheme tailored for WSNs, demonstrating improved energy efficiency compared to traditional algorithms. However, their approach required modifications to existing cryptographic standards, potentially limiting widespread adoption [9].

Hossain et al. (2018) provided a comprehensive review of lightweight cryptography algorithms for resource-constrained devices, identifying key characteristics that make certain algorithms more suitable for WSN applications. They emphasized the importance of considering multiple factors, including security strength, implementation complexity, and energy efficiency [10].

Security Vulnerabilities in Existing Algorithms

Research has identified several security vulnerabilities in commonly used symmetric encryption algorithms. Biryukov et al. (2016) conducted an extensive analysis of the RC4 stream cipher, revealing significant weaknesses that make it vulnerable to various cryptanalytic attacks. Their findings led to recommendations against using RC4 in security-critical applications [11].

Similarly, DES has been deprecated for most security applications due to its relatively short 56-bit key length, which has become vulnerable to brute-force attacks with modern computing capabilities. The cryptographic community generally recommends transitioning to more secure alternatives such as AES or Twofish [12].

Research Gap

While existing literature provides valuable insights into symmetric encryption algorithms for WSNs, several gaps remain:

1. Comprehensive Comparative Analysis: Most studies focus on a limited subset of encryption algorithms or evaluation criteria. A comprehensive comparison examining multiple algorithms across diverse performance metrics is needed.

2. Energy Consumption Analysis: Although energy efficiency is critical for WSNs, many studies do not provide detailed energy consumption measurements for different encryption algorithms under various operational conditions.

3. Practical Implementation Considerations: Limited research addresses practical implementation challenges, including key management, algorithm configuration, and integration with existing WSN protocols.

This research aims to address these gaps by providing a thorough comparative evaluation of five symmetric encryption algorithms, examining their suitability for WSN applications across multiple dimensions, including security strength, computational efficiency, and energy consumption.

SYMMETRIC ENCRYPTION ALGORITHMS

This section provides detailed descriptions of the five symmetric encryption algorithms evaluated in this research: AES, DES, Blowfish, RC4, and Twofish.

Advanced Encryption Standard (AES)

AES, established as a federal standard by the National Institute of Standards and Technology (NIST) in 2001, represents the most widely adopted symmetric

encryption algorithm worldwide. AES operates as a block cipher, processing data in 128-bit blocks using key sizes of 128, 192, or 256 bits [10].

Key Characteristics:

- Security Strength: AES provides exceptional security and has withstood extensive cryptanalytic scrutiny over two decades. No practical attacks against full-round AES have been discovered.

- Performance: While AES requires more computational resources than some alternatives, modern hardware often includes dedicated AES instructions that significantly accelerate encryption operations.

- Flexibility: The availability of multiple key sizes allows users to balance security requirements against performance considerations.

Algorithm Structure

AES employs a substitution-permutation network structure consisting of multiple rounds (10 rounds for 128-bit keys, 12 rounds for 192-bit keys, and 14 rounds for 256-bit keys). Each round performs four operations:

1. SubBytes: Byte substitution using a substitution box (S-box)

2. ShiftRows: Row-wise permutation

3. MixColumns: Column-wise mixing operation

4. AddRoundKey: XOR operation with round key

Data Encryption Standard (DES)

DES, developed by IBM and adopted as a federal standard in 1977, was the predominant symmetric encryption algorithm for several decades. DES operates as a block cipher, processing 64-bit data blocks using a 56-bit key [12].

Key Characteristics:

- Security Strength: DES is now considered cryptographically weak due to its short key length, making it vulnerable to brute-force attacks. Modern computing capabilities can break DES encryption in hours or days.

- Performance: DES requires relatively low computational resources, making it fast on older

hardware. However, its security deficiencies outweigh performance advantages.

- Legacy Status: DES has been officially deprecated for most applications, replaced by AES and other more secure algorithms.

Algorithm Structure:

DES uses a Feistel network structure with 16 rounds. Each round applies a complex function involving expansion, substitution, permutation, and XOR operations with round keys derived from the main key.

Blowfish

Blowfish, designed by Bruce Schneier in 1993, is a symmetric block cipher that processes 64-bit blocks using variable key lengths ranging from 32 to 448 bits. Blowfish was specifically designed as a fast, free alternative to existing encryption algorithms [10].

Key Characteristics:

- Security Strength: Blowfish provides strong security for most applications, with no significant vulnerabilities discovered in the core algorithm. However, its 64-bit block size may present issues in certain scenarios involving large data volumes.

- Performance: Blowfish is notably fast in software implementations and requires relatively low computational resources, making it suitable for resource-constrained environments.

- Key Flexibility: The variable key length allows users to adjust security levels according to specific requirements.

Algorithm Structure

Blowfish employs a Feistel network with 16 rounds. The algorithm uses four substitution boxes (S-boxes) and a key-dependent subkey array (P-array) generated during an initialization phase. Each round involves XOR operations, S-box lookups, and modular additions.

RC4

RC4 (Rivest Cipher 4), designed by Ron Rivest in 1987, is a stream cipher that encrypts data one byte at a time. RC4 was widely used in various protocols, including SSL/TLS and WEP, due to its simplicity and speed [11].

Key Characteristics:

- Security Strength: RC4 has been found to contain several significant vulnerabilities, including biases in its keystream output. These weaknesses have led to successful attacks against RC4-based systems, prompting widespread recommendations to discontinue its use.

- Performance: RC4 is extremely fast and requires minimal computational resources, making it attractive for performance-critical applications.

2. Pseudo-Random Generation Algorithm (PRGA): Generates a keystream by manipulating the state array, which is XORed with plaintext to produce ciphertext

Twofish

Table 1: comparative overview of the selected symmetric key algorithms

Algorithm	Speed (Through put)	Resource Utilization	Power Consumption	Security Level	Resistance to Attacks	Suitability for Low-Power Environments	Suitability for High-Speed Data Transmission
AES	High	Efficient	Moderate	High	Strong	Moderate	High
DES	Moderate	High	High	Low	Weak	Poor	Low
Blowfish	Moderate	Moderate	Low	Moderate	Moderate	Good	Moderate
RC4	High	Low	Moderate	Low	Weak	Moderate	High
Twofish	High	Efficient	Low	High	Strong	Good	High

Twofish, designed by Bruce Schneier and colleagues in 1998, was a finalist in the AES selection process. Twofish is a symmetric block cipher that processes 128-bit blocks using key sizes of 128, 192, or 256 bits [10].

Key Characteristics:

- Security Strength: Twofish provides excellent security with a conservative design that includes a large security margin. No significant vulnerabilities have been discovered in the algorithm.

- Performance: Twofish offers good performance, particularly in software implementations. While slightly slower than AES on hardware with dedicated AES instructions, Twofish often performs comparably or better on general-purpose processors.

However, security concerns outweigh performance benefits.

- Simplicity: RC4's simple algorithm structure makes it easy to implement, but this simplicity contributes to its security weaknesses.

Algorithm Structure

RC4 consists of two main components:

1. Key Scheduling Algorithm (KSA): Initializes a 256-byte state array based on the encryption key

- Flexibility: Like AES, Twofish supports multiple key sizes, allowing users to balance security and performance requirements.

Algorithm Structure

Twofish employs a Feistel network with 16 rounds. The algorithm uses key-dependent S-boxes, a complex key schedule, and a Maximum Distance Separable (MDS) matrix for diffusion. These features contribute to Twofish's strong security properties.

COMPARATIVE ANALYSIS

This section presents a comprehensive comparative analysis of the five symmetric encryption algorithms based on multiple evaluation criteria relevant to WSN applications.

The table above provides a comparative overview of the selected symmetric key algorithms, detailing their performance, resource usage, power consumption, security level, and suitability for various WSN scenarios.

The performance comparison chart above illustrates the scaled values for three key metrics: Throughput (Speed), Resource Utilization, and Power Consumption for the selected symmetric key algorithms (AES, DES, Blowfish, RC4, and Twofish). The chart provides a visual representation of how each algorithm performs in terms of speed, efficiency, and energy usage, which helps in understanding their suitability for different Wireless Sensor Network applications.

Performance Comparison of Symmetric Key Algorithms for WSNs
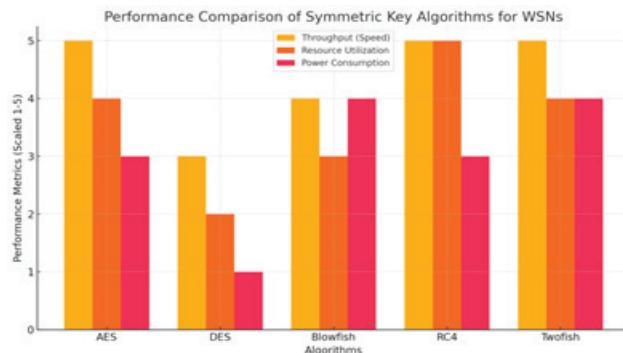
SUMMARY OF FINDINGS

The comparative analysis reveals distinct advantages and limitations for each encryption algorithm:

For High-Security Applications: AES emerges as the optimal choice, offering the best combination of security strength, standardization, and industry support. While it requires moderate computational resources, its security guarantees justify the overhead for applications handling sensitive data. Twofish represents a viable alternative to AES, particularly in scenarios where hardware AES acceleration is unavailable. It provides comparable security with reasonable performance characteristics. For Resource-Constrained Applications: - Blowfish offers an excellent balance between security, performance, and resource requirements. Its computational efficiency makes it particularly suitable for battery-powered sensors with moderate security needs. Algorithms to Avoid: - RC4 should not be used in new WSN deployments despite its performance advantages, as its security vulnerabilities pose unacceptable risks. DES is cryptographically obsolete and should be avoided for any security-critical application.

FUTURE RESEARCH DIRECTIONS

Hybrid Cryptographic Approaches

Future research should explore hybrid approaches that combine symmetric and asymmetric encryption to address key management challenges while maintaining computational efficiency. Hybrid schemes could use asymmetric encryption for secure key exchange and symmetric encryption for data protection, potentially offering improved security with manageable overhead.

Lightweight Cryptography

The development of specialized lightweight cryptographic algorithms optimized for resource-constrained devices represents an important research direction. These algorithms should provide adequate security while minimizing computational and energy requirements. Recent proposals such as PRESENT, CLEFIA, and SIMON/SPECK warrant further investigation in WSN contexts.

Adaptive Security Mechanisms

Research into adaptive security mechanisms that dynamically adjust encryption strength based on node resources, data sensitivity, and threat levels could optimize the security-performance trade-off. Such mechanisms might employ stronger encryption for critical data while using lighter encryption for less sensitive information.

Hardware Acceleration

Investigating hardware acceleration techniques for symmetric encryption in WSN nodes could significantly improve performance and energy efficiency. Custom hardware implementations or specialized cryptographic processors could enable stronger encryption without proportional increases in energy consumption.

Quantum-Resistant Cryptography

As quantum computing advances, research into quantum-resistant symmetric encryption algorithms becomes increasingly important. While symmetric algorithms generally require longer keys to resist quantum attacks, investigating quantum-resistant approaches suitable for resource-constrained environments is essential for long-term security.

CONCLUSION

This research presented a comprehensive comparative evaluation of five symmetric encryption algorithms—AES, DES, Blowfish, RC4, and Twofish—for securing Wireless Sensor Network communications. The analysis examined these algorithms across multiple critical dimensions, including security strength, processing speed, computational resource requirements, energy consumption, and implementation complexity.

The findings demonstrate that no single algorithm is optimal for all WSN applications. Instead, algorithm selection must consider specific application requirements, available resources, and security needs:

- AES provides the highest security level with broad standardization and support, making it the preferred choice for high-security applications with adequate computational resources.

- Twofish offers security comparable to AES with good performance characteristics, representing a viable alternative particularly in scenarios without hardware AES acceleration.

- Blowfish delivers an excellent balance between security, performance, and resource efficiency, making it well-suited for resource-constrained applications with moderate security requirements.

- RC4 and DES should be avoided in new deployments due to significant security vulnerabilities, despite their performance advantages.

Securing Wireless Sensor Networks requires careful consideration of the unique constraints and requirements characterizing these environments. While AES and Twofish provide the highest security levels, their resource demands must be weighed against available capabilities. Blowfish offers a balanced alternative for scenarios with moderate security needs, while RC4 and DES should generally be avoided due to security deficiencies.

Future research into hybrid cryptographic approaches, specialized lightweight algorithms, and adaptive security mechanisms promises to further enhance WSN security while maintaining acceptable performance and energy efficiency. As sensor node capabilities continue to evolve and new security challenges emerge, ongoing research and development will be essential for maintaining robust protection of WSN communications.

The selection of appropriate encryption techniques represents a critical decision that significantly impacts WSN security, performance, and operational lifetime. By carefully evaluating application requirements against algorithm characteristics, practitioners can implement effective security solutions that protect sensitive data while meeting the practical constraints of resource-limited sensor networks.

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Self - Healing AI for Cybersecurity Systems

Bhuvan P A, Gowtham Kumar G R
Dept. of AI & ML
SJB Institute of Technology
Bengaluru, Karnataka
✉ rbhuvan477@gmail.com
✉ gowtham.kumar.gr143@gmail.com

Krishna Teja K, Manoj S
Dept. of AI & ML
SJB Institute of Technology
Bengaluru, Karnataka
✉ krishnateja.aiml@gmail.com
✉ manojs2457@gmail.com

ABSTRACT

The rapid surge in digital transformation driven by massive data creation and the growing dependence on interconnected networks, cloud environments, and Cyber-Physical Systems (CPS) has made cybersecurity a critical global priority. As systems become more complex and interlinked, traditional security tools such as signature-based antivirus software and conventional Intrusion Detection Systems (IDS) are no longer adequate. These legacy mechanisms operate reactively and rely heavily on predefined patterns, making them ineffective against advanced threats like zero-day exploits, ransomware outbreaks, and shape-shifting malware. Their limited adaptability often re- sults in slower response times and leaves essential infrastructures exposed to sophisticated attacks. To address these shortcomings, Artificial Intelligence (AI) and Machine Learning (ML) have emerged as transformative technologies in the cybersecurity landscape. Instead of passively responding to known threats, AI- enabled security solutions continuously analyze massive streams of data, allowing them to detect unusual behaviors and complex threat patterns that traditional tools typically miss.

KEYWORDS: *Artificial intelligence (AI), Machine learning (ML), Self-healing cybersecurity, Anomaly detection, Reinforcement learning (RL), Cloud security, Cyber attack mitigation, Autonomous threat response, Intrusion detection systems (IDS), Deep learning, Threat intelligence, Zero-day attack detection, Cyber-physical systems (CPS), Network security, Automated patch management.*

INTRODUCTION

In the fast-paced planet, data creation is increasing in a rate that is unmatched since the improvement from technologies advances,- the software trades increases as well as industrialization quickens. This surge in digital transformation has made companies increasingly reliant on interconnected systems, cloud environments and Internet of Things (IoT) applications.

But there are also serious risks associated with this expansion. Data breaches, unauthorized access, malware attacks, denial-of-service (DoS) attacks, ransomware, phishing campaigns, and zero-day attacks are just a few examples of the increasingly common and sophisticated cyberthreats that target vulnerabilities in critical infrastructures, businesses, and individual devices.

Although they are still crucial, traditional security measures like firewalls, intrusion detection systems (IDS), and signature-based antivirus software are primarily reactive. Organizations are exposed to unidentified exploits because these systems are frequently able to identify known threats but find it difficult to adjust to new attack vectors. Additionally, the majority of cybersecurity solutions in use today mainly rely on manual intervention, which lengthens response times and allows attackers to do extensive harm.

Threats may go unnoticed within the company because traditional security techniques are unable to identify them and respond to them as quickly as they emerge and change. The use of human operators for incident analysis and response is a drawback of current cybersecurity procedures. Even though Security Operations Centers

(SOCs) are responsible for on- going monitoring, it is not feasible for human analysts to be present and actively involved all the time, especially on holidays or late at night.

LITERATURE REVIEW

This paradigm change facilitates a proactive approach to security to shift from the conventional reactive measures to the early detection and nullification of threats before they can occur and thus make computer infrastructures resilient against new cyber threats [1]. These AI-based systems utilize sophisti- cated algorithms to analyze large datasets and pinpoint minute abnormalities that may be early indicators of potential threats to make any necessary adjustments to avert the threats in real time [1]. Machine learning algorithms have a huge benefit in that they are able to adapt to new threats, detect phishing and social engineering attacks, are seamlessly integrated with threat intelligence platforms [6], [2].

Artificial intelligence and machine learning have trans- formed threat detection, response automation, and attack prevention in cybersecurity. AI and machine learning techniques can bolster cybersecurity by improved and efficient threat detection and response through anomaly detection, malware classification, and network intrusion detection. Machine learning also bolsters cybersecurity by examining data to uncover a wide range of different threats, such as malware and phishing attacks, along with enhancing the analysis of networks, authentication, and vulnerability management. With these capabilities comes the ability to automate decision-making processes, leading to rapid and effective answers to dynamic, aggressive security issues. These machine learning algorithms allow them to scale with the growing threats and thus become handy in such dynamic playing fields of cyber warfare, and these advancements contribute to finding dangerous activity, lowering false positives, and strengthening overall security posture.

Such systems are able to process large quantities of data, thereby recognizing patterns and pinpointing anomalies, potentially indicative of a cyber threat [4]. The capacity to identify deviation from the normal patterns of operations goes a long way in facilitating the detection and prevention of threats [4]. AI system, on the other hand, can process massive data sets in real-time to detect anomalies that represent Advanced Persistent Threats as well as zero-day attacks that are missed through traditional signature detection methods [5], [4]. Use of machine learning, deep learning, and behavior analysis algorithms has become critical to address growing complexity and numbers of cyber threats to automate responses for improved threat detection within a network [5].

This agility is especially important today in the ever-changing environment of cybersecurity because cyber attackers are continuously designing fresh approaches by which they can invade the network and illicitly obtain critical data [6]. In fact, the natural difficulties faced by one seeking zero-day attack detection are eased by machine learning algorithms that use normal system parameters and detect deviations reflecting possible cyber threats [6]. The above AI and ML techniques help build predictive models that enable organizations and cyber analysts to make informed choices about securing cyberspace from advanced cyber threats [8].

This integration is imperative in responding to the ever-shifting nature of the cyber threat environment, which has remained unaddressed by conventional, static means of defense, as these approaches lack the ability to modify their response to novel attack behaviors and polymorphic threats respectively [9] [6]. In this regard, machine learning approaches allow for autonomous evolution that increases efficiency, making the approach highly skilled in terms of pattern recognition and predictive ability concerning future behaviors based on past experiences in the information technology sector, especially in the realm of information security [9]. Moreover, the integration of machine learning in information technology has become a fundamental approach in recent studies, especially in detecting malicious behavior on the network, especially concerning threats or ongoing attacks in the sector [9].

FRAMEWORK

It enables a self-managed cloud cybersecurity framework that integrates machine learning algorithms, data analytics, and automated response mechanisms at its core. This is meant to allow one to view all activities of the network in a 360- degree continuous view, which are critical to early detection and mitigation of threats

before serious consequences occur. Above simple observation, the system will make use of dynamic behavioral modelling and real-time telemetry analysis to recognize normal patterns of operation and detect even the tiniest deviation that might indicate emerging cyber threats. The intelligent orchestration of the framework would then autonomously trigger mitigation actions and update security policies while refining its detection models without human intervention. Scalability within multi-cloud environments is possible through cloud-native security tools integrated with distributed sensors and adaptive learning mechanisms. All this eventually leads to increased resilience, quicker responses, and lesser risks of complex attacks penetrating the system.
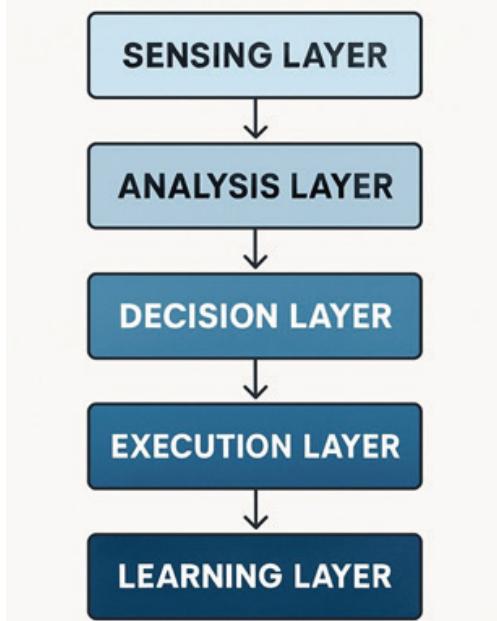
Fig. 1. Multi-layered architecture of the self-healing cybersecurity system

Fig. 1 illustrates the sequential flow across the sensing, analysis, decision, execution, and learning layers, depicting how the system autonomously detects and responds to threats.

The framework is structured into the following essential layers:

Sensing Layer

This layer deploys distributed sensors throughout the network, endpoints, cloud environments, and applications that continuously collect telemetry data in the form of network traffic, system logs, and user activity. This provides complete real-time visibility of the system's operational state [4], [5]. The constant flow of data forms the raw input required for detecting anomalies and potential security threats [3]. The continuity of data intake at this layer ensures that even minute deviations such as micro-latency in service calls or unusual privilege escalations are captured. Thus, raw, unfiltered inputs required for detecting abnormal behaviors, APTs, and early- stage security risks are supplied to the intelligence pipeline.

Analysis Layer

The next layer is responsible for the analysis of the collected telemetry data through the application of a set of sophisticated artificial intelligence and machine learning methods [5]. The techniques not only analyze behavioral patterns but also detect anomalies and correlate these anomalies from different sources in order to automatically isolate the suspicious behaviors [9]. Adding threat intelligence feeds enhances the context for this layer and enables the determination of both harmless and actual security anomalies [4]. The overall purpose is to make the massive amounts of collected data actionable and in a manner the system can trust [6]. The central purpose is to take massive amounts of unstructured and semi-structured data and develop actionable and trustworthy decisions to feed subsequent processes like risk assessment and evaluation.

Decision Layer

This layer assumes the responsibility of deciding on the best action that should be undertaken citeref2. The risk assessment at this layer considers various factors: the severity level of the threat detected, the criticality of affected assets, business impact, and the availability of resources. Along with reinforcement learning algorithms, this layer adapts its policies of decision-making dynamically with previous outcomes to arrive at a better selection of mitigation actions continuously [1], [6]. All these adaptive decision making steps ensure that the responses balance threat containment with minimizing disruption to normal operations [4].

Execution Layer

This layer implements the selected response by itself across the IT environment autonomously [2], [8]. This

layer orchestrates a wide variety of responses from simple measures like blocking malicious IP addresses or isolating suspicious devices to more complex workflows such as automatic patch deployment, network reconfiguration, or even triggering forensic data capture [1]. Notably, it may include verification to confirm that the mitigations succeeded and fallback procedures for escalating incidents where called for. This automation minimizes the response time, significantly shrinking the attack window for attackers [2], [6]. The fact that this is rapid and autonomous significantly reduces the mean time to respond, effectively shrinking the attack window.

Learning Layer

It continuously analyzes the efficiency of past responses in optimizing the underlying models and strategies [6], [9]. Feedback cycles from the incident results enable the system to upgrade the accuracy of anomaly detection as well as optimize reinforcement learning strategies [1]. This layer enables model optimization on-the-fly, sharing knowledge from different environments, thereby enabling the entire system to adapt to address ever-evolving threats efficiently, thus addressing model drift [3], [5]. In this manner, the Learning Layer enables the framework to be proactive, resilient, and responsive to novel zero-day attacks as well as evolving Adversarial TTPs.

CHALLENGES

This section briefs the reader about the facts associated with the challenges faced in self-healing AI for cybersecurity.

Though AI cybersecurity has evidenced immense possibilities in terms of improvement in the detection and removal of cyber threats, there still lie several hindrances and limitations in this process. These challenges include:

1) Quality of Data Representation: The creation of comprehensive and quality data sets, which serve as a true representation for various forms of cyber attacks, is a challenge. The quality and need for sufficient numbers of quality data sets can impede the quality of anomaly detection as well as the performance of models based on Reinforcement Learning, especially for zero-day

attacks. The proposed model should incorporate data compression, such as representing activation and weights with fewer bits.

2) What are False Positives?: The goal of achieving both sensitivity and specificity within anomaly detection is difficult to balance. Supporting false positives may overwhelm the response system and analysts and operators responsible for responding to those events, while false negatives are a risk for breaches that go undetected within the system. False negatives allow "stealthy or evolving threats to evade detection," which increases "the chances for successful breaches and system compromise."

Complexity of Reinforcement Learning Design

Cybersecurity contexts are quite challenging when it comes to designing an effective reward function and environment for an RL agent. A poorly designed reward function can cause undesirable and suboptimal actions as a result of mitigation strategies, and simulating a realistic environment for training an RL agent is a computationally expensive and challenging process.

Real-time Performance and Scalability

This is a system that requires a lot of processing of data and making decisions on a real-time basis. Such a system faces architectural and technological issues regarding how to provide low latency to detection and response capabilities. With an increase in the size of networks, scaling models using AI is difficult.

Explainability and Trustworthyness

AI-driven decisions, and specifically complex models such as deep learning and Reinforcement Learning, may be opaque. Failure to have well-explained decisions may lower the level of trust and compliance and may inhibit human oversight. Research on developing techniques for explainable AI in cybersecurity is still an area of ongoing work.

Coping with Dynamic Threat

The attackers keep changing, and this makes it imperative to continuously update these models. This is due to concept drift, which prevents catastrophic Forgetting.

METHODOLOGY

Fig. 2 illustrates how supervised, unsupervised, reinforcement, and deep learning methods enable threat classification, anomaly detection, and adaptive mitigation.
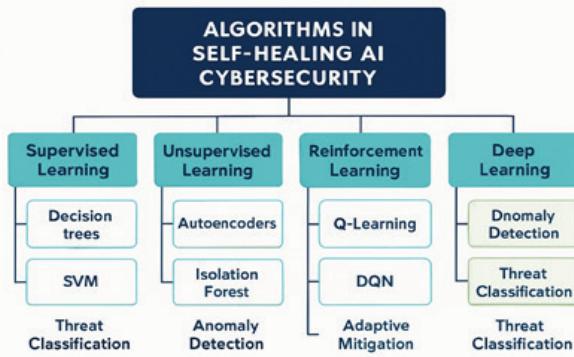
Fig. 2. Algorithms used in the self-healing AI cybersecurity framework.

Anomaly Detection

Anomaly detection systems involve machine learning techniques that learn the normal behavior of a system and mark anything that could pose a potential cyberattack. Such systems comprise the first defense mechanism, which identifies abnormal activity such as unknown malicious software, unauthorized access, and irregular traffic activity.

1) Autoencoders (Deep Learning): Autoencoders are trained neural networks that are used to compress their inputs and reproduce them. They learn the patterns and are fed only the normal data during the time of training. As soon as the input data is identified as an attack, the reconstruction error increases indicating that the data input is not normal. This, therefore, helps the system to identify unusual attack patterns that are different from the usual system process.

2) Isolation Forest: This algorithm uses recursive partitioning on the dataset to isolate anomalies. Because of their rarity and diversity, anomalies are usually isolated sooner and require fewer splits. There is now an easy-to-implement and efficient method for identifying outliers in network/system features, such as spikes in traffic level and unusual usage of protocols.

Cluster Analysis (e.g., K-Means)

Clustering algorithms cluster similar data points. Data points that are not similar to any cluster are said to be anomalies. For instance, data from a device that has abnormal patterns but do not cluster with normal user data could indicate that the device has been compromised.

Threat Classification

After identifying anomalies, classification algorithms determine the type of threat (such as malware, phishing, or DDoS attack) so that relevant actions may be taken.

1) Decision Trees and Random Forests: The trees divide the input data based on certain features (e.g., "port number," "traffic type") to predict an attack. Random Forest uses multiple trees to make accurate predictions by detecting those characteristics which distinguish between different cyber threats.

2) Support Vector Machines (SVM): SVMs produce optimal decision boundaries among classes in the higher dimensional space of features, which is effective in separating complex attacks and benign anomalies.

3) Deep Neural Networks (DNNs): Multiple layers are used to stack on top of each other in DNNs, covering the complex non-linear correlations found in cybersecurity information. For instance, it is used to examine the combination of logs or the series of incidents to pinpoint attack patterns.

Reinforcement Learning (RL) Algorithms

The RL algorithms also give the framework for the system to automatically determine and optimize mitigation strategies for learning from interactions within the environment. The decision of making a decision after detecting either an anomaly or a possible intrusion can be optimized. The traditional intrusion detection system (IDS) mainly aims at detecting intrusion. The RL makes the system automatically learn which mitigation decisions to make depending on the current system state.

The environment for the RL agent takes as input the anomalies found as well as the categories of threats. This allows the model to learn the defense actions most

likely to succeed against certain patterns of attacks, as determined through observation of system states and the success or failure of past mitigations (reward signals).

Deep Learning Concepts and Algorithms

It improves the system's ability to model complex patterns within high-dimensional data and temporal sequences. All these are important in cybersecurity applications involving differential data modalities.

Recurrent Neural Networks (RNNs) / Long Short-Term

Memory (LSTM): They are meant for processing sequential data, like packets and log records, over a period of time, and they can identify mounting attack behavior that spans several events.

Deep Q-Networks (DQN): This is an RL approach that unites deep learning with that of Q-learning to enable RL in graphics, which has large, continuous state spaces.

Future Scope

Explanation and Transparency Improvement

Create interpretable AI models that give a reason behind the autonomous decision made, and this will increase the acceptance of AI among the security team and pave the way for compliance with regulations.

Robustness of AI Models against Adversarial Attacks

Develop methods and techniques to resist attacks from adversarial machine learning for the purpose of evading or deceiving the model.

Human-AI Collaboration

Create interfaces and workflow structures in which human analysts and computers or AI interact smoothly and effectively. This will leverage both the immediacy of computers and human intuition.

Integration of Generative AI for Threat Simulation

Employ the use of either generative adversarial networks or large language models to create new sophisticated cyber-attacks that will enhance the quality of the datasets used in training.

CONCLUSION

This study proposes an innovative self-healing cybersecurity system that harnesses the power of artificial intelligence and combines anomaly detection and reinforcement learning for an adaptive and self-directed cybersecurity solution. Through its continuous monitoring process and accurate threat recognition and self-executed patching actions, this system can greatly improve the dependency on human intervention. Through its implementation of reinforcement learning techniques, this self- healing system can learn and develop optimal cybersecurity techniques and strategies through time and can effectively react and defend against ever-evolving cyber threats. Although some issues remain, including the existing concerns of data quality, and False positives, the proposed system provides an excellent framework and foundation for an anticipatory and resilient cybersecurity system. Future studies can enhance and improve this proposed system through its focus on applications of Explainable AI, Federated learning, Automatic patch generation, and increased robustness against attacks.

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Pedagogical Initiatives to Improve Classroom Teaching-learning

Shiwani Gupta
Assoc. Professor
AIML
Thakur College of Engineering and Technology
Mumbai, Maharashtra
✉ shiwanigupta3005@gmail.com

Archana Belge
Assoc. Professor
MME
Thakur College of Engineering and Technology
Mumbai, Maharashtra
✉ archanabelge3@gmail.com

Sujata Alegavi
Assoc. Professor
IoT
Thakur College of Engineering and Technology
Mumbai, Maharashtra
✉ sujata.alegavi@gmail.com

Hemant Kasturiwale
Professor
ENCS
Thakur College of Engineering and Technology
Mumbai, Maharashtra
✉ hemant.kasturiwale@tcetmumbai.in

ABSTRACT

This study evaluates the acceptance and effectiveness of pedagogical tools in engineering education. A questionnaire-based survey was conducted among students and faculty members to understand their awareness, preferences, and perceptions of various teaching modes, including offline, online, and blended. The survey examined the impact of these tools on student engagement, collaboration, comprehension, and their ability to bridge the gap between theoretical knowledge and practical application in engineering. The results showed a preference for traditional offline teaching, especially in analytical subjects, emphasizing the importance of face-to-face interactions. The study also highlighted the importance of problem-based learning, case study, brainstorming, and group discussions. The majority of respondents agreed that these tools significantly enhance student engagement, improve comprehension, and bridge the gap between theory and practical application in engineering education. The study proposes traditional face-to-face interaction, peer thinking, problem-based learning, exploration, case study presentations, and collaborative platforms for effective teaching and learning in engineering institutes.

KEYWORDS: Offline, Analytical, Primary, Pedagogy, Faculty, Engineering.

INTRODUCTION

PEDAGOGY refers to both the study and practice of teaching; it includes the theories, practices, and concepts that faculty employs to help their pupils learn. The Greek word "paidaggós" originally referred to the slave who accompanied and educated a young infant, and therefore the name "pedagogy" derives from this concept (Shulman, 2004; Batlolona et. Al., 2018; Graaff & Kolmos, 2003). Pedagogy is not just the act of imparting information, but also the methodical planning and execution of instructional strategies for optimizing student learning. Pedagogy, in its broadest sense, includes both the art and science of education. It changes as classroom practices, research, and technology do, and it has a major impact on the standard of education in

any setting (Loughran, 2013; Fink, 2013; Brroffield, 2015).

According to the guidelines of University Grant Commission (UGC), Quality Education for All, New Delhi, India (Loughran, 2013); for Innovative Pedagogical Approaches and Evaluation Reforms the teaching-learning process can adapt to new realities because of the variety of methods available. Teaching and learning are all enhanced through the use of experiential learning, inquiry-based learning, case-based instruction, problem-based learning, individual/group project-based learning, practical work and use of enhanced technology such as digital technologies and e-learning resources, and online platforms. The teaching methods like 1) Flipped classroom pedagogy,

2) Art Integrated Learning Pedagogy, 3) Project-based Learning Pedagogy, 4) Cutting Edge Pedagogy, 5) Critical Pedagogical Approach, are well suited to the demands of the 21st century classroom. The Fig. 1 shows the different modes of teaching along with the suggestive pedagogy as per UGC Anjum Sibia, 2020).

Fig. 1: UGC Pedagogy for different modes of teaching [8]

LITERATURE REVIEW

In paper (Jazuli et. al., 2019), The studies examined the effectiveness of different learning approaches on student outcomes. Ramdani et al. (2019) developed a problem-solving mathematical module using a reflective thinking framework, showing significant improvement in student assessments across four developmental stages. Conversely, Bilen et al. (2019) explored the impact of digital storytelling on science learning attitudes, revealing enhanced academic performance and more positive student perspectives compared to traditional methods. Both studies underscore the benefits of innovative pedagogical strategies in enhancing learning outcomes and fostering favorable student attitudes towards subjects like mathematics and science.

Domjanic et al. (2020) highlight the use of iPads and apps like "Preparing Solutions" and "Periodic Table" in Environmental Health Engineering and Laboratory Medical Diagnostics programs to enhance hands-on learning in biology and chemistry. While online education cannot fully replace traditional methods, it supports student comprehension. Louis & Cenat (2020) discuss the impact of COVID-19 on education, noting that some schools adapted well to online learning while others struggled. Sahu (2020) examines first-year college students' transition to virtual learning during the pandemic, revealing mixed feelings of anxiety and uncertainty, but also the importance of communication, LMS usage, and instructor support. Murphy et al. (2020) conducted a survey comparing online and traditional teaching methods, revealing that traditional "chalk-and-talk" is often preferred due to online sessions' limitations, such as inadequate facilities and internet connectivity. Naik et al. (2021) and Yazcayir & Gurgur (2021) examined remote special education during the pandemic, finding that students with special needs benefited from remote learning via online platforms and worksheets shared over WhatsApp. Abate et al. (2022) found that middle school students using a problem-based, visual learning strategy showed significant attitude improvements. Bal & Or (2023) explored students' problem-solving perceptions, revealing they often avoid solving problems despite their actual success rates.

METHODS / METHODOLOGY

To check out the acceptance of pedagogical tools laid down by UGC, we framed questionnaire and put forward to faculty of engineering colleges in India. The methodology diagram as in Fig. 2. below aims to enhance the pedagogical methods in engineering colleges across Maharashtra, with reference to UGC-recognized Pedagogical Tools of Level 1, 2, and 3. It begins with the creation of a comprehensive survey form designed for both faculty and students to gather feedback on current teaching and learning practices. The survey is then widely administered, ensuring representation from various institutions. Following this, a meticulous analysis is conducted on the collected responses to identify areas in Theoretical, Analytical, and Mathematical subjects that require improvement across Offline, Online, and Hybrid teaching modes. Subsequently, appropriate pedagogical tools are selected to address these specific needs. The result of 100+ respondents is shared further.

Although the majority of replies indicate agreement, the occasional presence of a "No" in Fig. 3 above implies that there is a lack of familiarity with these techniques among some of the individuals examined. The consistently elevated frequency of affirmative responses suggests a widespread familiarity with these instructional techniques among the participants.
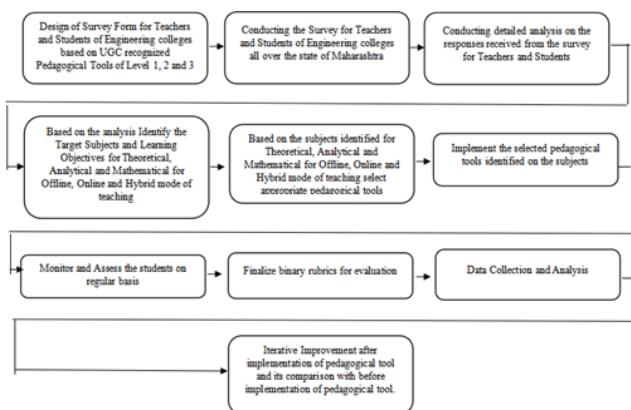
Fig. 2: Methodology Diagram

Are you aware of different pedagogical Tool of UGC/AICTE for Teaching-learning process?
50 responses
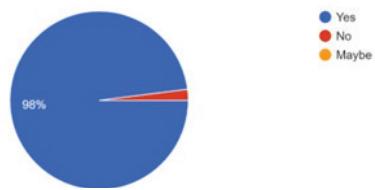
Fig. 3: Awareness of pedagogical tools

Do you feel for effective teaching-learning, pedagogical tools defined by UGC/AICTE are helpful?
50 responses
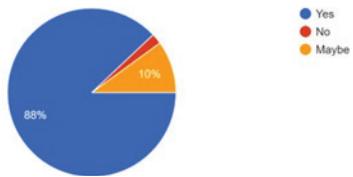
Fig. 4: Usefulness of pedagogical tools

The recurrence of affirmations in Fig. 4 above indicate a certain level of acquaintance with the tools introduced by the UGC and the All India Council for Technical Education (AICTE). The inclusion of "Maybe" responses indicates a certain level of ambiguity among certain participants, potentially attributable to their limited exposure or diverse experiences with these tools. The response indicating disagreement indicates that there is potential for improvement to meet the reservations of those who express uncertainty or dissatisfaction.

Responses in Fig. 5 above indicate diverse sample group to which survey has been put to. The disciplines are classified into various categories, including Analytical, Theoretical, and Mathematical.

Which type of subject currently you are teaching
50 responses
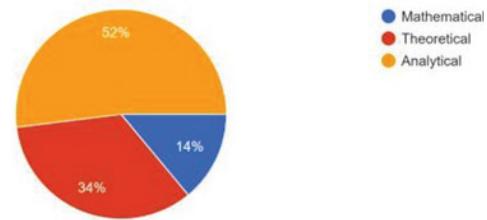
Fig. 5: Type of subject to which pedagogy has been applied

As per UGC five pedagogical tools are defined. Which pedagogical tools you are using for your subjects?
50 responses
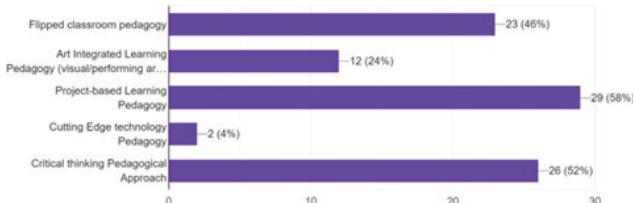
Fig. 6: Pedagogical tools used among participants

The responses as in Fig. 6. above contain a range of pedagogical tools encompassing Flipped Classroom Pedagogy, Project-based Learning Pedagogy, Critical Thinking Pedagogical Approach, and Cutting Edge Technology Pedagogy. After conducting a thorough analysis of the data, several discernible patterns become apparent. The disciplines classified as "Analytical" often incorporate instructional methodology such as Project-based Learning and Critical Thinking Pedagogical Approach. In contrast, the "Theoretical" subjects exhibit a preference for instructional methods such as Flipped Classroom Pedagogy, Project-based Learning Pedagogy, and Critical Thinking Pedagogical Approach while subjects classified as "Mathematical" encompass a combination of these instructional methodology.

In the past, teaching used to happen in offline mode. But with the advent of COVID-19, people had to migrate to online mode of teaching and the new normal post covid-19 times is blended mode of teaching learning. So in order to assess the preferred tools in these modes, we framed questionnaire.

As demonstrated in in Fig. 7. above, for offline modality of instruction, the strategies include collaborative techniques like Group Discussions and Brainstorming. More structured methods such as Case Studies, Guided

Questioning, and Problem-based Learning possess the ability to effectively engage students in critical thinking and real-world problem-solving. Moreover, instructional methods such as Talks and Presentations, Storytelling and Art Integration are utilized to incorporate a creative element into the pedagogical process.

For Offline Modes of teaching, which of the following pedagogy are you using?
50 responses
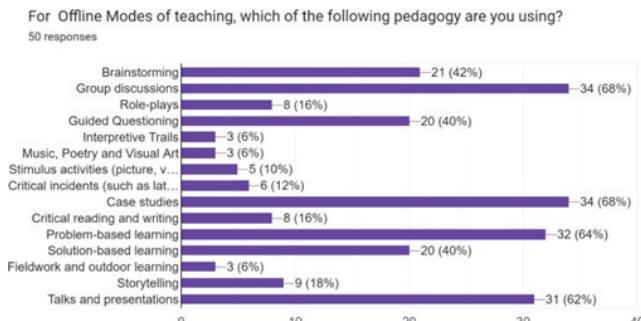
Fig. 7: Pedagogical tools used in offline teaching mode

For Online Modes of teaching which of the following pedagogy are you using?
50 responses
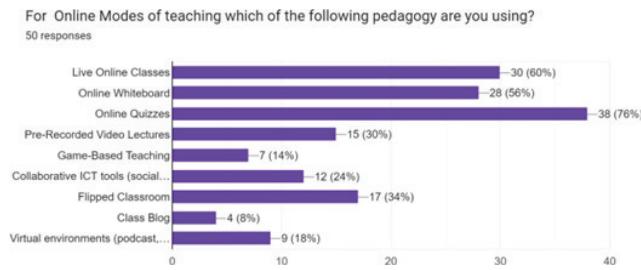
Fig. 8: Pedagogical tools used in online teaching mode

Pedagogical practices in online education, including live classes, online quizzes, pre-recorded lectures, and the flipped classroom model, support flexible, self-paced learning. Collaborative ICT tools, class blogs, virtual environments, and game-based teaching foster engagement, reflection, and dynamic content delivery, highlighting a shift toward hybrid and multimedia-rich education methods.

For Blended Mode of teaching which of following pedagogy are you using?
50 responses
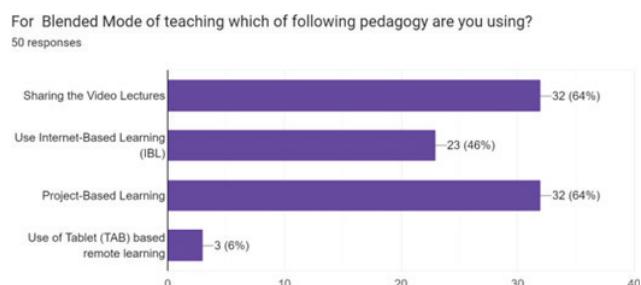
Fig. 9: Pedagogical tools used in blended teaching mode

The most notable instructional approaches as in Fig. 9 above for blended methods of instruction are utilization

of Sharing Video Lectures, implementation of Internet-Based Learning (IBL) and adoption of Project-Based Learning. The practice of sharing video lectures enables students to independently engage with educational material, promoting a self-guided learning experience and adaptability. The utilization of Internet-Based Learning (IBL) underscores the integration of digital resources to augment the educational experience. Project-Based Learning signifies development of critical thinking skills, problem-solving abilities, and active participation. Tablet-based remote learning is referenced in several contexts, demonstrating the incorporation of technology to facilitate learning in both real and virtual environments.

Finally, we asked respondents that which mode of teaching i.e. pre COVID-19, during and post is effective.

Which of the mode of teaching is more effective?
50 responses
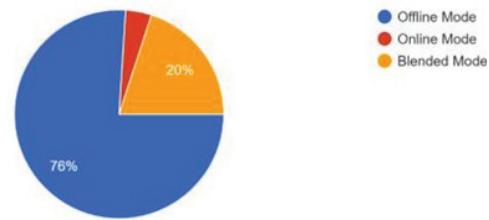
Fig. 10: Mode of teaching

The results supplied as in Fig. 10. above indicate inclination towards Offline Mode of instruction as the most efficacious mode due to direct interpersonal exchange that occurs in traditional classes, the opportunity to promptly resolve queries and issues, and the perceived level of involvement and connection typically associated with in-person instruction. It is noteworthy to add that a small number of participants also acknowledged the efficacy of Blended Mode, indicating an awareness of the benefits associated with integrating both face-to-face and virtual components.

The pedagogy laid down by UGC fall into 3 categories: Primary, Secondary and Tertiary. Thus in order to assess the preferred pedagogy under these categories, we framed questionnaire.

The responses presented in Fig. 11 above demonstrate a wide range of pedagogy that are favoured for promoting effective teaching and learning. The utilization of

"Chalk and Talk" technique in classroom sessions is a frequently seen approach, which suggests that direct instruction methods remain pertinent in the educational process along with implementation of additional tactics including the utilization of case study examples and learning via design situations, the incorporation of practical exercises utilizing information and communication technology tools and software, the adoption of content-based education, and the implementation of activity-based learning.

Among Primary pedagogy which you prefer for effectiveness in teaching, learning and evaluation
50 responses

Category	Value
Classroom lecture using Chalk and Talk technique	40 (80%)
Content based instruction	16 (32%)
Activity based learning	21 (42%)
Case study examples and learning by design situations	36 (72%)
Use of practical exercises using ICT tools and S/W	24 (48%)

Fig. 11 Primary Pedagogy

Among Secondary pedagogy which you prefer for effectiveness in teaching, learning and evaluation
50 responses

Category	Value
Jigsaws/Quiz	20 (40%)
Mind-Mapping	18 (36%)
Self Reflection	13 (26%)
Peer Teaching & think aloud pa...	23 (46%)
Group discussion with brainstor...	33 (66%)
Use of project work and field w...	27 (54%)
Scenario planning	9 (18%)

Fig. 12: Secondary Pedagogy

The responses offered in Fig. 12 above indicate a preference for diverse secondary pedagogical methods including the use of project work and field work, jigsaws/quiz activities, peer teaching and think aloud pair solving, group discussion with brainstorming, mind-mapping, self-reflection, and scenario planning. The absence of a clear consensus among the participants suggests a recognition of the various effective approaches for secondary pedagogy. The utilization of active learning strategies such as project-based learning, fieldwork, jigsaw activities, and group discussions demonstrates a dedication to fostering student engagement through experiential and collaborative learning opportunities. The use of reflective methodology such as "Self Reflection" implies the significance of students engaging in introspection. Moreover, the utilization of tactics such as "Peer Teaching & think aloud pair solving" highlights the significance of peer engagement and cooperative

problem-solving in augmenting educational learning.

The responses provided by participants in Fig. 13. above demonstrate a clear inclination of techniques for tertiary pedagogy that prioritize real-life problem-solving and reflective learning experiences. The aforementioned tools encompass various strategy such as providing opportunities for reflection on real-life situations, engaging with a varied group of individuals, facilitating exploration, encouraging debate, re framing challenges and utilizing creative skills like storytelling, dramatization/role play, and generating scenarios that are both known and non-familiar. The preference for "Real life problems allowing reflection time" as a prominent method highlights the requirement for students to apply theoretical principles to practical scenarios and engage in introspection over their experiences, so promoting enhanced comprehension and significant learning. The use of interactive components such as "Debate" and "Interacting with a diverse group" underscores the importance of collaborative learning and active engagement with a wide range of viewpoints. Moreover, instructional strategies such as "Exploration" and "Reframing problems" demonstrate a propensity for fostering students' disposition to critically examine assumptions, engage in creative thinking and tackle challenges from diverse perspectives.

Among Tertiary pedagogy which you prefer for effectiveness in teaching, learning and evaluation
50 responses

Category	Value
Storeytelling	12 (24%)
Dramatization/Role Play	7 (14%)
Real life problems allowing refl...	37 (74%)
Debate	19 (38%)
originating familiar and non fam...	7 (14%)
Interacting with a diverse group	13 (26%)
Exploration	20 (40%)
Reframing problems	15 (30%)
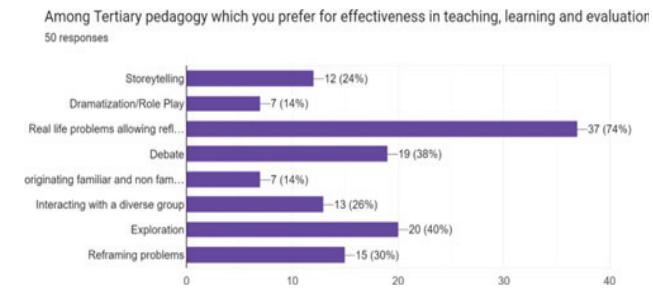
Fig. 13: Tertiary Pedagogy

Which level of pedagogy you prefer for effective teaching learning and evaluation?
50 responses

- Primary — 58%
- Secondary — 34%
- Tertiary — 8%
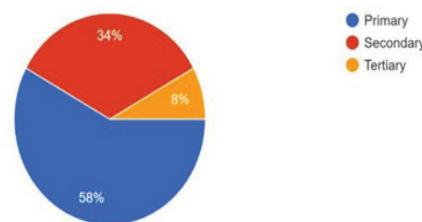
Fig. 14: Preferred level of pedagogy

The rise in popularity of "Primary" pedagogy as in Fig. 14. above can be ascribed to its emphasis on establishing a solid educational foundation, which plays a critical role in moulding a student's academic path. Although the "Secondary" and "Tertiary" levels of education also provide their own advantages in addressing more advanced learning requirements, the consistent preference for the "Primary" level indicates an acknowledgment of its significance in establishing a solid foundation for fruitful academic development.

We further tried to assess the effectiveness of these tools through strategically framed questions.
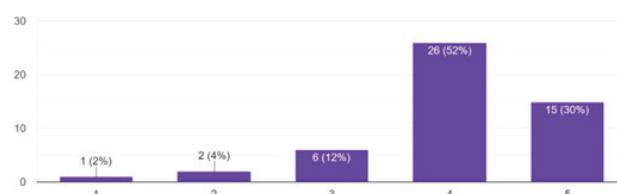
Fig. 15: Impact of pedagogical tools to connect theory to real world applications

The collected responses as in Fig. 15 above suggest that the integration of educational aids has a predominant effect on the capability to link theoretical concepts with practical applications in engineering courses. The response most commonly chosen by participants is 4 with 5 and 3 being the subsequent choices. This indicates that faculty believe that the integration of such tools effectively enhance their comprehension of the practical application of theoretical concepts within the engineering contexts. Based on a limited number of responses, specifically three and two, it appears that although most faculty perceive the incorporation of educational tools as advantageous, there may exist certain discrepancies in the degree to which these tools effectively facilitate the linkage between theoretical principles and practical implementations. These variances may be influenced by factors such as the characteristics of pedagogical instruments, their application strategies, and individual preferences for learning.

The high incidence of favourable ratings (4 and 5) in Fig. 16. above indicates that a significant number of participants hold the belief that instructional tools are

crucial in effectively catering to the varied requirements of engineering students. These tools are expected to offer educators the freedom to utilize diverse teaching methodologies, so improving their capacity to accommodate a broad spectrum of learning styles and abilities within a single classroom. Conversely, the existence of ratings falling within the range of 1, 2 and 3 indicates the potential for enhancement in specific instances.

Fig. 16: Impact of pedagogical tools to cater to diverse needs of engineering students

Fig. 17: Level of student engagement and participation using pedagogical tools

The ratings most frequently noticed in Fig. 17. above are clustered around the values of 4 and 5. The correlation shown between higher ratings and increased engagement suggests that such settings are crucial in engineering education as they promote critical thinking, cooperation, and active learning. Nevertheless, a few replies in the questionnaire have lower ratings (1 and 2), indicating instances where certain pedagogical methods may have failed to achieve the intended level of student engagement.

The ratings received in Fig. 18 above span from 2 to 5, indicating different degrees of achievement in utilizing these platforms to enhance collaborative skills. The high prevalence of ratings falling within the upper range (4 and 5) indicates that a significant number of instructors have reported witnessing enhancements in students' collaboration and collaborative abilities as a result of

integrating online platforms into their instructional practices. Nevertheless, a subset of respondents expressed lower ratings (2 and 3) in their feedback, indicating concerns over platform usability, students' level of familiarity with the technology and the specific execution of collaborative activities within the course.
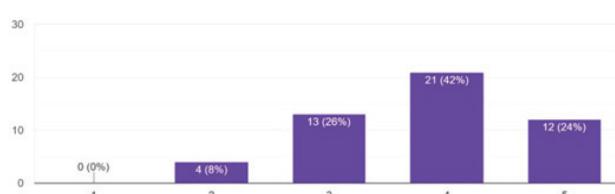
Fig. 18: Enhanced team work and collaboration with use of collaborative online platforms
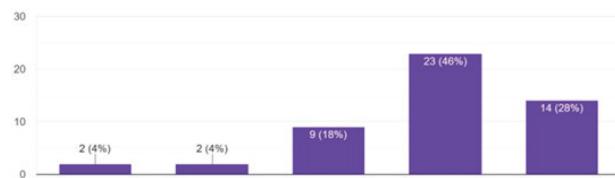
Fig. 19: Transformation in classroom dynamics and student interaction utilizing pedagogical tools

The most frequently given ratings in Fig. 19. above are in the range of 4 and 5, signify that these tools have facilitated more interactive and engaging learning experiences, enabling students to actively participate in discussions, collaborate with peers and engage in hands-on activities. Conversely, the presence of some lower ratings (1 to 3) suggests that, for a subset of educators, the impact of pedagogical tools on classroom dynamics and student interactions might not have been as transitional.

Fig. 20: Effectiveness of pedagogical tools in providing real time feedback of student understanding

The majority of responses in Fig. 20. above tend to cluster around the 4 and 5 range, indicating a substantial proportion of respondents holding the belief that these tools are efficacious in delivering timely feedback. Nevertheless, it is worth noting that a portion of educators have assigned lower scores (ranging from 1 to 3), suggesting that they may perceive the pedagogical tools to be less effective in delivering immediate feedback. The disparity in viewpoints may stem from various factors, including the efficacy of the tools, their alignment with the curriculum, or the extent to which they promote student participation.

Fig. 21: Level of challenges faced during integration of pedagogical tools

The responses received in Fig. 21. above offer insights into the difficulties encountered while implementing educational tools at the institutional level as well as the perceived efficacy of the approaches employed to tackle these difficulties. The majority of assessments tend to cluster around the scale of 3 and 4, suggesting that a significant number of participants faced moderate difficulties while incorporating the pedagogy. The potential obstacles encompass technical constraints, opposition towards adopting new practices, insufficient training, and the complexities associated with integrating educational technologies into the curriculum.

The pedagogical survey conducted in Mumbai among students in technological fields revealed that offline teaching is preferred, with problem-based learning considered the most effective method. While live online classes, virtual environments, and online whiteboards were deemed useful for online learning, class blogs were the least effective. Blended teaching methods, combining online and offline approaches, were moderately favored in unavoidable situations. Most students found analytical subjects more engaging than theoretical ones. Over 85% agreed that pedagogical tools

enhanced their understanding of theoretical concepts, and over 94% felt that collaborative tools improved interaction and discussions during the learning process.

ANALYSIS AND DISCUSSION

To test these pedagogical tools on a theoretical, a mathematical and an analytical subject of engineering disciplines we conducted evaluation pre and post usage of pedagogy and present the results:

We have implemented the UGC pedagogy on Third year engineering students for semester VI Advanced Instrumentation System subjects of Electronics Engineering. The subject being a theoretical subject; to give them basic understanding and to initiate critical thinking, about functioning of various hydraulic and pneumatic valves and processes used in industries; primary pedagogy like Use of practical exercises using ICT tools and software introduced in the autonomy curriculum. Case study related to different valves used in industries are discussed and presentations are held for the same for better understanding, during the laboratory hours and demonstration during lectures. As a results students understanding increased and attendance in the class is improved along with active participation. Also, for making students enable to design the valves as per the industrial application; various situations/scenario are given to them. Through secondary pedagogy like Group discussion & Brainstorming students becomes able to design it as per the requirement. Also, by discussing various situations in different industries i.e. by scenario planning they are able to identify and design different valves for respective applications. To improve the understanding of subject tertiary pedagogy; like interaction with a diverse group is applied by planning and executing industrial visit at nearby product industry, guest lecture is conducted from instrumentation domain to understand the recent industry trends and interaction with industry experts one to one. This helps in creating interest in students about the subject and practical applications of the same.

It is observed that before the implementation of different pedagogical tool in teaching learning for Theoretical subject's students get monotonous, dull in lectures and attendance was less and Term work & Viva marks are less than average but after applying primary, secondary and tertiary pedagogical tool students are now showing

more interest in the learning the subjects and attendance in the class is increased and significant improvement in the marks of term work and viva is observed. Fig. 22. and Fig. 23. shows the sample for calculation of term work and viva marks for batch 2021. The actual statistics for the previous batches is shown in Table 1 & Table 2.

Date: 22/04/21									
Roll No.	Name of the Student	Experiments	AVG	Assignments	AVG	Attendance		Overall Performance	Total Marks
	Marks Out of	100	10 Marks	100	5 Marks	100	5 Marks	5 Marks	25 Marks
1	BAJORIA SHRUTI VISHNU ANJU	100	10	100	5.00	100	5	4	24
2	BARUDGAR MOHD SHAFFIQUE MOHD SIDDIQUE FATIMA	71	7.07	40	2.00	81	4.05	4	17
3	CHAVAN MAYUR PRADEEP PRANALI	82	8.2	60	3.00	100	5	2	18
4	DALVI NIHAR PRAKASH SHILPA	94	9.4	95	4.75	100	5	3	22
5	DANDEKAR VEDANT SANJAY MONIKA	100	10	85	4.25	100	5	2	21
6	GHARAT PRITIKA MANOJ PRACHI	100	10	100	5.00	100	5	4	24
7	GOYAL KULIN JAGDEEP NEELU	85	8.5	50	2.50	71	3.55	2	17
8	GUPTA AMARNATH CHHATHU MUNNI	92	9.15	80	4.00	100	5	3	21
9	GUPTA ANIKET DEVDAS MEENA	84	8.35	50	2.50	71	3.55	4	18
10	GUPTA ANMOL SANJEEV ALKA	97	9.7	100	5.00	95	4.75	2	21
11	GUPTA ESHAAN BAIKUNTH RASHMI	80	8	50	2.50	57	2.85	3	16
12	GUPTA ROHAN RAM KUMAR SHANTI DEVI	100	10	100	5.00	100	5	3	23
13	INDULKAR HRISHIKESH SUNIL	95	9.5	80	4.00	100	5	2	21
14	JAIN AKSHAT DEEPAK PREMLATA	100	10	100	5.00	90	4.5	2	22
15	JAIN DIPESH NAVRATAN LEENA	100	10	80	4.00	95	4.75	1	20
16	JAIN SHREYANSH SHRIPAL HARSHA	100	10	100	5.00	100	5	1	21
17	JAISWAL ARYAN BRIJESH ARCHANA	58	5.77	45	2.25	29	1.45	3	12
18	JALAN NAVENDU SANJEEV VRINDA	82	8.2	45	2.25	62	3.1	3	17
19	KAMAT ROHIT SHASHANT SANJANA	90	9	80	4.00	100	5	2	20
20	KHANNA SWATI RAJESHKUMAR KAMAL	81	8.1	63	3.13	90	4.5	3	19

Fig. 22: Sample of term work marks rubric for the Theoretical subject (AIS)

Date:					EXAMINER:	
Roll No.	Seat No.	Name of the Student	Practical (10 Marks)	Oral (10 Marks)	Overall Performance/Apperanace on Zoom (5 Marks)	Total Marks (25 Marks)
1		BAJORIA SHRUTI VISHNU ANJU	8	8	4	20
2		BARUDGAR MOHD SHAFFIQUE	6	6	4	16
3		CHAVAN MAYUR PRADEEP PRANALI	6	6	5	17
4		DALVI NIHAR PRAKASH SHILPA	8	8	5	21
5		DANDEKAR VEDANT SANJAY MONIKA	8	6	4	18
6		GHARAT PRITIKA MANOJ PRACHI	8	8	5	21
7		GOYAL KULIN JAGDEEP NEELU	6	6	4	16
8		GUPTA AMARNATH CHHATHU MUNNI	8	8	5	21
9		GUPTA ANIKET DEVDAS MEENA	6	6	5	17
10		GUPTA ANMOL SANJEEV ALKA	8	8	5	21
11		GUPTA ESHAAN BAIKUNTH RASHMI	8	7	5	20
12		GUPTA ROHAN RAM KUMAR SHANTI DEVI	8	8	5	21
13		INDULKAR HRISHIKESH SUNIL	8	8	5	21
14		JAIN AKSHAT DEEPAK PREMLATA	8	6	3	17
15		JAIN DIPESH NAVRATAN LEENA	6	8	5	19
16		JAIN SHREYANSH SHRIPAL HARSHA	7	6	4	17
17		JAISWAL ARYAN BRIJESH ARCHANA	6	4	3	13
18		JALAN NAVENDU SANJEEV VRINDA	7	5	4	16
19		KAMAT ROHIT SHASHANT SANJANA	6	7	4	17
20		KHANNA SWATI RAJESHKUMAR KAMAL	8	7	4	19

Fig. 23: Sample of viva marks rubric for the Theoretical subject (AIS)

For the calculation of term work the rubrics considered are: 1) Average of weekly performance during laboratory hours, 2) Assignment submission,

3) Attendance during lectures & lab hours, and 4) Overall performance during lab hours. For the calculation of viva, the rubrics considered are: 1) Performance at the time of exam, 2) Oral given based on questions and 3) Overall performance/ appearance during exam.

Table 1 Term Work Marks

Year	No. of students	Range of Term work			
		0-9 Marks	10-14 Marks	15-19 Marks	20-25 Marks
2018	**70**	0	9	28	33
2019	**69**	0	8	27	34
2020	**70**	0	9	25	36
2021	72	0	1	17	54

Table 2 Viva Marks

Year	No. of students	Range of Term work			
		0-9 Marks	10-14 Marks	15-19 Marks	20-25 Marks
2018	70	0	14	41	15
2019	69	0	13	42	14
2020	70	0	15	40	15
2021	72	0	3	43	20

The above statistics show that adopting various UGC pedagogy has impacted students in terms of enhancing their basic knowledge about the subject a lot, creative thinking, logical thinking, presentation, and adaptability skills. During assessment of students, it is observed that term work marks and viva marks both have increased over the years. This can further be improved by consistently implementing appropriate pedagogical tools with respect to variety of students.

Teaching Deep Learning with a strong emphasis on mathematical aspects using pedagogical tools is of paramount importance. Deep learning, with its intricate algorithms and Neural Networks relies heavily on mathematical foundations. Pedagogical tools help bridge the gap between theoretical and mathematical concepts and their practical application in Deep Learning tasks. They enable students to grasp complex mathematical principles, cultivate problem-solving skills, and encourage critical thinking all of which are essential for success in this rapidly evolving field. Furthermore, these tools make the learning process engaging and interactive, fostering a deeper understanding of mathematical underpinnings. By integrating pedagogical tools effectively, students have not only developed mathematical understanding required for Deep Learning but also were inspired by

the innovation and creativity in tackling real-world challenges within the domain.

Table 3 Performance Matrix

Sr. No.	Number of Students	ISE - I Average Out of 20 Marks (Before implementing Pedagogy tools)	ISE - II Average Out of 20 Marks (After implementing Pedagogy tools)	ESE Average Out of 60 Marks (Final Impact)
1	35	9.94	16.60	53.15

Table 4 Rubrics

Pedagogical Approach	Effective Implementation	Ineffective Implementation
Problem-Based Learning	Adequate real-world problem integration Encourages critical thinking and problem-solving	Limited relevance to real-world applications Fails to stimulate critical thinking
Chalk and Talk	Clear and concise explanation of complex concepts Promotes student-teacher interaction	Incomprehensible or disorganized explanations Lack of student engagement and interaction
Game-Based Teaching	Enhances engagement and motivation Encourages practical application of concepts	Fails to engage students effectively Lacks alignment with learning objectives
Peer Think Aloud	Encourages articulation of thought processes Facilitates collaborative problem-solving	Students struggle to articulate thoughts Inadequate peer interaction

Exploration	Encourages active engagement with concepts Fosters practical relevance Enhances problem-solving skills	Lacks real-world application Fails to engage students in exploration activities

Based on the marks achieved by the students in ISE-I, ISE-II and ESE as in Table 3 and the rubrics used for the different pedagogical tools as in Table 4 for teaching the mathematical subject of Deep Learning, following analysis can be drawn:

Problem-Based Learning (PBL) and Chalk and Talk have proven highly effective in teaching Deep Learning, especially for clarifying complex mathematical concepts and promoting critical thinking. Game-Based Teaching boosts student engagement and motivation by applying Deep Learning theories to real-world problems. Peer Think Aloud encourages collaborative learning and problem-solving, enhancing student achievement. Exploration bridges theory and practice, improving academic performance. These teaching strategies led to significant improvements in students' marks, with average ESE marks rising to 53.15 out of 60 and ISE-II marks increasing from 9.94 to 16.60 out of 20, reflecting better understanding of Deep Learning concepts.

We have implemented the UGC pedagogy on Machine Learning elective for Sem V students of Computer Engineering. This being an analytical subject; to initiate critical thinking, Project Based Learning through capstone projects has been included in the autonomy curriculum. To bring out the quality in projects involving team work and collaboration, Case study presentations are held, based on Real life problems during the early weeks in the laboratory. Before presentations students utilize Internet based learning through Flip classroom. The content development requires Exploration, Peer discussion and Think aloud pedagogy. Students utilize ICT tools and S/W for project development so as to link theory to real world. Projects are allocated catering to students' diverse skills. During presentations engagement and participation is executed through probing questions which ascertain real time feedback

of understanding. Being an elective course, game based evaluation is incorporated to improve interaction among sections. Challenge with implementation of this pedagogy is in making students novice to the subject engage in learning, so project group is made of students with diverse skills w.r.t. the course. The rubric used for evaluation involves measuring the quality of content, presentation ability, commitment to task, participation during session and quality of documentation.

We find in Table 5,6 below that in the year 2020 and before when students were engaged only through experimentation, there critical thinking ability was not developed while utilizing primary, secondary and tertiary pedagogy laid by UGC, students' participation has considerably increased in hackathons related to ML at department, institute, city and nation level and the accolades have increased over these years. Figure below presents these statistics:

Table 5 Department Level Hackathon

Year	Duration	No. of registered groups	No. of participating groups	No. of winners	Level
2020	84 hour	17	8	5	Department
2021	100 hour	10	7	4	Interdepartment
2022	64 hour	17	9	6	Department
2023	88 hour	24	6	3	Interdepartment

Table 6 Nation Level Hackathon

Year	No. of teams participated	No. of teams won	Prize money
2017	1	1	50,000
2018	3+1+1	1	1,00,000
2019	5	3	2,75,000
2020	3	1	1,00,000
2021	COVID TIME NOT HELD		
2022	6+2	5+1	5,00,000

The above statistics show that adopting various UGC pedagogy has impacted students in terms of enhancing

their problem analysis, creative thinking, presentation, domain knowledge, project management, team work and adaptability skills. Participation and winning both have increased over the years. Thus to further increase the chances of winning we hold scrutiny of the solutions at department and institute level. So current year statistic demonstrates that for uploading 35 solutions to Problem Statements uploaded by various industries at national level, 150 teams showed interest of which 133 presented at department level and around 50 were taken to the round at institute level.

CONCLUSION AND RECOMMENDATIONS

This comprehensive survey and its implementation on the acceptance and impact of pedagogical tools in engineering education reveals several noteworthy findings. Offline teaching, particularly in analytical subjects, remains the preferred mode, emphasizing the enduring value of face-to-face interactions in education. Active learning strategies like problem-based learning and case studies are highly endorsed, underlining their effectiveness in fostering student engagement and comprehension. Online teaching, while appreciated, faces some challenges that may require refinement. Collaborative online platforms have proven to be valuable for enhancing teamwork and collaborative skills. The overall perception of pedagogical tools is positive, with consensus on their ability to improve student engagement, comprehension of theoretical concepts, and the practical application of knowledge in engineering. The research underscores the need for a balanced integration of these tools, customized to the subjects' requirement and students' needs to enhance the quality of engineering education in both offline and online contexts. Furthermore, the implementation of UGC and AICTE recommended pedagogical tools in various engineering courses, as detailed in the study, has led to significant improvements in students' learning experiences and outcomes, demonstrating the transitional impact of these pedagogical approaches across theoretical, mathematical, and analytical domains in engineering education. These tools have revitalized traditional lectures, increasing student attendance and academic performance in subjects like Advanced Instrumentation Systems, facilitated a deeper understanding of complex mathematical principles in Deep Learning, and fostered critical thinking and problem-solving abilities in Machine Learning. The study highlights the importance of adapting and integrating diverse pedagogical tools to create enriching learning environments that prepare students for success in the dynamic field of engineering.

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EFEMS: Design of a High-Efficiency fMRI Representation Model via Combination of Ensemble Feature Extraction & Multimodal Segmentation

J. L. Mudegaonkar

Department of Electronics & Telecommunication
GH Raisoni College of Engineering and Management
Wagholi, Pune, Maharashtra
✉ jagdishmudegaonkar@gmail.com

D. M. Yadav

Principal
SND College of Engineering and Research Centre
Yeola, Nashik, Maharashtra

ABSTRACT

Functional magnetic resonance imaging (fMRI) is a technique opted by neurologists to identify changes in brain activity via observation of blood flow. They estimate blood flow in brain segments, and estimate neurological activities using flow information. A wide variety of fMRI representation models are proposed by researchers, and each of them have their own nuances, advantages, limitations, & applicability, depending upon their internal design characteristics. However, the majority of these models are specific to particular contextual regions, and are targeted at region-level, for instance, fMRI representation models for posterior cingulate cannot be used to describe superior and middle temporal gyri regions. Moreover, these models are view dependent, and thus frontal-view fMRIs representation methods are not useful for side-view fMRI representations. Therefore, to address these limitations, this paper suggests designing a high-efficiency fMRI representation model by combining ensemble feature extraction and multimodal segmentation methods. The proposed model initially segments fMRI images via bias-field estimation fuzzy C Means (BFCM), which assists in identification of Grey Matter, while Matter, and Brain fluid regions. These regions are processed via an ensemble of colour map, edge map, texture map, and convolutional features, which assists in region-level representations. A Maximal Variance Model is deployed, which assists in redundancy reduction from these features, and improves quality of fMRI representation. The enhanced representation model underwent evaluation using Support Vector Machine (SVM) and Naïve Bayes (NB) classifiers to classify input fMRI data into tumour and non-tumour classes. Observations revealed an improvement of 8.5% in accuracy, 6.2% in precision, 7.1% in recall, and 15.8% in computational speed compared to various state-of-the-art methods. With these advantages, the proposed model demonstrates capability for deployment across a wide array of clinical application scenarios.

KEYWORDS: *fMRI, Representation, Segmentation, BFCM, Colour, Texture, Shape, Convolutional, Tumour, Classification.*

INTRODUCTION

Segmentation and classification of fMRI images constitute a multidisciplinary task, encompassing the design of modules for data acquisition, data pre-processing, categorization, feature representation, feature selection, stratification, and post-processing operations. Due to advances in VLSI (Very Large-Scale Integrated circuits) technology, data capturing & pre-processing models are capable of high-efficiency operations, with good quality image representation, that can be used for classification & post-processing operations. But performance of image segmentation, feature extraction & feature selection models vary widely w.r.t. type of application & type of input images. A standard feature extraction and selection framework for fMRI datasets is presented in figure 1 [1], where it can be seen that after segmentation, a diverse range of feature representation models are applied to the images. These models include, shape features, statistical features, wavelet features, textural features, etc. Results of these feature representation models are processed via

a feature selection layer, which assists in maximizing inter-class variance levels.

Due to this variance maximization, a Radiomic Model is built, which aids in high-accuracy fMRI stratification, with minimum error performance. The subsequent section of this text delves into comparable models [2, 3], exploring their nuances, advantages, limitations, and potential avenues for future research. From this discourse, it became evident that the majority of these models are tailored to specific contexts and are focused on the region level. For instance, fMRI representation models for posterior cingulate cannot be used to describe superior and middle temporal gyri regions, which limits their scalability performance under different image types. In response to this limitation, Section 3 suggests designing a high-efficiency fMRI representation model through the combination of ensemble feature extraction and multimodal segmentation techniques.. The proposed model underwent testing across a diverse range of classification applications, with its performance assessed and compared in Section 4. Metrics such as accuracy, precision, recall, and processing delay were evaluated and contrasted. This comparative analysis enables researchers to determine the applicability of the proposed model for their context-specific fMRI analysis applications. Lastly, this text concludes with noteworthy observations regarding the proposed model and suggests methods to enhance its performance further.
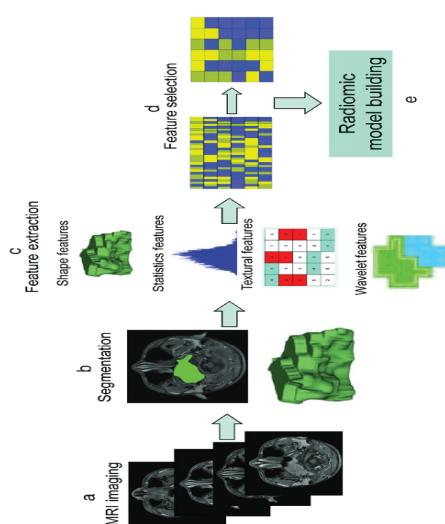
Figure 1. A standard feature extraction and selection framework for fMRI datasets

LITERATURE REVIEW

Researchers propose a wide array of fMRI processing models, each exhibiting its own performance variations. For example, research in [4, 5, 6] suggests use of Bayesian Classification with Intrinsic Connectivity Maps, rLDA (regularized linear discriminant analysis), and SNNs (spiking neural networks) for black-box classification of fMRI images. These models are highly generic, and thus cannot be used for application-specific deployments that require higher accuracy performance. To address this limitation, research in [7] suggests utilizing Tensor Neural Network (TNN) that can be tuned as per deployment application, and showcases good performance under different image types. Building upon this model, research in [8, 9, 10] suggests use of 3-D CNN, Multiple Feature Image Capsule Network with Ensemble classification, and low-dimensional subspace representation that is spanned by wavelet packets. These models are highly effective for context-sensitive images, and showcase good accuracy for classification & post-processing operations. The effetiveness of these models is further augmented through the application of Structural Group Classification Technique (SGCT). [11], Local Meshes for representation of Brain imagery (LMR) [12], spiking neural networks (SNNs) [13], and Fuzzy-Rule-Based model with Chaotic Swarm Intelligence (FRCSI) [14] are discussed. These models assist in low-redundancy feature selection via use of multiple operators that reduce redundancies between different feature sets.

Models that are deployed for application specific classification tasks are explored in [15, 16, 17], where researchers have advocated for the utilization of sparse inverse covariance estimation (SICE), constraint independent component analysis (CICA), and Euler's Elastica (EE) with regularized multinomial logistic regression methods. These methods are applicable to particular types of fMRI data, and cannot be scaled to large-datasets. To address this constraint, research in [18, 19, 20] suggests employing 2D MRI based CNN, Artificial Neural Network (ANN) with cross validations, CDAE (convolutional denoising autoencoder) with AdaDT (adaptive boosting decision trees), that can be applied to a diverse range of fMRI image datasets. However, these models demonstrate only moderate

accuracy performance, constraining their applicability and scalability for real-time images. In order to address this limitation, Voxel Selection Frameworks [21], Total Variation Regularization [22], Hierarchical SVM [23], and functional connectivity (FCs) between the activity voxels [24] are explored for different datasets. However, these models are exceedingly intricate and cannot be employed for general-purpose fMRI imagery. To address these constraints, the subsequent section proposes the development of a novel high-efficiency fMRI representation model by combining ensemble feature extraction and multimodal segmentation techniques. This model aims to be applicable across a broad spectrum of clinical scenarios. Furthermore, its performance is assessed and compared with several state-of-the-art models.

DEVELOPMENT OF THE SUGGESTED HIGH-EFFICIENCY FMRI REPRESENTATION MODEL THROUGH A FUSION OF ENSEMBLE FEATURE EXTRACTION AND MULTIMODAL SEGMENTATION

From the literature survey, it was noted that current models for segmentation & feature extraction are context region specific, and are targeted at region-level segmentation process. Some of the models are view dependent, and thus frontal-view fMRIs representation methods are not useful for side-view fMRI representations. Due to these characteristics, these models' efficiency is constrained concerning representation accuracy, classification precision, recall performance, and so forth. To address these constraints, this section examines the design of a novel high-efficiency fMRI representation model via combination of ensemble feature extraction & multimodal segmentation methods, which results in better classification & representation performance under different application datasets. The overarching workflow of the proposed model is illustrated in Figure 2, showcasing the processing of multiple fMRI datasets, as well as their feature extraction, feature selection, and classification processes. Initially, the model estimates bias field components from input images, and processes them via Fuzzy C Means (FCM), which assists in initial clustering & segmentation operations. Clustering results are processed through a combination of color mapping,

edge mapping, texture mapping, and convolutional mapping operations. This process yields a super feature vector (SFV), enhancing the representation of fMRI images.
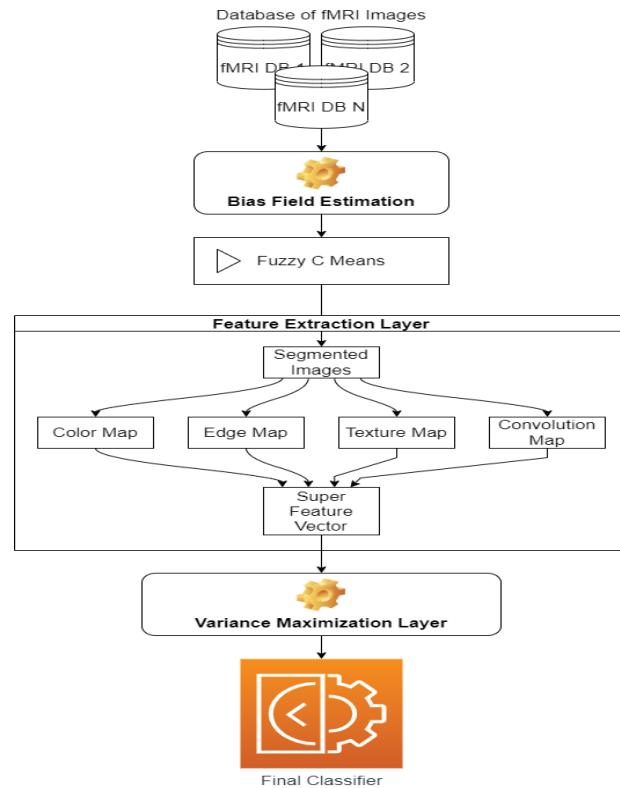
Fig. 2. The overarching workflow of the proposed model

This SFV metric has feature redundancies, which must be removed for improving speed & accuracy of classification process. For executing this task, a Variance Maximization layer is incorporated, which facilitating in inter-class features that have higher variance levels. The selected features are processed via a final application-specific classification layer, which is deployed to categorize input fMRI data into 1 of N classes. This design flow is divided into multiple sub-modules, each of which is elaborated on in different subsections of this text. Following this discussion, researchers can deploy these modules either individually or collectively, depending on their application requirements and process specifications.

Design of Bias Field Estimation with Fuzzy C Means for cluster-based segmentation process

For estimating bias field, histogram of input image

is evaluated via equation 1, and then local minima is identified for extraction of different image regions.

$$H_i = \sum_{r=1}^{R} \sum_{c=1}^{C} fMRI(r,c)$$

(1)

Where, H_i represents histogram of fMRI image with i^{th} intensity level, $i \in (0,255)$, while R, C represents number of rows & columns. Evaluate 2nd and 3rd level polynomial surfaces via equations 2 and 3 respectively,

$$P_2 = p_0 + p_1 * x_i + p_2 * y_j + p_3$$
$$* x_i^2 + p_4 * y_j^2 + p_5 * x_i * y_j$$

(2)

$$P_3 = p_0 + p_1 * x_i + p_2 * y_j + p_3 * x_i^2 + p_4 * x_i * y_j$$
$$+ p_5 * y_j^2 + p_6 * x_i^3 + p_7 * x_i^2 * y_j + p_8 * x_i$$
$$* y_j^2 + p_9 * y_j^3$$

(3)

Where, P_2 & P_3 represents 2nd and 3rd level bias field components, while p_i represents probability of image representation for the ith bias field, and is evaluated via equation 4, and x_i, y_j represents differential image components in the x & y directions respectively, which are evaluated via equation 5 & 6 as follows,

$$p_i = \frac{\sqrt[i]{\sum_{j=0}^{255} H_j^i}}{256}$$

(4)

$$x_i = \sum_{j=1}^{R} fMRI(j,C) - fMRI(j+1,C)$$

(5)

$$y_i = \sum_{}^{C} fMRI(R,j) - fMRI(R,j+1)$$

(6)

Both the components are combined via equation 7 to evaluate the final bias field component, which represents input image in terms of directional fields.

$$BF_i = P_2 * w_{2i} + P_3 * w_{3i}$$

(7)

Where, w_{2i} & w_{3i} represents 2nd and 3rd order weights of the given bias field components. These weights are initialized depending upon intensity of image components at the output, and assist in improving visual representation for the images. The bias field components are given to FCM for clustering, wherein Grey Matter,

while Matter, and Brain fluid regions are extracted via continuous cluster formations. Here, cluster centroids are initialized stochastically via equation 8, and are continuously updated to obtain final clusters.

$$C_i = STOCH(0, 255)$$

(8)

Distance between each pixel of all bias field image pixels is evaluated with the cluster centroid via equation 9,

$$D_{i,j} = \sqrt{\sum_{j=1}^{N(BF)} (c_i - BF_{i,j})^2}$$

(9)

Where, N(BF) stands for number of bias fields. Based on this distance, a cluster membership is evaluated via equation 10,

$$\mu_{i,j} = \frac{1}{\sum_{l=1}^{c} \left(\frac{D_{i,j}}{D_{i,l}}\right)^{\frac{2}{p-1}}}$$

(10)

Based on this membership value, centroid is updated via equation 11 as follows,

$$C_i^{new} = \frac{\sum_{j=1}^{N} \mu_{i,j}^p * C_i^{old}}{\sum_{j=1}^{N} \mu_{i,j}^p}$$

(11)

Where, p is a fuzzy factor in the range (0,1), while N & c represents number of bias field components, and number of clusters respectively. Based on this process new cluster centroids are initialized, and elements are grouped into these clusters. This process is repeated for multiple iterations, until cluster centre values are constant between these iterations. The final cluster values are used for estimation of Grey Matter, while Matter, and Brain fluid regions, each of which is processed via augmented feature extraction layer, which is elaborated upon in the subsequent section of this text.

Development of the feature extraction and selection layer for generating the super feature vector

The segmented regions undergo processing through a feature extraction layer, aiding in the evaluation of Color Maps, Edge Maps, Texture Maps, and Convolution Maps. These Maps are integrated to form a Super Feature Vector (SFV) that can effectively represent the input image with improved efficiency. The Colour

Map features are evaluated via equation 12, wherein quantized value of each input image component is used for evaluation as follows,

$$CMap_i = \bigcup_{j=0}^{255} \sum_{r=1}^{R} \sum_{c=1}^{C} QBF_i(r,c) == j \tag{12}$$

Where, QBF represents quantized bias field component of the image, and is calculated via equation 13 as follows,

$$QBF = \frac{BF - \min(BF)}{\max(BF) - \min(BF)} \tag{13}$$

Similarly, edge map for each bias field component is evaluated via equation 14 as follows,

$$EMap_i = \sum_{r=1}^{R} \sum_{c=1}^{C} Canny[QBF_i(r,c)] == 1 \tag{14}$$

Where, Canny[I] represents Canny edge components for the input image I, and is used to estimate edge-level components. These components are extended via use of a Texture Maps, which estimates Grey Level Co-occurrence Matrix (GLCM) via equation 15 as follows,

$$TMap_i = GLCM[QBF_i] = \bigcup_{j=0}^{255} \sum_{r=1}^{R} \sum_{c=1}^{C} QBF_i(r,c) == QBF_i(r,c+1) \tag{15}$$

Similarly, Leaky Rectilinear Unit (LReLU) is used for feature-level activation as follows in equation 16, where convolutional features are evaluated,

$$ConvMap_i = \sum_{a=-\frac{m}{2}}^{\frac{m}{2}} \sum_{b=-\frac{n}{2}}^{\frac{n}{2}} LReLU\left(\frac{m}{2}+a, \frac{n}{2}+b\right) * QBF_i(j-a, k-b) \tag{16}$$

In this context, LReLU represents the Leaky ReLU kernel, while m and n denote the convolutional window size in terms of rows and columns respectively, and 'a' and 'b' represent the corresponding convolution stride sizes. The convolutional features are extracted for different window & stride sizes, and combined with other features for the formation of Super Feature Vector (SFV) which is calculated using equation 17,

$$SFV = \bigcup_{i=1}^{N(BF)} \left(\begin{matrix} CMap_i \bigcup EMap_i \\ \bigcup TMap_i \bigcup ConvMap_i \end{matrix} \right) \tag{17}$$

The post-processing of SFV features involves a Variance Maximization layer, which aids in reducing class-level redundancies by estimating the inter-class feature variance threshold using equation 18,

$$V_{th} = \sqrt{\frac{\sum_{a=1}^{m}(SFV_a - \frac{\sum_{i=1}^{m}\sqrt{\frac{\sum_{j=1}^{n}(SFV_j - \frac{\sum_{k=1}^{n} SFV_k}{n})^2}{n-1}}}{m})^2}{m-1}} \tag{18}$$

In this context, Number of features in current class is represented by 'm', Number of features in other class is represented by 'n', and 'SFV' is Super Feature Vector values. Attributes that have variance less than V_th are discarded, while others are used for classification and post-processing purposes. A sample classification application that uses these features is continued in the next section of this text.

The design of the final classification layer aims to evaluate performance across different image types

Upon extraction of the Variance Maximized feature vector, an ensemble of SVM (Support Vector Machine), and NB (Naïve Bayes) classifiers are used to classify fMRI images into tumour and non-tumour categories. To perform this task, both classifiers are used in their original form with the following parameters,

- SVM

  - Regularization parameter, C=0.5

  - Polynomial Kernel with 5th degree of control

  - Kernel coefficient, k=0.5, because there are 2 classes (tumour and non-tumour)

- NB

  - Priors, which are estimated via Edge Probability of pixels

  - Smoothing value, SV=1e^(-9), which is used to control classification accuracy for different inputs

Based on these parameters, classification process is performed, and final class is estimated via equation 19 as follows,

$$C_{out} = C(NB)*W(NB) + C(SVM)*W(SVM) \qquad (19)$$

Where, C(I),& W(I) represents output class by the classifier, and weight of the classifier respectively. The weight is evaluated using equation 20,

$$W(I) = \frac{N(Test)_{correct}}{N(Test)_{total}} \qquad (20)$$

Where, N_correct & N_total represents number of correctly classified entries, and total entries used for classification from the testing dataset respectively. In the next section of this text, The effectiveness of this model was evaluated on different datasets, and was compared with various edge cutting models.

COMPARISON AND EVALUATION OF RESULTS

The EFEMS model proposed utilizes a combination of bias field-based segmentation and augmented feature extraction, incorporating Variance-based feature selection for effectively representing input images. The proposed model underwent evaluation across multiple datasets, considering accuracy of classification (A), precision of classification (P), recall of classification (R), and the required delay for classification (D). The following sources provided the datasets that were downloaded for this study,

- Kaggle Brain Tumour Dataset, downloaded from https://www.kaggle.com/datasets/navoneel/brain-mri-images-for-brain-tumor-detection

- Figshare T1-weighted contrast-enhanced images with three kinds of brain tumour, available at https://figshare.com/articles/dataset/brain_tumor_dataset/1512427

- Open fMRI dataset, available at https://openfmri.org/dataset/ds000002/

To form an aggregated set of 10,000 images, all these datasets were combined, and then divided into 60:20:20 ratios. Specifically, 60% of the images were allocated for training, while 20% each were reserved for testing and validation purposes. Using this strategy, classification

metrics were compared with SNN [6], 3D CNN [8], and FR CSI [14] for all images. The classification accuracy can be observed in table 1 as follows,

Table 1. Average classification accuracy for multiple images

Num. Images	A (%) SNN [6]	A (%) 3D CNN [8]	A (%) FR CSI [14]	A (%) EFE MS
500	96.50	91.50	93.83	97.58
1000	96.65	91.60	93.96	97.72
1500	96.74	91.80	94.08	97.84
2000	96.83	91.90	94.19	97.96
2500	96.91	92.05	94.34	98.12
3000	97.15	92.19	94.50	98.28
3500	97.26	92.33	94.61	98.39
4000	97.34	92.47	94.71	98.49
4500	97.35	92.61	94.78	98.57
5000	97.36	92.75	94.86	98.65
5500	97.39	92.89	94.94	98.73
6000	97.41	93.03	95.02	98.82
6500	97.43	93.17	95.10	98.90
7000	97.45	93.31	95.19	98.99
7500	97.49	93.45	95.28	99.09
8000	97.54	93.59	95.37	99.18
8500	97.59	93.73	95.46	99.27
9000	97.61	93.87	95.55	99.36
9500	97.65	94.01	95.64	99.46
10000	97.71	94.15	95.73	99.56
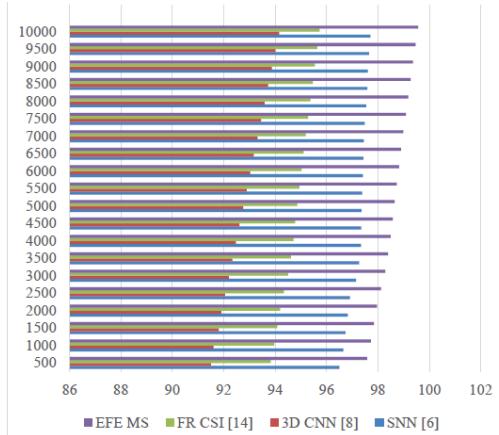
Fig. 3. Average accuracy of classification for multiple images

From this assessment and Figure 3, it's evident that the proposed model outperforms SNN [6] by 2.3%, 3D CNN [8] by 5.2%, and FR CSI [14] by 4.6% in terms of accuracy across different datasets. This improvement is attributed to the utilization of multiple feature extraction and selection models, which enhance the representation of images. Similarly, the precision of classification can be observed in Table 2 as follows.

Table 2. Average precision of classification for multiple images

Num. Images	P (%) SNN [6]	P (%) 3D CNN [8]	P (%) FR CSI [14]	P (%) EFE MS
500	94.32	91.70	87.46	95.39
1000	94.42	91.84	87.57	95.52
1500	94.54	91.99	87.70	95.66
2000	94.67	92.12	87.82	95.79
2500	94.80	92.26	87.94	95.92
3000	94.90	92.40	88.05	96.03
3500	94.95	92.54	88.13	96.12
4000	94.99	92.68	88.21	96.20
4500	95.00	92.82	88.28	96.28
5000	95.02	92.96	88.36	96.37
5500	95.04	93.10	88.43	96.45
6000	95.07	93.24	88.51	96.54
6500	95.10	93.38	88.59	96.63
7000	95.14	93.52	88.67	96.72
7500	95.18	93.66	88.76	96.81
8000	95.22	93.80	88.84	96.90
8500	95.26	93.94	88.93	96.99
9000	95.30	94.08	89.02	97.09
9500	95.37	94.22	89.12	97.20
10000	95.44	94.36	89.21	97.31

From this assessment and Figure 4, it's apparent that the proposed model outperforms SNN [6] by 1.9%, 3D CNN [8] by 2.85%, and FR CSI [14] by 8.3% in terms of precision across different datasets.
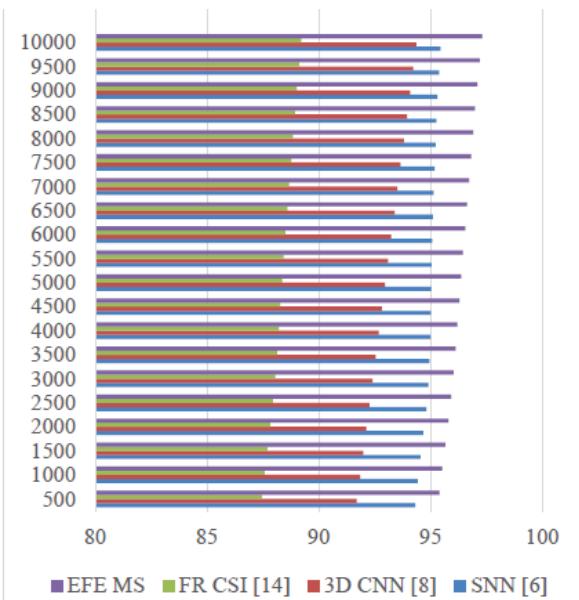
Fig. 4. Average precision of classification for multiple images

This improvement can be attributed by utilization of multiple feature extraction & selection models along with bias field for segmentation, which assist in better representation of images. Similarly, recall of classification can be observed in table 3 as follows,

Table 3. Average recall of classification for multiple images

Num. Images	R (%) SNN [6]	R (%) 3D CNN [8]	R (%) FR CSI [14]	R (%) EFE MS
500	96.37	92.53	91.56	97.46
1000	96.50	92.65	91.69	97.60
1500	96.61	92.82	91.81	97.73
2000	96.72	92.94	91.92	97.86
2500	96.82	93.09	92.06	98.00
3000	97.00	93.23	92.19	98.13
3500	97.08	93.37	92.29	98.24
4000	97.13	93.51	92.38	98.33
4500	97.15	93.65	92.46	98.41
5000	97.16	93.79	92.53	98.49
5500	97.19	93.93	92.61	98.58
6000	97.21	94.08	92.69	98.66
6500	97.24	94.22	92.77	98.75
7000	97.27	94.36	92.86	98.84

7500	97.31	94.50	92.95	98.94
8000	97.35	94.64	93.04	99.03
8500	97.40	94.78	93.12	99.12
9000	97.43	94.92	93.21	99.22
9500	97.48	95.07	93.31	99.32
10000	97.55	95.21	93.41	99.43

|				
5000	10.46	20.50	24.25	6.49
5500	10.38	20.08	24.01	6.24
6000	10.31	19.65	23.78	5.98
6500	10.23	19.23	23.53	5.72
7000	10.14	18.81	23.28	5.45
7500	10.02	18.39	23.01	5.17
8000	9.89	17.97	22.74	4.88
8500	9.75	17.55	22.49	4.61
9000	9.67	17.13	22.22	4.32
9500	9.50	16.70	21.93	4.01
10000	9.30	16.28	21.64	3.70

Fig. 5. Average recall of classification for multiple images

From this evaluation and Figure 5, it's evident that the proposed model surpasses SNN [6] by 1.85%, 3D CNN [8] by 4.1%, and FR CSI [14] by 5.9% in terms of recall across different datasets. This enhancement is attributed to the utilization of multiple feature extraction and selection models, which improve the representation of images. Similarly, the delay required for classification can be observed in Table 4 as follows.

Table 4. Average delay needed to classify multiple image

Num. Images	D (ms) SNN [6]	D (ms) 3D CNN [8]	D (ms) FR CSI [14]	D (ms) EFE MS
500	12.80	24.27	27.16	9.56
1000	12.43	23.92	26.78	9.15
1500	12.11	23.39	26.41	8.77
2000	11.78	23.04	26.07	8.39
2500	11.47	22.60	25.66	7.96
3000	10.95	22.18	25.27	7.56
3500	10.71	21.76	24.96	7.24
4000	10.54	21.34	24.71	6.98
4500	10.50	20.92	24.48	6.74

Fig. 6. Average delay needed to classify multiple images

From this evaluation and Figure 6, it's apparent that the proposed model demonstrates significant efficiency gains, being 16.5% faster than SNN [6], 23.8% faster than 3D CNN [8], and 28.9% faster than FR CSI [14] in terms of delay across different datasets. This notable improvement can be attributed to the implementation of highly efficient feature selection models, which not only enhance image representation but also contribute to faster classification results. Consequently, the proposed model stands out as highly efficient and suitable for the classification and post-processing of various fMRI image sets.

CONCLUSION & FUTURE SCOPE

The model proposed uses a combination of bias fields with FCM to form clusters that represent Grey Matter, while Matter, and Brain fluid regions. Each of these regions are further processed using an augmented feature extraction layer, which combines Colour Map, Edge

Map, Texture Map, and Convolutional Map to form a SFV (Super Feature Vector), which has redundancies at feature-level. To reduce these redundancies, a Maximal Variance layer is deployed, that evaluates inter-class variance levels to identify features that can be used for high-efficiency classification & post-processing applications. The proposed model also demonstrates design of a SVM & NB based classifier that combines both the models via augmented learning to classify between tumorous and non-tumorous fMRI images. Due to this combination, it was noticed that the proposed model was 2.3% accurate than SNN [6], 5.2% accurate than 3D CNN [8], 4.6% accurate than FR CSI [14], 1.9% precise than SNN [6], 2.85% precise than 3D CNN [8], 8.3% precise than FR CSI [14], and showcased 1.85% better performance than SNN [6], 4.1% better than 3D CNN [8], and 5.9% better than FR CSI [14] in terms of recall for different datasets. This performance improvement was obtained due to combination of different feature extraction techniques, and performing feature selection via variance maximization, which assisted in high-efficiency representation for different image types. As a result of utilizing feature redundancy reduction, the proposed model was 16.5% faster than SNN [6], 23.8% faster than 3D CNN [8], and 28.9% faster than FR CSI [14], This characteristic renders it valuable for diverse real-time classification applications. In the future, researchers could integrate advanced deep learning models such as Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), and Q-Learning to enhance classification performance even further. Moreover, the proposed model must be validated on other fMRI datasets, and their performance must be compared in terms of other metrics for better evaluation under different deployment scenarios.

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Plant Disease Classification using Hybrid Deep Learning and ResNet50V2 Model

Jayesh K. Kokate
Associate Professor
Department of Electronics & Telecommunication
Mauli Group of Institution's, College of Engineering and Technology
Shegaon, Maharashtra
✉ jkokate18@gmail.com

ABSTRACT

India is an agricultural nation, and the majority of its citizens make their living from it. The traditional methods are very time-consuming and inefficient for detecting crop diseases. Numerous biotic and abiotic diseases have an impact on agricultural productivity. Early detection of crop disease is crucial to preventing yield declines. Conventional disease detection techniques depend on the ability to visually verify, which can be labor-intensive and frequently impractical for large-scale farming. An accurate and practical solution to this issue can now be found in automatic disease detection systems. This paper presents a comparative study of plant disease classification using the hybrid deep learning model and the ResNet50V2 model. Experimental results demonstrated that the ResNet50V2 model achieved an accuracy of 96%, and hybrid deep learning model achieved an accuracy of 94% for the classification of plant diseases. The findings highlight the effectiveness of deep learning-based approaches for accurate and efficient plant disease detection.

KEYWORDS: *Agriculture, Automatic plant disease detection, Classification, Hybrid deep learning, ResNet50V2.*

INTRODUCTION

Plant diseases reduce agricultural yield and increase food safety risks. Prompt detection and efficient management of these illnesses are essential to limit their spread and minimize loss. Conventional disease detection methods rely on the visual inspection, which is labour-intensive and is often impractical for large-scale agriculture. Recent advances in artificial intelligence techniques facilitated automatic disease detection systems to provide a precise and effective solution to this problem. Various factors like pathogens, environmental factors (EF), abiotic factors, genetic factors, poor cultural practices, insect and animal pests, human activities, etc. contributes reduction in the productivity of plants. Successful strategies for recognizing and classifying diseases using leaf imaging are essential to allow timely steps in and lower the risk of disease transmission. The implementation of computational software can enhance the efficacy and precision of quality assurance techniques. According to Shukla et al. (2022), in India 5 million tons per year of crop yield is infected by the fungal diseases [1]. Deep learning plays a vital role in the early plant disease detection. The research is conducted with the objective of designing the automatic leaf classification system using the ResNet50V2 model and hybrid deep learning model.

LITERATURE REVIEW

Upadhyay et al. (2025) presented advancements in plant disease diagnosis from machine learning methods to advanced deep learning methods. CNN were identified as the most widely used model for plant disease diagnosis [2].

Hemanth et al. (2025) proposed an Android application for illness detection of plants. In this approach, users have to take real-time images of plants, and if the illness is detected, then the application suggests appropriate treatment [3].

A system for plant disease detection based on a two-step convolutional neural network was presented by

Lumbantoruan et al. (2025) achieving an accuracy of 95% [4].

A MobileNetV3 based model for disease detection in jasmine plants was presented by Shwetha et al. (2024). They achieved accuracies in the range of 94% to 96% for real-world testing [5].

Indira and Mallika (2024) developed a CNN model with different convolution layers, MobileNet and AlexNet, to classify twenty-six plant diseases in tomato, potato, bell pepper, rice, sorghum, and apple. The model achieved 84.24% accuracy with CNN model, 91.19% accuracy with the pretrained AlexNet model, and 97.33% accuracy with the MobileNet model [6].

Santoshi et al. (2024) presented a web application based on CNN for detection of disease. The application was designed in such a way that it not only predicts the disease but also suggests preventive methods [7].

Pipawala and Choudhary (2024) presented VGG16 based model for plant disease detection and classification of tomatoes achieving accuracy over 92% [8].

Prashanthi et al. (2024) developed a deep learning model using Vision Transformers and Explainable Artificial Intelligence (XAI) properties to efficiently identify and categorize leaf diseases. The model achieved a test accuracy of 92.33%, a training accuracy of 95.22%, and a validation accuracy of 96.19% [9].

Kunduracıoğlu and Paçal (2023) presented a deep learning-based disease detection model for sugarcane using 6,748 images of 11 different disease classes. EfficientNet-B6 (93.39%) and InceptionV4 (93.10%) models yielded the highest accuracies [10].

Lathamaheswari and Jebathangam (2023) investigated a number of methods and approaches for using image-based algorithms to classify leaf diseases [11].

Shafik et al. (2023) reviewed 176 research papers. Crops such as maize, rice, tomatoes, grapes, apples, potatoes, cucumbers, and wheat were examined using vision-centered and hyperspectral imaging methods. Experimental results showed that logistic regression (LR) and support vector machine (SVM) classifiers achieved higher accuracy than conventional classifiers [12].

Gurunathan et al. (2023) proposed an image processing for detection of plant disease using a KNN classifier. Preprocessing images, contrast enhancement, RGB conversion, feature extraction, segmentation, and K-nearest neighbors classification were the involved steps in the process of diagnosing an illness of a plant [13].

Sharia et al. (2023) presented the classification of fifteen different disease categories, including healthy leaves, using the EfficientNet-B1 architecture. The model achieved accuracy, recall, F1-score, and precision consistently surpassing 98% and occasionally 99% [14].

Dixit & Verma (2023) proposed a hybrid deep learning model to provide results for paddy disease detection and identification that are more reliable. The model attained 85% validation accuracy and 95% training accuracy with the DST model for rice plants [15].

Hari and Singh (2023) proposed a CNN based accurate and lightweight deep learning model for detecting sick leaves in mango fruit, banana, and guava harvests. The model achieved 99.14% accuracy using 101,000 parameters [16].

Ramanjot et al. (2023) reviewed 75 papers and suggested integration of drones, mobile technology, and artificial intelligence in the future to detect the plant diseases [17].

Pendyala and Jayachitra (2023) focused on integrating transfer learning algorithms into practice for feature extraction [18].

DATASET

Data used in this study were obtained from the online database Kaggle and Plant Village, which have a combination of healthy and unhealthy leaf images, along with samples collected from the field. The dataset includes one healthy class and 21,846 photos that represent 14 different plant disease categories that affect tomatoes, potatoes, and peppers. The dataset was divided into 80% and 20% for training and testing respectively. Details of the dataset used in this study, like Class, Plant Name, Disease Type and Image Count are presented in table 1.

Table 1: Leaf Dataset Details

class	Plant Name	Disease Type	Image count
0	Pepper bell Plant	Bacterial spot	1301
1	Pepper bell Plant	healthy	1478
2	Potato Plant	Early blight	1000
3	Potato Plant	healthy	608
4	Potato Plant	Late blight	1000
5	Tomato Plant	Bacterial spot	2127
6	Tomato Plant	Early blight	1000
7	Tomato Plant	healthy	1591
8	Tomato Plant	Late blight	1909
9	Tomato Plant	Leaf Mold	952
10	Tomato Plant	Mosaic virus	821
11	Tomato Plant	Septoria leaf spot	1771
12	Tomato Plant	Spider mites Two spotted spider mite	1676
13	Tomato Plant	Target Spot	1404
14	Tomato Plant	Yellow leaf Curl Virus	3208

METHODOLOGY

Figure 1 illustrates the workflow of the model training process. It included several steps from collecting a large dataset of healthy and unhealthy leaf images to preprocessing, which involves data cleaning, removing duplicates, and addressing any missing or incorrect information. The preprocessed images are divided into training and testing set. The training dataset undergoes data augmentation. The data augmentation uses techniques such as image rotation, scaling, and flipping. The next stage involves applying training and validation sets of data for a predefined number of epochs, or iterations. The model goes through optimization processes throughout the training phase with the goal of increasing its accuracy and reducing its loss. One

often used method is backpropagation, which involves adjusting the model's weights to lessen the difference between the predicted and actual outputs. Finally, after training, the model saved in an HDF5 file (.hdf5 or .h5).
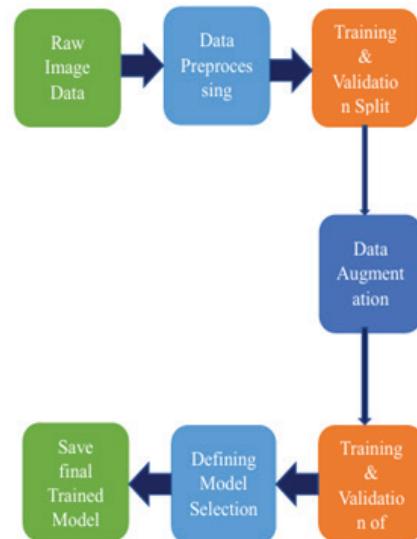
Fig. 1: Model Training Flow

Figure 2 outlines the training model deployment flow. The leaf image is provided as input and preprocessing is performed includes processes like removing noise, resizing the image, etc. The trained model is loaded from the disk and applied to preprocessed image. The trained model predicts whether the input leaf has disease or not. The predicted result interpreted and mapped to a specific disease class, yielding the final output.
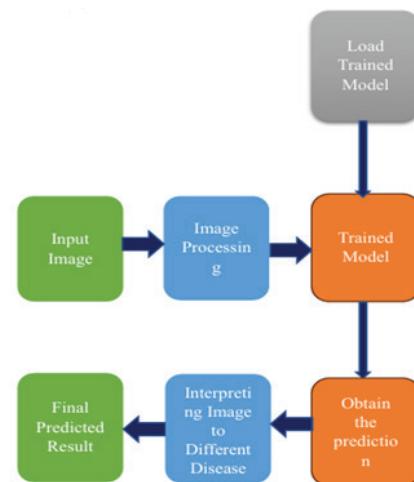
Fig. 2: Model Training Deployment Flow

Hybrid Deep Learning Model based on VGG16

The hybrid deep learning model was developed using VGG16 architecture. The VGG16 architecture is a convolutional neural network that has been pre-trained and consist of 16 layers. The hybrid deep learning model consists of 3 layers. VGG16, a Flatten, and two Dense layers layer as shown in figure 3.

Fig. 3: Hybrid deep learning model layer connectivity

RESULTS & DISCUSSION

Classification Report

The classicisation report for the hybrid deep learning model and the ResNet50V2 model is as shown in table 2. Precision measures the correctly identified positive instances out of all instances that were predicted as positive. Recall refers to the proportion of actual positive cases for a given class that are correctly identified as positive. The F1-score, which is a composite of the precision and recall metrics, has a range of 0 to 1. The provision of support for datasets is achieved through the utilization of class instances.

The hybrid deep learning model achieved classification accuracy of 94%. The model exhibits consistent performance across categories, as evidenced by the macro-average and weighted-average values of precision, recall, and F1-score, which are all 0.94. The ResNet50V2 model achieved classification accuracy of 96. The model exhibits uniform performance across categories, as evidenced by the macro-average and weighted-average values of precision, recall, and F1-score, which are all 0.96.

Table 2: Classification report for the Hybrid Deep Learning and ResNet 50V Model

Class	Hybrid Deep Learning Model				ResNet50V2 Model			
	Precision	Recall	F1 Score	Support	Precision	Recall	F1 Score	Support
0	0.95	0.93	0.94	260.00	0.94	0.84	0.89	196
1	0.98	0.97	0.97	295.00	0.95	0.97	0.96	905
2	0.96	1.00	0.98	200.00	0.85	0.98	0.91	616
3	0.96	0.91	0.93	121.00	0.93	0.96	0.94	613
4	0.97	0.85	0.91	200.00	0.81	0.82	0.85	91
5	0.94	0.97	0.95	425.00	0.98	0.97	0.97	1252
6	0.84	0.91	0.87	200.00	0.97	0.95	0.96	617
7	0.98	1.00	0.99	318.00	0.99	0.97	0.98	1133
8	0.94	0.88	0.91	381.00	0.94	0.95	0.94	563
9	0.94	0.92	0.93	190.00	0.98	0.97	0.97	1067
10	0.90	0.94	0.92	354.00	0.98	0.98	0.98	980
11	0.91	0.94	0.92	335.00	0.98	0.99	0.98	848
12	0.93	0.88	0.90	280.00	0.95	0.99	0.98	1963
13	0.98	0.96	0.97	164.00	0.91	0.96	0.94	216
14	0.96	0.98	0.97	641.00	0.97	0.99	0.98	910
accuracy			0.94	4364.00			0.96	11970
macro avg	0.94	0.94	0.94	4364.00	0.96	0.96	0.96	11970
weighted avg	0.94	0.94	0.94	4364.00	0.96	0.97	0.96	11970

Confusion Matrix

The confusion matrix reflects model working well for most classes, with high numbers of correctly classified instances. The confusion matrix for hybrid deep learning model is as shown in figure 4, which shows the model struggles for some classes, such as class 1 and class 10, where there are relatively high numbers of incorrectly classified instances.

The confusion matrix for ResNet50V2 models is as illustrated in figure 5. The initial row in the confusion matrix signifies the actual category 'Pepper_bell_Bacterial_spot', and the model predicted it correctly 188 times and misclassified it as 'Pepper_bell_healthy' 8 times.
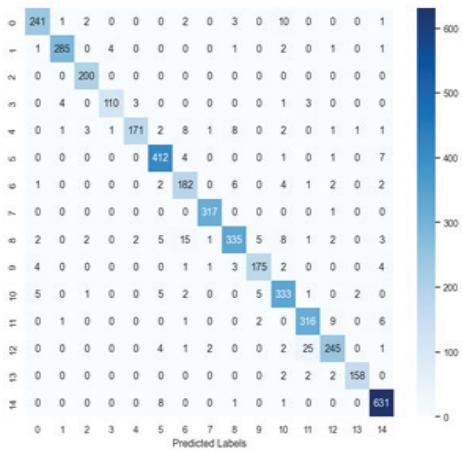
Fig. 4: Confusion matrix Hybrid deep learning
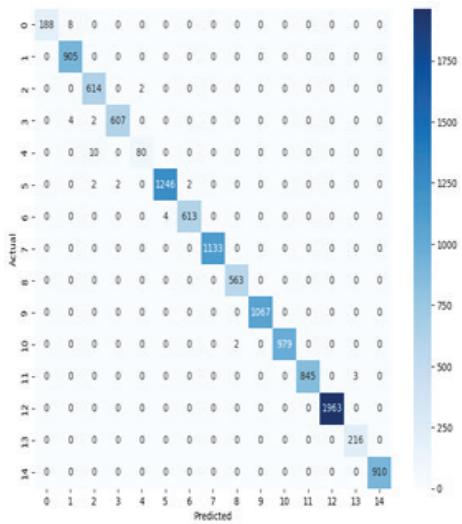
Fig. 5: Confusion matrix ResNet 50V2

Accuracy and Loss Graph

Figures 6 & 7 show the accuracy plot and loss plot for hybrid deep learning model respectively. Figures 8 & 9 show the accuracy plot and loss plot for ResNet50V2 model respectively.

Fig. 6: Accuracy Plot of Hybrid Deep Learning Model

Figures 6 and 8 demonstrate that the model achieves a steady increase in accuracy over time, indicating that it is performing well on the training data.

Figures 7 and 9 demonstrate that the model validation loss has a decreasing trend, indicating that the model is enhancing on the validation set gradually over time.
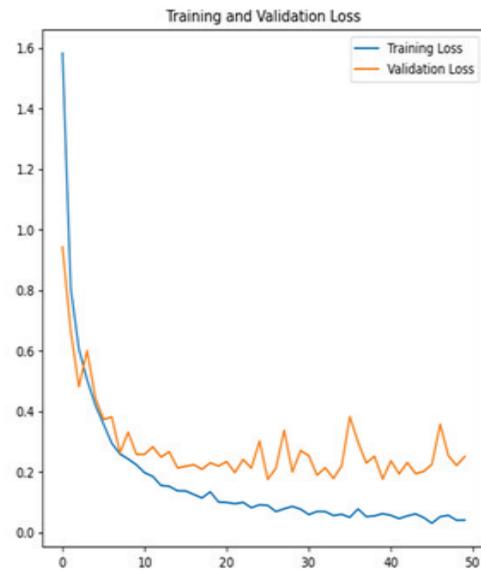
Fig. 7: Loss Plot of Hybrid Deep Learning Model
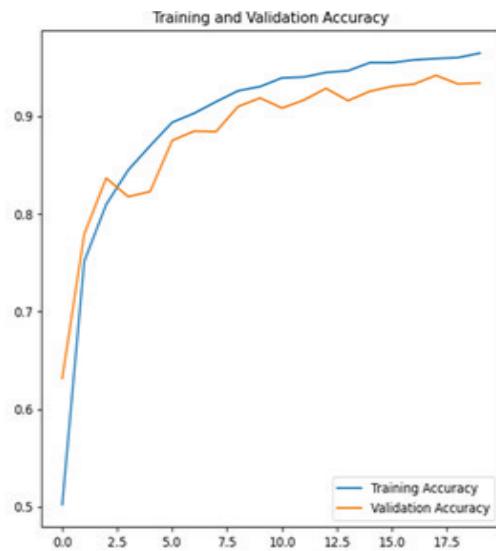
Fig. 8: Accuracy plot of ResNet50V2 Model
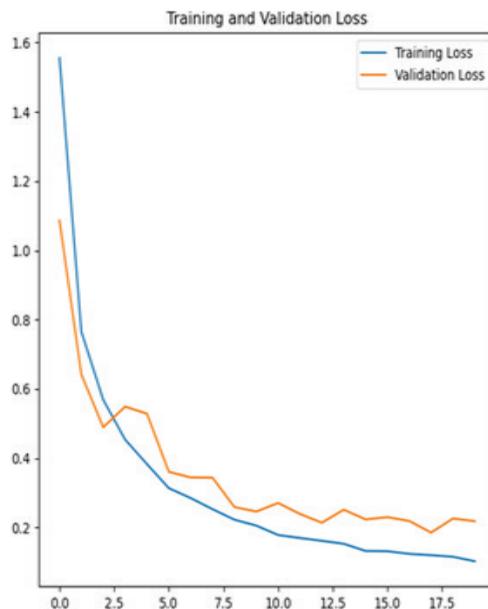
Fig. 9: Loss plot ResNet50V2 Mode

CONCLUSION & FUTURE SCOPE

The ResNet50V2 model achieved more accuracy than the hybrid deep learning model. The model performance varied across disease classes, with some conditions better detected by the hybrid model and others by ResNet50V2. Overall, ResNet50V2 outperformed the hybrid deep learning model, with statistically significant improvements confirmed by pairwise t-tests ($p = 0.001$) and Bonferroni post-hoc tests (adjusted p $= 0.03$). Per-class analysis highlighted that the hybrid model remained more effective for certain diseases, underscoring the importance of considering class-specific performance when selecting models for multi-disease classification. To improve the hybrid deep learning model class 1 and class 10 discrimination, oversampling or data augmentation could be used to train the model. A hybrid deep learning model can be created by integrating different neural network architectures, including but not limited to CNNs, RNNs, and deep belief networks (DBNs). The findings suggest that the ResNet50V2 model is proficient in the classification of tomato plant diseases, and it can furnish precise prognostications with a considerable level of assurance. To achieve more accuracy, it is suggested to implement recent models like EfficientNet, Vision Transformers, YOLO, and MobileNet for classification of plant disease.

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Inverted L-Shaped Dual Band Antenna for Energy Harvesting

Ramalakshmi P.
Assistant Professor
Dept. of Electronics and Communication Engineering
Kamaraj College of Engineering and Technology
Tamil Nadu
✉ ramalakshmigold@gmail.com

N. M. Mary Sindhuja
Associate Professor
Dept. of Electronics and Communication Engineering
Kamaraj College of Engineering and Technology
Tamil Nadu
✉ mary.sindhuja@gmail.com

R. Sureshbabu
Professor
Dept. of Electronics and Communication Engineering
Kamaraj College of Engineering and Technology
Tamil Nadu
✉ rsbmemba@gmail.com

Muthumari P.
Professor
Dept. of Electronics and Communication Engineering
Kamaraj College of Engineering and Technology
Tamil Nadu
✉ Assistant Professor

ABSTRACT

This work represents a dual-band microstrip-fed patch antenna for effective energy harvesting, in which the radiating structure is formed with a pair of inverted L-shaped patches, and the ground plane is modified to a + shape. Both the radiating patch and modified ground plane are perfect electric conductors. The patch is printed on a readily available Epoxy Glass (FR-4) substrate with a thickness of 1.6 mm, relative permittivity 4.4, and loss tangent 0.0024. People are surrounded by radio waves just like the light around them. Our phones, laptops, routers, satellites, antennas almost everything around the world emits radio waves. With increasing pollution, it is necessary to use a greener way to harvest, conserve, and use energy. The readily available RF (Radio Frequency) waves are the best way to do it. Though the output voltage is not enormous but it can still be amplified and used for several applications for daily use. It might also be helpful when the renewable sources are unavailable. This paper focuses on an RF energy harvesting system using a dual-band microstrip patch antenna that can be applied to various wireless sensor network applications (WSNA). These include different monitoring, sensing, and detection systems. The proposed Micro strip patch antenna (MPA) design is capable of generating two distinct operating bands with 10-dB return loss as follows: 3.34–3.54 GHz and 4.90–6.26 GHz with adequate bandwidth of 200 MHz and 1.36 GHz, respectively. So, there should be effective energy harvesting. The impedance bandwidths are wide enough to cover the required bandwidths of 3.3– 3.5 GHz, 5.15–5.35 GHz, 5.725–5.825 GHz for wireless local area network, 3.3–3.5 GHz for multiple input multiple output, 5.25–5.85 GHz for world-wide interoperability for microwave access, 5.650–5.670 GHz for up links and 5.830–5.850 GHz for down links of Amateur Satellite, and 5.9 GHz wireless access in the vehicular environment (WAVE- IEEE 802.11p).

KEYWORDS: *Micro-strip patch antenna, Defected ground structure, Dual band, Inverted L-shaped patches, Wireless sensor networks.*

INTRODUCTION

The process of extracting energy from the ambient environment to generate electricity is termed energy harvesting or energy scavenging. The design of a micro strip patch antenna (MPA) is one of the most exciting developments in electromagnetic history because of its salient features which are not commonly exhibited in other antenna configurations including ease of fabrication, good radiation control, low cost of production, low profile, lightweight, simple, and inexpensive to fabricate using modern day printed circuit board technology, compatible with microwave and millimeter-wave integrated circuits, and ability to conform to planar and non-planar surfaces [13].

The performance and operation of an MPA are driven mainly by the geometry of the printed patch and the material characteristics of the substrate onto which the antenna is printed. A modern antenna requires not only the function of providing a dual or multi-band operation but also a simple structure, compact size, high gain, and easy integration with the system circuit. Dual-band multi frequency systems combining various IEEE 802.11 wireless standards are becoming more attractive [1] & [2]. Furthermore, the gains of reported single-fed dual-band antennas are lower than 6 dBi, and faced difficulty in meeting the requirements for applications such as long-range communications or point-to-point communications devices running on a battery [3] & [4]. To achieve a high gain for the purpose of energy harvesting, a high-gain dual-band MPA with a pair of inverted L-shaped patches printed on a FR-4 substrate with defected ground structure (DGS) is presented for effective energy harvesting. The constructed antenna has two inverted L-shaped patches separated by a small gap 'g'. These design skills are introduced to approach the excitation of dual-resonant modes because of two current paths accompanied by stable radiation characteristics over the entire operating band. The performance of the proposed antenna is simulated using commercial software HFSS (High Frequency Structure Simulator). From the measured results, the proposed antenna shows two operating frequency bands with 10-dB return loss as follows: 3.34–3.54 GHz and 4.90–6.26 GHz, with adequate bandwidths of 200 MHz and 1.36 GHz, respectively. The obtained bandwidth of 1.36 GHz (4.90–6.26 GHz) for the upper resonating band is quite higher than the existing dual/multiband antenna designs, and all this is because of the defected structure embedded in the ground plane, which makes it suitable to be used in various wireless communication systems as well as for energy harvesting. Both the inverted L-shaped patches and the + shaped ground plane play a vital role in rejecting the interference in desired frequency bands. Among the available ambient energy sources, RF energy has greatly grown due to the preponderance of wireless signals, such as mobile base stations and Wi-Fi networks, radio and TV transmitters, microwave radios, and mobile phones [5] & [6].

In this paper, the author focus on ambient RF energy harvesting technology that will have an important potential to impact sensors located in harsh environments or remote places, where other energy sources as wind or solar sources, are impractical. This technique attracted significant attention and multiple RF energy harvesting systems including receiving antennas, matching circuits, and rectifying circuits, which have been developed for the green supply of low consumption electronics [7] & [14]. The comprises of receiving antenna along with a circuit capable of converting RF signals into DC voltage. The antenna picks up the RF power sent out by the network controller, the impedance matching network ensures maximum power transfer in the system, and the rectifier converts the RF power to a DC voltage.

The power harvested at a distance of over 6.3 km from the TV broadcast source is successfully used to power and sustain a 16-bit embedded microcontroller for sensing and machine-to-machine applications without the use of batteries [8]. The proposed system can achieve 15% more efficiency compared to a single-frequency RF harvester. The measured received power from harvesting RF energy at three bands simultaneously is 6.6 times more than that at a single 900 MHz band [9]. In this paper, a novel dual-band antenna is designed operating at Wi-Fi bands 3.48 GHz and 5.25 GHz and is presented in order to successfully harvest RF power.

LITERATURE REVIEW

From basic single-band antenna systems to sophisticated dual-band rectenna designs, the given literature review clearly illustrates the development of radio frequency (RF) energy harvesting. For low-power applications like Wireless Sensor Networks (WSNs), early research, including the work by Thakar et al. [9], concentrated on proving the feasibility of capturing ambient RF energy using simple structures like monopole antennas. By maximizing single-band rectenna efficiency for important communication bands, later research improved this foundation. For example, Taryana et al. [10] set a standard for single-frequency performance by concentrating on a rectifying antenna design for wireless power transfer at the 2.45 GHz.

In a similar vein, Kumar and Nakkeeran [11] shown the advantages of customized antenna shape and differential feed techniques for enhanced gain and efficiency at a particular frequency by introducing a high-gain differential microstrip antenna aimed at the

GSM900 band. The development of the dual-band energy harvesting antenna, as demonstrated by the study of Sharma et al. [12], is ultimately the result of this body of work. By simultaneously capturing energy from two different ambient sources, aggregating the harvested power, and providing a more reliable and consistent energy supply for contemporary wireless applications, the dual-band approach overcomes the inherent challenge of low-power density and is essential for achieving optimal RF energy harvesting. Triple-band designs have been introduced to further aggregate power and increase reliability in RF energy harvesting devices. A big advancement has been made with the work by Chandravansh et al. [14], which describes a Triple Band Differential Rectenna that can simultaneously collect energy from three key ambient communication bands: WiMAX (3.3-3.8 GHz), WLAN/Wi-Fi (2.4-2.48 GHz), and UMTS (2.1 GHz). By enhancing the rectifier circuit using interdigital capacitors, this design not only validates the benefits of multiband harvesting but also revitalizes the differential feeding strategy, reaching a high peak RF-to-DC conversion efficiency of 68%. Concurrently, the pursuit of small, multi-band antennas is a crucial prerequisite for all contemporary RF fields. For example, Sengar and Malik [13] proposed a compact tri-band microstrip patch antenna operating at substantially higher frequencies (about 10 GHz, 28 GHz, and 38 GHz) to address the problem of high data rate needs in 5G millimeter wave (mm Wave) applications. This dual focus shows that the creation of complex multi-frequency antenna geometries is still a crucial goal in contemporary antenna engineering, whether for effective energy capture in ambient low-power environments or for compact, fast connectivity in emerging mm Wave spectrums [16],[17].

PROPOSED ANTENNA DESIGN

The MPA consists of a radiating patch on one side of a dielectric substrate, which has a ground plane on the other side. Dielectric constant of the substrate (fir) is typically in the range 2.2 < fir < 12. The radiating patch and the feed lines are usually photoetched on the dielectric substrate. MPAs radiate primarily because of the fringing fields between the patch edge and the ground plane. In our present design structure, the antenna is etched on both sides of the FR-4 substrate

with a relative dielectric constant of 4.4, thickness 1.6 mm, loss tangent 0.0024, and a total area Ls x Ws 70 x 60mm2. Also,the substrate used has a metal thickness of 0.07mm.

Dimensions of the proposed antenna

Table 1: Parameters of proposed MPA

Parameters	Unit (mm)
W_s	60
L_s	70
L_1	11.7
L_2	33.5
L_3	5
W_1	23
W_2	3
L_{g1}	8
W_{g1}	31
g	2
d	2

This symmetrical dual-inverted L-shaped patch antenna design is widely used in wideband antennas or in MIMO (Multiple-Input Multiple-Output) systems because of their compactness and ease of tuning. The substrate has a length and width of Ws = 60 mm and Ls = 70 mm, resulting in a total area of 4,200 mm². The design makes use of a center-line symmetry concept, which plays a vital role in ensuring a steady pattern of radiation and equal behavior of the inverted L-patches. The "Inverted L" shape is a conventional way of miniaturizing a resonating patch. The radiating part is segmented by the length (L_1 = 11.7 mm) and width (W1 = 23 mm). The difference in the value of the width (W1), being considerably larger than the length (L_1), indicates the involvement of the wider part in processing the higher-frequency bands or the bandwidths. The smaller part of the radiating unit has a length of L_2 (33.5 mm) and a width of d (2 mm). Since L_2, L_1, the part behaves like an inductive loading part that enhances the electrical length of the antenna. This enables the antenna to resonate at a lower frequency without raising the Ws and/or Ls physically. The small distance between the two symmetrical patches is a critical parameter for tuning.
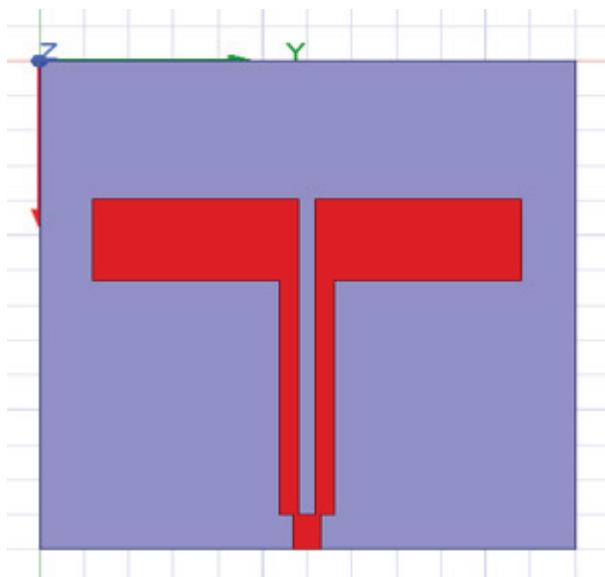
Fig. 1. Inverted L-shaped MPA
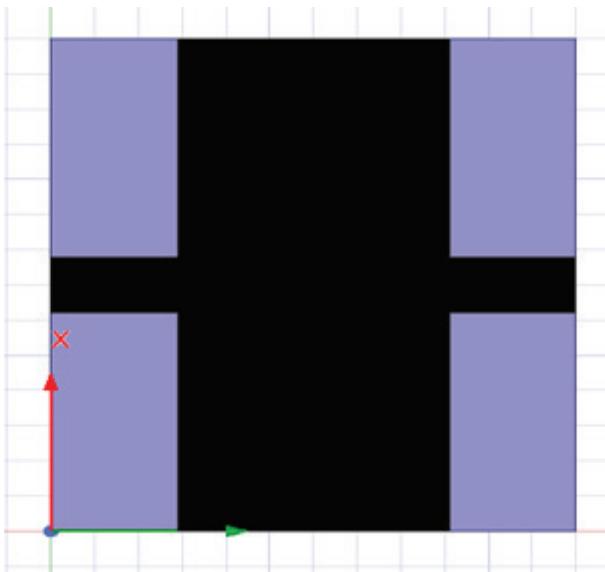
Fig. 2. Defected Ground Structure

A 2 mm separation between the two patches indicates strong coupling between the two patches. This can be explored for bandwidth enhancement by integrating two resonances into one or for implementing a differential-fed configuration. The length Lg1 = 8 mm and width Wg1 = 31 mm may specify a partial ground plane or "Defected Ground Structure" (DGS). As Lg1 = 8 mm is well below the total length of the substrate, Ls = 70 mm, this geometry specifies a partial ground plane configuration. This is a typical aspect of Ultra-Wideband antennas, which facilitates impedance matching over a much broader frequency band.

For good radiation characteristics, the positions, lengths, and widths of a pair of inverted L-shaped patches and DGS were adjusted carefully. The gap "g" between two inverted L-shaped patches also plays a major role in the successful excitation of two appropriate desired resonating frequency bands. The front and back views of the proposed antenna have been shown in Figures 1 and 2, respectively.

RESULTS AND DISCUSSION

To investigate the performance of the proposed antenna configuration, the simulation software HFSS was used for the required numerical analysis and optimization of geometrical parameters. To simulate the antenna, transient solver was chosen. During simulation, a hexahedral mesh cell with 20 lines per lambda was selected. The geometrical parameters were adjusted carefully after performing a number of experimental iterations by using the option of parameter sweep in the transient solver. Return loss is a convenient way to characterize the input and output signal sources. S_{11} represents how much power is reflected from the antenna. If S_{11} = 0 dB, it shows that all power is reflected from the antenna and nothing is radiated. The proposed configuration results a return loss of -14 dB and -18 dB at two strong resonating frequencies, 3.48 and 5.25 GHz, respectively. The dielectric constant is varied from 4.3 to 4.7. As the frequency increases, the first and the second resonant frequencies are shifted to the left, and the return loss value decreases for the lower band. So, the FR-4 substrate with dielectric constant 4.4 is preferred to cover the WLAN/multiple input multiple output MIMO/WiMAX/AMSAT/WAVE frequency bands. Measured return loss of proposed MPA indicates that the impedance bandwidths of the two distinct operating bands with 10-dB return loss were about 200 MHz (3.34–3.54 GHz) and 1.36 GHz (4.90–6.26 GHz) which are wide enough to cover the required bandwidths of 3.3–3.5, 5.15–5.35, and 5.725–5.825 GHz for WLAN, 3.3–3.5 GHz for MIMO, 5.25–5.85 GHz for WiMAX, 5.650–5.670 GHz for uplinks and 5.830–5.850 GHz for downlinks of AMSAT, and 5.9 GHz WAVE-IEEE 802.11p.
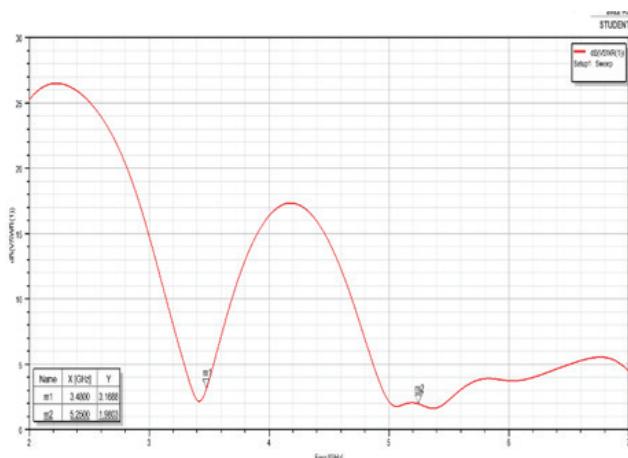
Fig. 3. VSWR plot

A 50-ohm microstrip line is used to feed the patch for impedance matching. The simulated impedance bandwidths of the two distinct operating bands with 10-dB return loss are about 300 MHz (3.32–3.62 GHz) and 2.11 GHz (4.72–6.83 GHz). Another parameter that is used to judge the performance of any antenna is its voltage standing wave ratio (VSWR) measurement. For an ideal match, the VSWR should be 1, which means no reflections.

Table 3: VSWR values with corresponding meaning

VSWR Value	Meaning	Efficiency
1.0	Perfect match (Ideal)	100% power transmitted
1.5	Excellent match	~96% power transmitted
2.0	Acceptable/ Good match	~89% power transmitted
> 3.0	Poor match; significant loss	< 75% power transmitted
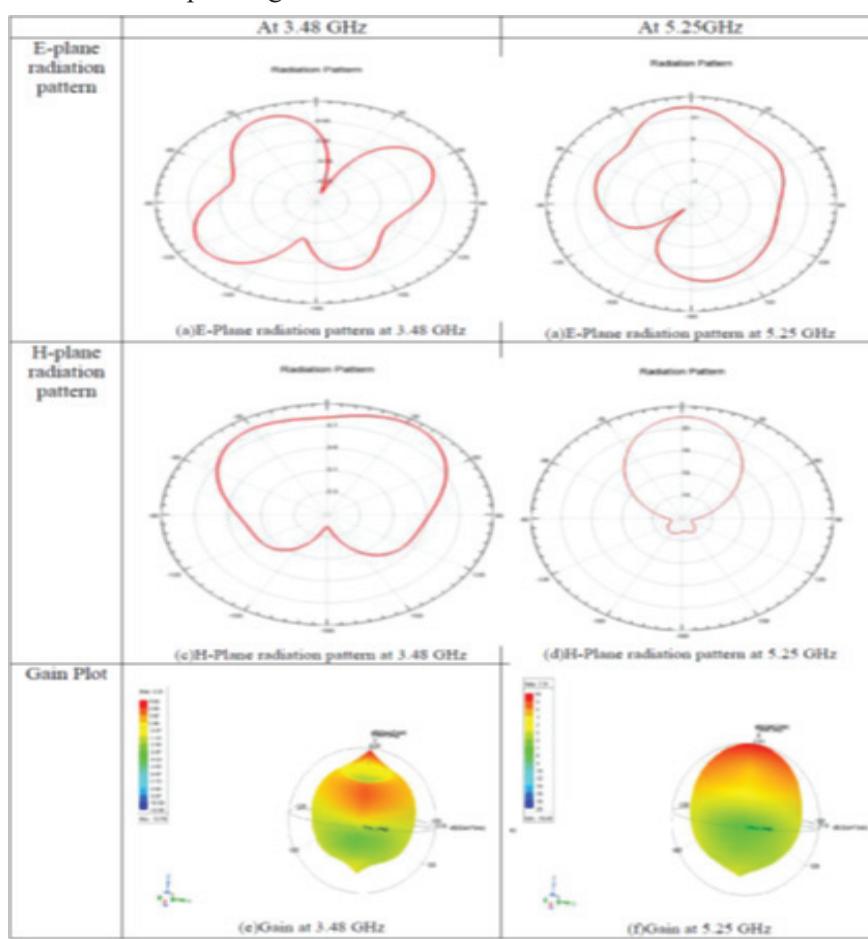
Fig. 4:

In Table 2, the different kinds of VSWR values and its meaning is discussed. In our present design structure, Figure.3, the graph plots the ratio of the maximum to the minimum voltage on the transmission line, that essentially the amount of power accepted by the antenna versus the amount of power reflected back to the source because of the mismatch. The x-axis denotes the Frequency (GHz), and the y-axis denotes the value of the VSWR. For wireless communications, a VSWR ≤ 2 is the accepted standard for a "good match". It indicates that about 90% of the power is coupled to the antenna. Marks m1 and m2 generally go to these dips to measure the value of the frequency and the corresponding VSWR. The lowest point of these dips indicates the resonant frequency of dual L-shaped antennas. At 3.48 GHz (VSWR = 3.1) - Poor match. If the VSWR is 3.1, it indicates that about 26.2% of the power is reflected back to the source, and the rest is radiated. In simple words, it could be on the border of operational frequency range or the point where the L-shaped patches' design for optimum power absorption is not yet achieved. At 5.25 GHz (VSWR = 1.9) - This is a good match. The fact that the measurement is below the standard limit of 2.0 means that the antenna is performing well at this frequency. Also, the reflected wave is only 9.6%, and this means that more than 90% of the energy is being properly delivered to the radiating element. Results to explain more details on the excited resonant modes of the proposed antenna, the simulated current distributions at two upper band resonating at 5.25 GHz and inverted L-shaped patches fed by a microstrip line were responsible for resonance at 3.48 GHz. Further, a gap between a pair of L-shaped patches also play an important role in the sufficient excitation of two resonant modes covering WLAN/ MIMO/ WiMAX/ AMSAT/ WAVE wireless communication standards. [21]&[22].The inverted L-shaped patches fed by a microstrip line were responsible for a resonance at 3.48 GHz, and DGS was responsible for enhancing the impedance bandwidth for the upper band resonating at 5.25 GHz. Further, a perfect gap between a pair of L-shaped patches also plays an important role in the sufficient excitation of two resonant modes. The optimal values of parameters "d" and "Lg1" improved the impedance matching condition, gain, and radiation characteristics of the proposed antenna. Thus, using this specific antenna structure with DGS, a wide operating band with a bandwidth of 24% from 4.90 to 6.26 GHz can be achieved.

Figure.4.(a/b/c/d) depict both the simulated and measured farfield radiation patterns of the proposed antenna in the E-plane and H-plane at the operating frequency bands of 3.48 GHz and 5.25 GHz, respectively. Setting the maxima to 0 dB. Reasonable agreement was found between the simulated and measured values of radiation patterns in two distinct operating frequency bands. Some slight differences between the simulated and measured field patterns may be attributed to alignment error and the possible presence of interference and noise. The E-plane and H-plane co-polarization at 3.48 and 5.25 GHz of the antenna during measurement. Both radiation patterns are observed to have monopole-like pattern.

Figure.4.(e/f), the 3D polar gain plot, the radiation pattern is depicted, with a notable maximum value of 3.25 dB at 3.48 GHz and 7.58 dB at 5.25 GHz are observed. It is noteworthy to mention that while the proposed antenna demonstrates relatively modest gain values, these values remain adequate for facilitating the reception module within a rectenna system to effectively capture ambient energy from its surroundings.

CONCLUSION

In this article, a compact, high-gain, and dual-band MPA is presented, formed with a pair of inverted L-shaped patches and a + shaped ground plane, which is suitable for effective energy harvesting. The frequency bands with return loss below 210 dB cover 3.34–3.54 and 4.90–6.26 GHz with maximum gain values of 3.25 and 7.5 dB in the lower and higher frequency bands, respectively, thus making the proposed antenna appropriate for high-gain applications. The microstrip line feeding method enables direct feeding of the structure without using a complicated impedance transformer wide impedance bandwidth of 24% from 4.90 to 6.26 GHz. Taken as a whole, the performance of the antenna meets the desired requirements in terms of return loss, high gain, and VSWR at the two operating frequencies. From this article, it can be concluded that the performance of the microstrip antenna depends heavily on the dimensions of the inverted L-shaped patches and DGS used. The type, thickness, and dielectric constant of the substrate also contribute to the antenna performance. In this paper, a

novel receiving antenna capable of dual-band operation has been proposed for an RF energy harvesting system. A dual-band with wide bandwidth characteristics is observed, which covers Wi-Fi bands. The results obtained indicate a good overall performance of the proposed antenna at the required frequency range: return loss is better with impedance close to 50Ω and quasi-omnidirectional radiation patterns. Based on the results achieved, the current work aims to improve the antenna performance in order to cover the complete required bandwidths of IEEE 802.11b/g and IEEE 802.11a. Therefore, the challenge is to expand the bandwidth in order to make an antenna for a wideband energy harvesting environment. Table 3 shows the comparison of proposed design with the existing methods.

Table 3: Comparison with existing methods

Feature	Conventional Rectangular Patch	Planar Inverted-F (PIFA)	Proposed Design
Resonance Mechanism	Single λ/2 length.	λ/4 length + shorting pin.	Dual λ/4 branches.
Size Efficiency	Low (Large footprint).	High (Very compact).	Moderate to High.
Tuning Flexibility	Difficult (Global change).	Moderate (Pin location).	Easy(Arm lengths L1/ L2).
VSWR Performance	Typically < 1.5 (Narrow).	Typically < 2.0 (Dual-band).	3.1 (3.48 GHz) & 1.9 (5.25 GHz).
Ground Plane	Full Ground.	Full Ground.	Partial Ground (Lg1=8mm).

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Performance Analysis and Complete Testing Setup of Transmission Line using IoT and ML

Kishor V. Bhadane
Associate Professor
Department of Electrical Engineering
Amrutvahini College of Engineering
Sangamner, Maharashtra
✉ kishor.bhadane@avcoe.org

Supraja Jadhav, Avdhut Bhangare
Akshay Deshmukh
UG Scholars
Department of Electrical Engineering
Amrutvahini College of Engineering
Sangamner, Maharashtra

ABSTRACT

Detection of transmission line fault is significant problem in current context. 80-85% of power system issues and problem in the transmission line happen in this overhead transmission line. The study examines several techniques for managing transmission line faults providing real time solution. The arduino and Internet of Things (IoT) - based software at the centre module will identify the type of fault , its precise location , its current in that line and its fault . This information is send to the control room and will appear on the display and in the software. In doing so, we forecast the transmission lines real time data using machine learning. Machine learning display the power factor, voltage and current.

INTRODUCTION

In power systems reliability and security are the most important requirements. Transmission lines are the backbone of the grid, but many faults are occurs in transmission lines that can disrupt the flow of power Detection and minimizing downtime. This paper is about the hardware modeling of a transmission line to analyze various faults such as symmetrical, unsymmetrical and series fault. Moreover, the model supports all forms of remuneration. In the event of a fault, the system not only identifies which type of fault occurred but also shows where on its network the fault is. This information is then sent in real-time to the power system operator using IoT (Internet of Things) technology, enabling quick responses to minimize downtime and prevent further issues. And by using a capacitor we reduced the impedance of the line. In addition to fault detection, the data collected from this hardware model is used to train a machine-learning model. This model can predict future faults and evaluate the transmission line's performance, similar to how digital twin technology works. By creating a digital replica of the transmission line, the system can simulate and predict issues before they happen, leading to better maintenance and performance management.

LITERATURE SURVEY

"Transmission line Monitoring By Using IOT" Sarthak Sanjeev monitoring the whole transmission line is the primary motive of the paper. They test all the parameters,sag, temperature and wind speed to monitor it .Locate fault in the system with IoT techniques .Forward the data to the operator.

"Krushna Nikam: IOT Based Three Phase Transmission Line Fault Detection and Classification." An arduino with IOT software model is designed in this paper to overcome the consumer problems. This model is very efficient in terms of detection the range, type and rectification of fault occur in real-time. In smaller time it does its work of containing the fault where the exact operation is wrong. Precludes the transmission line with additional difficulties in the future.

"Machine Learning Advances in Transmission Line Fault Detection": A Literature Review "JUDY LHYN SARMIENTO". The research in this field to study machine learning with new approaches for the fault localization study of transmission lines that indicates an emerging field which can improve the system reliability and overall efficiency of power systems. Many machines learning approaches are analyzed by experts

to detect transmission line faults with higher accuracy, speediness and reliability. They used sophisticated algorithms, including artificial neural network, decision tree and deep learning models to successfully achieving fault detection and classification over power-line communications.

PROPOSED RESEARCH METHODOLOGY

In this case design and development of prototype model of a phase distribution/ transmission line fault detection system using IoT and Machine Learning is initiated. The detection of faults in transmission lines involves advanced technology for efficient and accurate identification of the fault. The continuous data such as voltage, current and power can be calculated with the help of IoT and this data is transmitted to a microcontroller where the Machine Learning algorithms analyze it to detect the faults and predict the faults. To identify faults allowing for proactive maintenance and reducing downtime by using Machine Learning model which trains on historical fault data. The compiling of both Internet of Thing and Machine Learning improves the system reliability and efficiency of the power transmission system with maintaining the stability of electric grid system. In the reactance part, to increase the power in the transmission lines by using the capacitor bank series with the inductor which gives the difference between the inductive reactance and the capacitive reactance. In this, it gives an increase in the power.

OBJECTIVE

- To study and understand the basic performance of transmission lines.

- To execute the hardware model of the transmission line for analysis of symmetrical and unsymmetrical faults also exact location of the fault can be shared with the power system operator by using IoT.

- To study and execute hardware model real-time values of transmission line (power, voltage, current, etc.) by using Machine Learning.

FLOW CHART OF THE SYSTEM
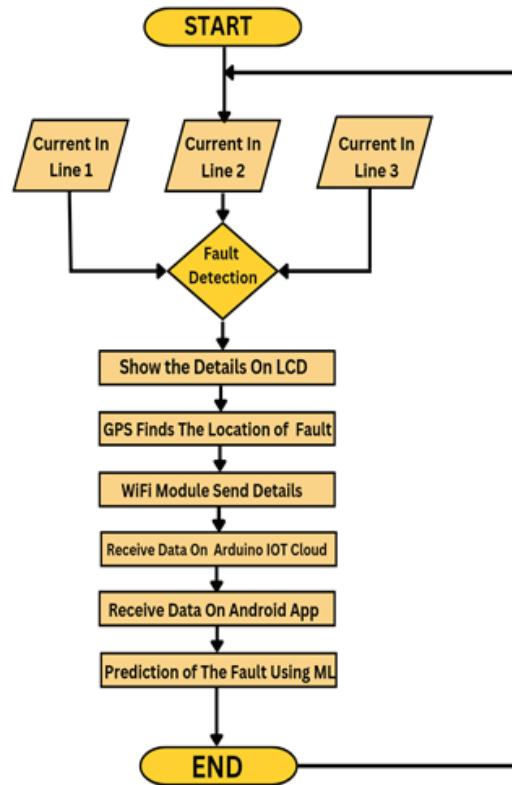
SYSTEM DEVELOPMENT
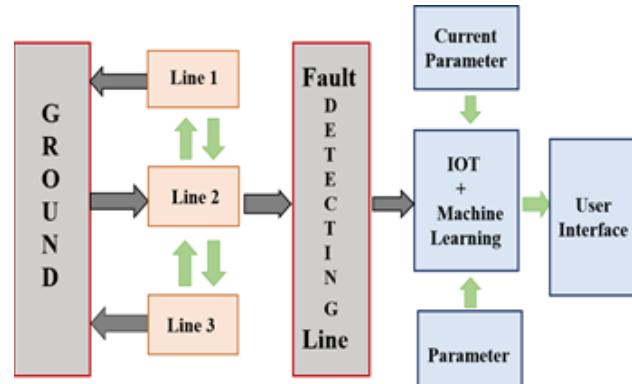
EQUIPMENTS INTERFACED

Display of LCD

It is basically liquid crystal display and it is electronic module of display utilized in various electronic circuits. It is ideal in multi segment application and in light emitting diodes and seven segments. The programming in LCD display is easy with animation and infinite displaying of custom characters.

$$\text{Distance of fault \%} = \frac{\text{Measured R}}{\text{Total R}} *100$$

$$= \frac{120\ \Omega}{200\ \Omega} *100$$

$$= 0.6*100$$

$$= 60\%$$

In this case, it will be a fault between R and Y phases.

$$Z_F = \frac{V_{ry}}{I_{ry}}$$

$$I = \frac{V}{R}$$

$$= \frac{12}{120} = 0.1\Omega \text{ but it is twice}$$

Voltage Transformer

The voltage transformers are measuring and provide accurate voltage ratios for having negligible loading on the power supply.

Iot Module

ESP8266 is nothing but Wi-Fi module with its chip which permits to your microcontroller to connect the internet at economical way. IoT is inbuilt best alternative for the project execution but initially basic knowledge of the various modules indeed required.

Relay

The one-channel 5 volt relay board module for Arduino. Wider range based microcontroller can be used in the relay such as AVR, Arduino, etc. Each element requires drive current in between 15 mA to 20 mA ,equipped with high current relays.

Calculations

1)   LL Fault.

2) Phase to Ground Fault

Positive Sequence $\quad Z_F = \dfrac{V_r}{(I_r + KI_r)}$

$$K = \frac{(Z_{0L} - Z_{1L})}{3Z_{1L}}$$

Fault location is then determined by,

$$\text{Fault Location (per unit)} = \frac{Z_F}{Z_{1L}}$$

3) The resistance of a conductor is calculated by,

$$R = \frac{pL}{A}$$

p = is property of any conductive material

A = area of conductor constant

L = length of conductor

R α L

according to Ohm's law

$$I = \frac{V}{R}$$

Then, the voltage of the transmission line is constant

$$I \propto \frac{1}{R}$$

CONCLUSION

The hardware model for transmission line fault detection utilizing IoT technology has demonstrated the ability to identify both symmetrical and unsymmetrical faults. By transmitting fault details, including distance and fault type, to the power system operator in real time, the system enhances the monitoring and management of transmission lines. The integration of compensation using capacitors has effectively reduced the line impedance, improving overall efficiency and system reliability. Moreover, the data collected from the hardware model has been instrumental in training a machine learning model to predict future faults, providing a proactive approach to fault management. This combination of hardware-based detection and AI-driven prediction offers a solution which enhances the stability, reliability, and efficiency of transmission systems.

This paper showcases the potential for IoT, machine learning, and recent development based compensation techniques to revolutionize fault identification and predictive maintenance in modern power systems.

FUTURE SCOPE

- The real time data on various parameters as voltage, current, etc which can be provided with the help of IoT sensors. This allows for continuous monitoring of transmission line conditions and immediate detection.

- ML algorithms can analyze historical data and identify patterns that proceed failures or degradation. This can enable predictive maintenance, where issues are addressed before they lead to failures, thus reducing downtime and maintenance costs.

- Advanced ML models can help in detecting and diagnosing faults in the transmission lines more accurately and quickly than traditional methods. This improves response times and minimizes service interruptions.

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Advanced LPG Gas Leakage Detector for Safety Applications

Vishalagoud S. Patil
Associate Professor
Dept. of Mechanical Engineering
Government Engineering College Talakal
Koppal, Karnataka
✉ vspatil.gec@gmail.com

Shaila R. Hallur
Faculty
Dept. of E&C Engineering
Government Engineering College Talakal
Koppal, Karnataka
✉ Shaila.hallur@gmail.com

Ashwini Wali
Faculty
Dept. of E&E Engineering
Government Engineering College Talakal
Koppal, Karnataka
✉ ashwiniwali86@gmail.com

Umamaheshwari
Faculty
Dept. of E&C Engineering
Government Engineering College Talakal
Koppal, Karnataka
✉ uma.sharanayya@gmail.com

ABSTRACT

The present work, formulated a system which is capable to detecting fire and provides the location of the fire affected region. A confirmation of the fire suspecting system to avoid any false alarm is included in the work. The system will immediately send a message along with the image of the affected spot and Ensuring Arduino's location. An admin can confirm or deny the impeachment and if the admin confirms the situation as a breaking out of fire, then the system will immediately raise an alarm. Fire is the most widespread cause of deaths by accident. Immediate alerting of the fire department is very necessary to ensure immediate action. Every minute is precious and can save many lives in such situations. Hence, an GSM based automatic fire alerting system is provided which immediately and automatically alerts the fire department. Also informs about the situation of gas leakages results a serious problem in household and other areas. Therefore, this system is developed to take immediate action against the fire hazards.

KEYWORDS: *LPG, Arduino, Bizzer, Battery, Microcontroller.*

INTRODUCTION

Liquid petroleum gas is also referred to as simply propane or butane. These are flammable mixtures of hydrocarbon gases and used as fuel in heating appliances, cooking equipment, and vehicles.

Unlike natural gas, LPG has more weight than air, so it will flow along floors and tend to settle in low spots. There is a possible explosion if the mixture of LPG and air is within the explosive limits and there is an ignition source. The fire detection system uses MQ6 gas sensor and LPG gas leakage sensor for efficient detection of fires and alert fire department over GSM. The Arduino uno is used to check whether a sensor is triggered. The fire detection system utilizes a Wi-Fi connection to access GSM server and transmit data about the incident

through the internet. The GSM Gecko platform will develop the web-based GSM interface. GSM Gecko system receives the sensor data and it checks the device id data and displays it. The system displays the fire incident with alarm buzzer and removes the power supply in the house. Then the persons are alerted about the incident to take necessary action. If there exists a gas leakage detection, then the model identifies the leakage of gas and turns off the servo motor and reduces the loss and minimizes the effect.

LITERATURE REVIEW

Gas is the commonly used fuel in Nigerian homes and industry in which some required measures have to be strategized in other to protect against incidents and accidents such as suffocation and explosion associated

with its usage [1]. For improving the usefulness of the gas leakage detector, a circuit having an alarm system is applied on the prototype to warn users about the gas leakage incidence, and also put into operation the GSM modem, which can send an awareness SMS to the owner of the mobile number [2].

LPG is used as a cooking gas, but also as a fuel that activates the generator. It is further utilised as a water heater, but is primarily used for cooking and as cooking gas. However, LPG gas is highly pressurized and cold, and will be stored in the cylinder [3]. The LPG characteristics are very uncommon than those of other general gaseous fuels. The ignition response of LPG increases the total volume of the products along with the creation of heat. LPG required 50 times the volume of air for complete ignition. LPG has only a faded smell, so to smell the LPG, some odorants are added to ensure that the gas is escaping. LPG is slightly toxic; it is not toxic but can create damage to humans and animals. LPG gas leaks as a liquid or gas. There will be heavy impact if the leaked gas is escaped as a liquid form, it will evaporate suddenly but it takes too much time to resolve in the air because LPG has more weight than air [4]. A small fire element contact may produce a large explosion because LPG is a highly flammable gas [5].

PROBLEM FORMULATION

• The problem is formulated based on the following points.

• The need of a gas detection system is not only to watch the environment continuously but also must prevent the further leakage of gas within the environment to attenuate the probabilities of fireside.

• Leakage of any kind of gases has become a drag in present times whether it's with regard to a domestic household, factory, kitchens in restaurants, canteens, etc.

• Many things are not identified by human senses like toxicity in gases, oxygen deficiency, flammable gases and also vapours. All these hazardous possess a serious risk to human life.

OBJECTIVES

In gas leak detection system,

• To make the microcontroller capable of integrating with a suitable gas sensor, such as an MQ series sensor, for detecting the gas leakages.

• To make the microcontroller for allowing the users to set a limit level for gas concentration.

• To activate the microcontroller, continuously monitor the gas sensor output and provide real-time gas concentration readings for analysis.

METHODOLOGY

Software Requirement: Arduino Ide
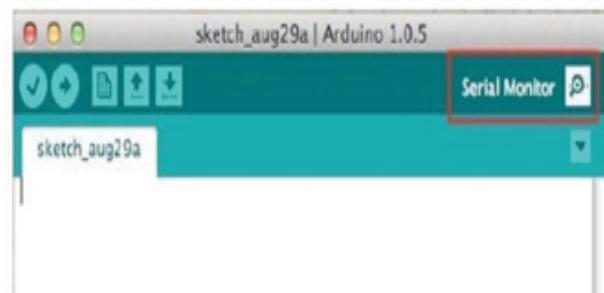
Fig. 1 Arduino IDE

The Arduino software is used to provide programmers with a single, integrated environment to write, test, and debug software more efficiently. Arduino Software (IDE) contains a toolbar with most useful buttons for gas leakage detection and a series of functions and menus as shown in figure 1.

Hardware Requirements

The hardware requirements that are necessary to build the assembly of the temperature-based fan speed control and monitoring using Arduino are:

A. Arduino Board

B. Gas Sensor

C. Fan

D. Servo motor

E. Resistor

F. GSM Module

G. Buzzer

H. Gas regulator

I. Battery

ARDUINO UNO board
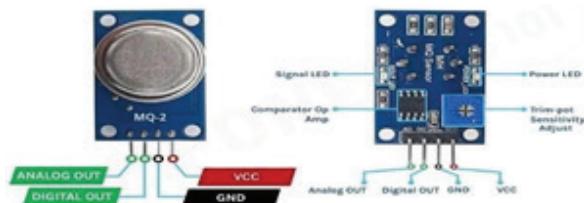
Fig. 2 Arduino UNO board

ATmega328P is a high concert yet low power consumption 8-bit AVR microcontroller that is able to achieve the most execution in single cycle of 131 powerful instructions. It can commonly be found as a processor in Arduino boards such as Arduino Uno board as shown in figure 2.

Gas Sensor

Fig. 3 Gas Sensor

This is used in the MQ sensor series. It is a Metal Oxide Semiconductor sensor (MOS). These are also called as Chemi resistors due to the change in resistance of the sensing material as it is exposed to gasses.

Fan

Fig. 4 Fan

It is an electronic appliance used to flow the air around its environment. The exhaust fan plays a important role in ensuring safety and efficiency.

Buzzer

Fig. 5 Buzzer

An Arduino buzzer is also called a piezo buzzer. It is small speaker that can be connected directly to an Arduino. It will make a sound for a tone at a frequency set. The buzzer produces sound based on reverse of the piezoelectric effect.

GSM Module

Fig. 6 SIM900A GSM Module

A Global System for Mobile Communications (GSM) module is a hardware component that allows a device to establish communication over a cellular network. It enables devices to send and receive data, including text messages and voice calls, through the use of standard cellular network protocols. The operating voltage of this module ranges between 6 volts to 12 volts and it has a data transmission capability will be Grps, edge,3g and 4g.

Servo Motor

Fig. 7 Servo motor

It is a closed-loop servomechanism that uses position feedback for controlling its motion and final position.

BLOCK DIAGRAM & METHODOLOGY

Block Diagram

The block diagram of an LPG leakage detector with SMS alert includes the following components as shown in figure 8.
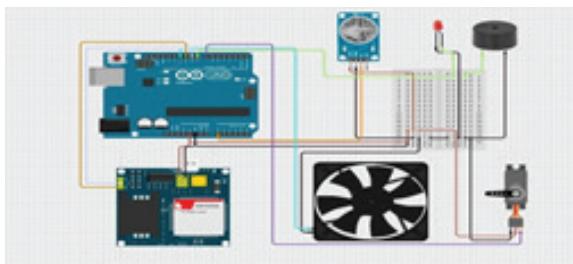
Fig. 8 Block diagram of LPG gas leakage detector

Methodology
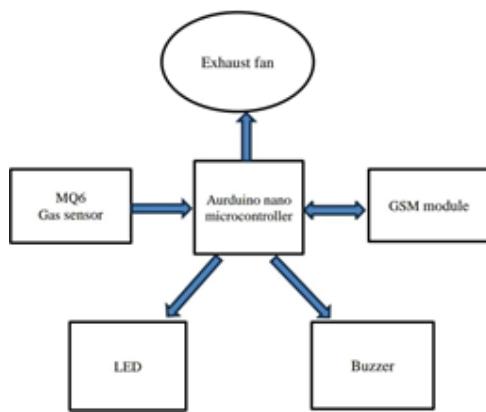
Fig. 9 Connection diagram

An LPG leakage detector with buzzer, SMS alert and phone call functionality typically operates in the following way:

- Gas Sensing: The LPG leakage detector is equipped with a gas sensor. This sensor continuously monitors the air for the presence of LPG. When concentration of the LPG in the air exceeds a pre-set threshold, the sensor detects the leakage and triggers the system.

- Signal Processing: The sensor sends the data of gas concentration to a microcontroller. The microcontroller processes this data and checks if the gas level crosses the danger threshold.

- Buzzer Activation: If the gas concentration very high, the microcontroller activates a buzzer. The loud sound of the buzzer is meant to alert people nearby about the potential danger of a gas leak.

- SMS Alert: Simultaneously, the microcontroller can be connected to a GSM module (e.g., SIM800 or SIM900) or Wi-Fi. The internet connection enables the system to send an SMS to a pre-programmed phone number. This SMS serves as a warning, informing the user about the LPG leak in the area.

- Phone Call Alert: In some systems, the GSM module can be programmed to make an automated phone call to the registered phone number. The call would inform the user about the gas leakage and can also deliver a pre-recorded message or a custom alert.

- Power Supply: The system is typically drove by a DC power or batteries. In more advanced systems, there may be a backup power system to ensure the gas detector functions even during a power outage.

- Real-time Monitoring (Optional):

- Some advanced versions of these detectors may also be equipped with Wi-Fi/Bluetooth connectivity to enable real-time monitoring of gas levels remotely via a smart phone app or a web dashboard.

RESULT AND DISCUSSION

Connection and Displaying the Output
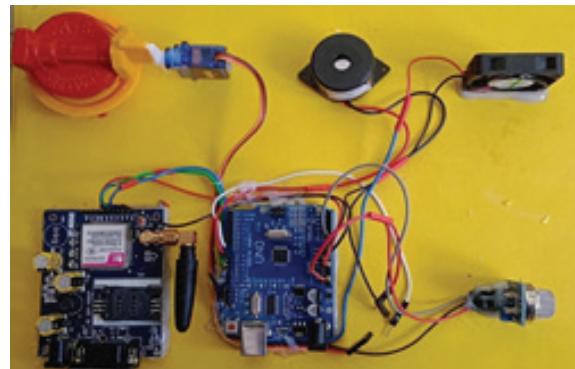
Fig. 10 Connections and displaying the output

The connections of all the hardware components are made as shown in the figure 10. As the LPG gas is made on, the alert message to the operator will appear as shown in figure 11, if any leakages are sensed by the sensor.

SMS Indication

1. Gas leakage detection results typically involve identifying the gas leakage and providing information on its location, severity, and any necessary actions to mitigate the risk.
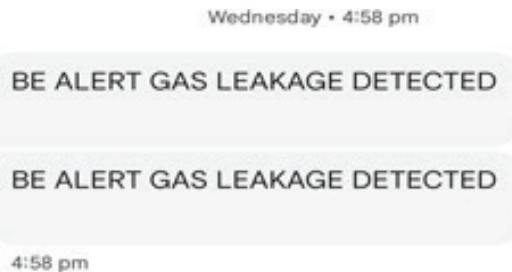
Fig. 11: SMS Alert indication

2. The specific result may differ depending on the technology or system used for detection, such as gas. sensors, alarms, or monitoring systems.

ADVANTAGES AND DISADVANTAGES WITH APPLICATION

Advantages

1. Flexibility for customization and adaptation.

2. Ensure worker's health.

3. Integration with displays and user interfaces.

4. Get real-time alerts about the gaseous presence in the atmosphere

5. Real-time updates about leakages.

6. It informs about the gas leakages which causes serious problem in household

Disadvantages

1. LPG gas detectors may generate false alarms due to interference from other gases, humidity, or temperature changes.

2. Over time, the sensor's sensitivity can drift, leading to inaccurate readings or false alarms.

3. LPG gas detectors typically have a limited detection can make it difficult to detect leaks in large areas or complex systems

4. LPG gas detectors require regular maintenance, including sensor replacement, calibration, and cleaning, which can be time-consuming and costly.

Application

This system can be used in;

1. Residential Buildings

2. Commercial Kitchens

3. Warehouses and Storage Facilities

4. Laboratories

5. Hotels and Resorts

6. Gas Distribution and Supply Stations

CONCLUSION

The development and applications of a gas leakage detection systems represent a critical step for enhancing safety and security in various environments. Through the utilization of advanced technologies like the MQ-6 sensor and GSM module, the system demonstrates remarkable accuracy and responsiveness in identifying potential gas leaks. Its integration with an alert system and advanced security features further fortifies its effectiveness, providing timely warnings and ensuring reliable operation even in high-risk scenarios. This work highlights the significance of such advancements and sets a foundation for future developments in this critical field of study. With further refinements and broader adoption, systems like the one presented here hold the potential to significantly enhance the safety standards across various sectors, ultimately safeguarding lives and property from the risks associated with gas leaks.

ACKNOWLEDGEMENT

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Study on Digital Marketing Impact on Purchase of Dream Car in MSIL With Reference To Thanjavur

S. Ramshankar
Ph.D Research Scholar (Full- Time)
PG & Research Department of Management
Maruthupandiyar College
(Affiliated to Bharathidasan University)
Thanjavur, Tamilnadu
✉ ramshankars2711@rediffmail.com

R. Arumugam
Assistant Professor & Research Advisor
PG & Research Department of Management
Maruthupandiyar College
(Affiliated to Bharathidasan University)
Thanjavur, Tamilnadu
✉ arumugam2glowplus@gmail.com

ABSTRACT

Creating awareness of digital marketing is of paramount importance for marketing Digital marketing. More number of marketing Digital marketing tools are available for each business to choose from based on their preference. Nowadays, digital marketing tools are at the apex of marketing Digital marketing which is a deconstruction of the traditional marketing tools. This plays a good interface between the marketers and the consumers. A systematic and strategic use of digital marketing tools is a compliment to attain competitive advantage for a business. This study is an earnest effort to investigate the choice of appropriate digital marketing Digital marketing tools that would create brand awareness among prospective consumers. The study adopted Delphi Method to understand the impact of digital marketing Digital marketing tool and brand awareness. Interviews with panel participants gave insights indicating that the paid digital content having a greater impact than the proactive content.

KEYWORDS: Digital marketing tools, Dream car, Paid digital content, Proactive content.

INTRODUCTION

Dream Usually dreams will come in the sleeping at night. The psychology domain said the drinks are the reflection of feelings thoughts emotions of the daytime what we are thinking by cyclical or circular in our mind always comes in dreams in our sleeping at the night. Dream sir really vibrant because a positive thought what we are thinking in the day time it is comes in the night has dream really vibrant and also it is range oriented what we are not thinking what we are not able to process that things are also came in the dreams. These dreams are always associated with the emotional state of mind even after the dream they can feel it is real people will say the dreams are going to happen once it happens What they are seen in the dreams they realised the dream is good. Already we know the dream sir reflection of peoples thoughts and feelings as well as worries and happiness. The behaviour science said the dream are going to help in the peoples goal achieving process and progress and their emotions strong connections and it gives percentage to the betterment of life.

Dreams are only dreams if they are not tried and achieved with the desired purpose of life. In our earth men may come and when may go, but their dreams are forever. The great achievers are all once upon a time, they dreamed that the life today they are living. The purpose of the dream in life is always achieving the Great thing what they confined as dream. Dreams or not just dreams, they are either fuel or boost for future life. The dreams only gave them the burning desire for achieving their life goals. All the people living in the society have dreams from their childhood itself, all the people' dreams arr self oriented very few people can only having dream for society welfare or common wealth.

The people willing or plan to buy new things means, first of all they are confined to their ideology of dreaming. This kind of dreams are strengthening their intention and thoughts if they have a dream means they have to try everyday to achieve it then only their dreams becomes true and the dreamers are loving their dreams. If the people never trying to accomplish their dream means

they are called as day dreamers. According to Dr. APJ. Abdul Kalam the dreams coming in sleep is not a dream rather that dream have to make the dreamer must not sleep. the dreams are always coming together all the ways and means of life. These dreams only give the determinant goals on their life to achieve and succeed. The motivational speakers told about dreams, the people have to believe their dreams and they have to think like that their dreams are seems to have be happened. Lot of people achieved dreams by seeing and thinking and fell to their dreams become true, this is an effective and fruitful ways and means of each Walk of life.

Dream car

To the middle class people regarding the concept of royal life living is a dream. Especially they are willing to live such a life ever before their fore fathers are not yet lived such one. The parents in the Indian societies are willing to give a royal life to their children means, first of all they will offer big own house and a brand new car and what kind of things they are think to use or consume in their childhood. Especially they are willing to provide the basic amenities of sophisticated life of the human beings. The parents' dreams in the Indian societies are fulfilling their children dreams. Without the dream car the dream life never fulfilled. Especially in the dream car segment the people are willing to buy a car in the following criteria:

The power of the car engine with high horse power for the extreme performance and long run durability and the power of engine depends upon the horse power used to the engine and it will increase the mechanism such as combustion chambers and pistons depends that only it will load and burn more fuel for the energy boosting to run the car. The globally renowned brands like Ferrari 812 cars are only purchased by the people only for its speed and performance.

The car lovers all over the world willing to buy the car for the purpose of its grand look and exciting performance of speed Especially the people willing to buy a brand new foreign car for not only for their status also for their performance. by driving such a cars they'll offer them an excellent experience and feel. Because of that only they are eager to drive such kind of cars again and again and that'll keep them to be delightful. The traveling lovers felt the difference between the day

driving as well as night driving and also they never worried about to press the accelerator of their car and make it to run more fast than those who are traveling together with them on the road and more over they will change their speed range quickly as soon as possible tom get maximum speed performance of the car. a blend of performance, luxury, and daily usability.

why The people usually willing to buy an blend of performance oriented cars because the cars are designed and produced for the people those who are loving the speed performance and smooth handling of cars and willing to have a nice experience while drive a car.

The people those who are loving long run drives and willing to drive like professional drivers are emotionally connected with their cars. Especially car driving persons are like to have thrilling oriented experience while driving their own cars. If the owners are driving the car means definitely the ultimate care will be there in all aspects.

In particular the people living in Indian society are really keen on maintaining their social status and specific image among their friends and relatives. For the purpose only they are buying brand new cars. They will prefer the new model car that is not available among their relatives group. If they owned such a branded car means really they feel pride. This kind of feelings are psychological based the people felt it is the success of their life and they had that thing is one of the goal and they are like to be achieve it. It is a social experience of all people those who are all travelled in the same range of social status.

People are usually willing to buy a blend of performance-oriented cars for several reasons, often tied to both emotional and practical factors. Here's a breakdown of the key motivations:

In the segment of technological era the customers are willing to buy latest featured cars only, they are least bother about the price. Because that kind of cars only give an excellent performance and provides extreme level of safety as well as satisfaction to the end users. Also the car buyers give utmost importance to the production technology and innovative designs of their cars. In the mind of the car lovers the comfortless of the car is playing vital role and the people given utmost

priority to the comfortless. If the cars are designed and produced with an excellent manner such as master piece means really it has resale value in the existing markets. Even though the cars are used in rough manner too they are in good condition after some period of time, so the people willing to pay good price for that one and also it is called as real time value for used cars. some extent the people in the society are having passion about life style and by living that kind of life they make an identity. Also they are living that passionate life. The people around them also willing to live such a life by imitating them.

The digital touch points really useful to the consumers of the passenger cars industry, not only car industry all the industry. Mostly the digital touch points are influence the consumers decision making process. The usage of social media through the internet nowadays become vital and the maximum usage of smart phones and social media. The purchase journey of a dream car starting from the online itself. Nowadays people never going to showroom to purchase the car or anything, all the process completed by online to take the delivery may they go to the offline showroom. The digital touch point guiding the people ultimately to get the awareness of the car buyers, it create them to potential buyers and it gives many ideas to the people to buy the beloved dream car and the digital touch points offered customized as well as memorable experience to them and they won't forget forever and they're not get such kind of experience ever before. The foremost and important phase in the online purchase dream car by digital marketing is getting awareness. First of all in the online digital marketing journey, usually they won't focus on the car model or brand or any other, by random manner they will search all the options of brand based on the price. They are willing to get awareness on the car model, price, discount, brand, colour and features etc…. The automobile sector in India at the post globalization growth era, especially in the passenger car industry the customers are using the digital touch points for their purchase of new cars for own use or rental purpose. Now a day's all over the world the people spent more time in their smart phone usage and the huge usage of the social media for the digital touch points are playing vital role in the digital marketing.

BACKGROUND OF THE STUDY

The automobile industry in India has witnessed significant transformation over the past few decades, both in terms of technological innovation and shifting consumer preferences. India, being one of the largest automobile markets in the world, has experienced rapid growth in vehicle production, sales, and exports. This growth is not just quantitative but also qualitative, with the industry embracing new technologies such as electric mobility, artificial intelligence, automation, and digital interfaces. Among the states contributing significantly to this development, Tamil Nadu stands out as a prominent hub, earning the nickname "Detroit of India" due to its well-established automobile manufacturing ecosystem. According to the Government of Tamil Nadu (2021), the state houses numerous major automobile manufacturers and suppliers, including both Indian and multinational companies. The presence of an extensive supply chain network, skilled workforce, favorable government policies, and advanced infrastructure makes Tamil Nadu a pivotal player in India's automotive landscape.

In recent years, the traditional methods of purchasing vehicles have evolved considerably. Earlier, consumers largely depended on physical visits to showrooms, word-of-mouth recommendations, and print advertisements to make purchase decisions. However, with the rapid digitalization of the economy, especially after the advent of high-speed internet and widespread smartphone usage, the consumer decision-making process has become more dynamic and informed. The accessibility to information, user reviews, expert opinions, and detailed product comparisons on digital platforms has empowered buyers like never before. Digital marketing has emerged as a powerful tool in this context, influencing every stage of the consumer journey — from awareness and interest to evaluation, purchase, and post-purchase engagement.

According to Chaffey & Ellis-Chadwick (2019), digital marketing encompasses a wide range of strategies including search engine marketing, social media marketing, email campaigns, influencer partnerships, and mobile advertising, all of which contribute to building brand awareness and engaging potential customers. Car buyers today are increasingly using platforms such as Google, YouTube, Instagram, and

various automotive review websites to research vehicles before stepping into a showroom. This shift highlights the growing importance of a strong digital presence for automobile brands.

Moreover, the COVID-19 pandemic has further accelerated the adoption of digital platforms in the automobile sector. Social distancing norms and lockdowns prompted many dealerships to enhance their online services, offering features such as virtual car tours, online booking, and doorstep test drives. Consumers now expect seamless digital interactions, which has led companies to invest heavily in digital transformation strategies. In states like Tamil Nadu, where both urban and semi-urban populations are showing rising disposable incomes and increasing digital literacy, digital marketing has become not just a complementary strategy but a necessity.

Therefore, understanding the impact of digital marketing on consumer behavior, particularly in the automobile sector, is essential for both marketers and policy makers. It offers valuable insights into how brands can effectively influence potential buyers and remain competitive in a rapidly evolving market. This study aims to explore these dynamics, focusing on how digital marketing affects dream car purchases in Tamil Nadu's vibrant automotive landscape.

STATEMENT OF THE PROBLEM

In today's digital era, car manufacturers and dealerships are increasingly shifting their marketing focus from traditional media to digital platforms. Online advertising, social media campaigns, influencer collaborations, and website optimization have become key tools for reaching prospective buyers. While these efforts are expanding rapidly across India, their actual influence on consumer behavior remains ambiguous in specific regional markets, such as Tamil Nadu.

Much of the available research tends to generalize findings across India without accounting for regional diversity. Tamil Nadu, with its unique linguistic identity, cultural preferences, and digital consumption habits, presents a consumer segment that may not align with broader national patterns. For instance, the way consumers in Tamil Nadu engage with online car reviews, regional influencers, or Tamil-language

content might differ significantly from that of buyers in North India or metropolitan cities. These subtle, localized behaviors often go unnoticed in mainstream academic discourse.

Furthermore, while digital marketing has become a standard strategy for many automotive brands, there is limited empirical data on whether these efforts actually influence consumer attitudes and decisions in semi-urban and urban Tamil Nadu. It remains unclear which digital channels—such as Instagram reels, WhatsApp business messages, or vernacular YouTube content—are most effective in engaging potential buyers in this region.

Without localized insights, marketers may rely on assumptions or apply strategies designed for broader markets, which may not yield the desired impact. This gap in academic understanding and market-specific knowledge creates a pressing need for focused research. Therefore, the central problem lies in the insufficient scholarly exploration of how digital marketing shapes consumer behavior in the automotive sector within the socio-cultural context of Tamil Nadu.

SCOPE OF THE STUDY

This study specifically examines the impact of digital marketing on passenger car purchase behavior within the geographical boundaries of Tamil Nadu. It narrows its focus to include both new and pre-owned car buyers, thereby providing a comprehensive understanding of digital influence across different stages of car ownership and affordability levels. However, the study excludes two-wheelers and commercial vehicles, as these segments follow distinct buying patterns and often involve different decision-making factors and marketing strategies.

The scope further limits itself to exploring consumer interaction with key digital marketing platforms, namely social media channels (such as Facebook, Instagram, and WhatsApp), YouTube automotive content, Google Ads/search engine promotions, email campaigns, and official dealer or brand websites. The research is not intended to evaluate the effectiveness of offline marketing methods such as TV, radio, print media, or outdoor advertisements, as these fall outside the domain of digital marketing.

The study includes urban, semi-urban, and select rural areas of Tamil Nadu to reflect varying levels of digital literacy, infrastructure access, and consumer readiness to engage in online platforms. By doing so, it aims to uncover how regional, demographic, and psychographic factors influence digital engagement and car purchase decisions.

Importantly, the research focuses on the consumer perspective—how potential buyers perceive, respond to, and are influenced by digital marketing efforts. While data may include insights from dealership digital strategies, the primary lens remains the buyer's behavioral and attitudinal response to online marketing inputs.

Additionally, the study is time-bound, reflecting digital marketing trends and consumer behavior within a recent two-year window. This ensures that findings are relevant to the current technological landscape and consumer mindset, making the results more applicable for immediate strategic use by marketers and car dealers in Tamil Nadu

SIGNIFICANCE OF THE STUDY

Building upon this gap, it becomes essential to explore not just the reach but the resonance of digital marketing messages among Tamil Nadu's diverse consumer segments. The rapid penetration of smartphones and affordable data packages has enabled wider digital access, yet consumer trust, purchase intent, and decision-making processes remain highly influenced by cultural values, local language content, and peer recommendations. This suggests that digital campaigns cannot be treated as universally effective across all Indian states.

In Tamil Nadu, family involvement in major purchase decisions, including automobiles, is culturally significant. Therefore, digital strategies that target only individual users may overlook the collective nature of decision-making in many households. Similarly, the popularity of local car review channels, regional comparison videos, and Tamil-speaking automotive influencers suggests that consumers are actively seeking culturally relatable and linguistically accessible content before making purchase decisions.

Moreover, the digital behaviors of consumers in tier-2 and tier-3 cities within Tamil Nadu may differ markedly from those in Chennai or other major metros. Factors such as trust in online information, preference for face-to-face interactions despite online research, and reliance on localized online groups or forums highlight the complexity of digital consumer engagement in the region.

Thus, there is a compelling need for empirical investigation into how various digital marketing elements — from content language and format to platform preferences and influencer credibility — align with the specific expectations of Tamil Nadu's car buyers. Such an inquiry will bridge the disconnect between national marketing strategies and local consumer realities, offering actionable insights for brands aiming to optimize their regional outreach. Ultimately, the problem extends beyond platform usage to the effectiveness and contextual fit of digital marketing initiatives within a culturally distinct and economically evolving regional market.

REVIEW OF LITERATURE

Ramanathan, S. & Devi, M. (2023). A recent local study conducted in Thanjavur examined the decision-making behavior of car buyers, emphasizing the combined influence of family, product features, financial arrangements, and dealer selection. The findings revealed that while prospective buyers primarily depend on digital platforms for initial information gathering, the final purchase decision is strongly influenced by interpersonal factors such as family opinions and direct interactions with dealers. The study further observed that visual digital materials—such as promotional videos and high-quality images—play a crucial role in stimulating aspiration and purchase intent, particularly among younger consumers. Additionally, the research identified an increasing trend of consumers consulting online reviews and feedback before engaging with showrooms. Based on these insights, the authors recommended the implementation of region-specific digital marketing campaigns that effectively link consumers with reliable local dealerships and customized financing solutions. Overall, the study underscores that semi-urban consumers in Thanjavur integrate online-driven aspirations with offline validation, illustrating a hybrid decision-making pattern in automobile purchases.

Ramesh, V. & Kapoor, D. (2023) This exploratory research investigates how social media platforms shape brand visibility and customer engagement within the Indian automobile industry. The study reveals that interactive digital content and active community participation enhance brand consideration, while engagement metrics such as likes, shares, and comments strongly correlate with showroom inquiries. It also highlights the post-pandemic surge in digital interaction, particularly the superior effectiveness of video-based content like test drives and virtual tours compared to static advertisements. The paper concludes that aspirational car purchases benefit most from storytelling that merges lifestyle appeal with product experience. However, it notes methodological constraints such as cross-sectional data and limited geographic representation, suggesting a need for deeper localized studies in semi-urban regions.

Prakash, L., & Joseph, K. (2024). This study evaluates the transformative role of digital media strategies in the Indian automobile sector during and after the COVID-19 pandemic. It documents a strategic shift toward online vehicle launches, virtual showrooms, and enhanced CRM-driven digital lead management. Findings indicate that digital initiatives helped reduce lead friction and expanded dealer outreach to semi-urban and first-time car buyers. Nonetheless, offline dealer trust remained indispensable in securing sales, particularly in non-metropolitan regions. The study recommends integrating online-to-offline (O2O) marketing workflows and improving digital finance tools to facilitate aspiration-driven purchases. These insights provide a national-level foundation for localized studies, including the current Thanjavur-focused research.

Kumar, R., & Sharma, A. (2024). This regional analysis from Coimbatore explores how various digital marketing tools—such as SEO, social media advertising, email campaigns, and brand websites—affect automobile purchase behavior. The results reveal that website quality and prompt dealer responsiveness significantly influence buying intentions, while social media advertisements primarily enhance brand awareness but require targeted retargeting strategies for conversion. Using convenience sampling, the study acknowledges its methodological limits but emphasizes that the insights are particularly relevant for neighboring regions like Thanjavur. The research underscores that quick, personalized dealer follow-ups on digital leads are pivotal in converting consumer interest into actual sales.

Nair, S., & Mehta, P. (2024) This comprehensive overview examines evolving customer trends in the Indian car market, noting generational differences in digital adoption. Younger consumers increasingly depend on online resources for vehicle research, while older buyers continue to value personal dealer interactions. The study attributes the rise of SUV and premium feature demand to aspirational online content and enhanced digital visibility. Moreover, it observes that transparent online financing options, such as EMI calculators, have positively shaped purchase deliberations. This national analysis establishes a macro-context for understanding the local digital influences on car purchases in Thanjavur.

Singh, T., & Varma, N. (2024). This empirical survey investigates the multi-stage decision-making process of Indian car buyers, with a focus on information sources and feature preferences. Results indicate that digital channels—such as brand websites, YouTube reviews, and third-party portals—play a dominant role in the initial information phase, whereas offline engagement remains crucial during final purchase decisions. The study highlights that online reviews serve as key risk-reduction tools, especially for aspirational and high-value purchases. It further contributes validated scales for measuring purchase intention and information search behavior, offering a valuable framework for adaptation in regional contexts such as Thanjavur.

OBJECTIVES

- To assess the impact of Digital marketing on dream car Purchase at thanjavur

- To Suggest feasible solutions to the effective car purchasing tools by digital marketing.

METHODOLOGY

This study is an earnest effort to investigate the choice of appropriate digital marketing Digital marketing tools that would create awareness among dream car buying

consumers. The research method used Delphi Analysing Technique. The researcher used both primary and secondary data for the study and the sample size is 120 and the by the simple random sampling the respondents of the study is the dream car buyers of Thanjavur city. The researcher used the Correlation analysis Delphi Survey for assess the results.

DATA ANALYSIS

Table 1 Correlation among selected determinants and Purchase Intention

DETERMINANTS	VALUES	
	R – Value	P - Value
Digital awareness	-.046	.241
Consumer Attitude	.293	.000
Social Media Influence	.416	.000
Digital content	.187	.001
Digital benefits	.197	.000
Digital satisfaction	.170	.002

Source: Primary data, ** Significant at five percent level

To test the correlation between independent variables on dependent variable Pearson correlation was applied. The independent variables of the study were Digital awareness, Consumer Attitude, Social media Influence, Digital content, Pay benefits and Digital satisfaction and dependent variable is purchase intention The following Hypothesis was formulated to test the relationship.

Ho7 : There is no relationship among the selected study variables and purchase intention

From the result it was observed that there was positive correlation between all dependent variables and Values. It implies that all independent variables contribute to Purchase intention. All independent variables are having lowest r-value (r < 0.40) that is Digital awareness r value = -.046,Consumer Attitude r value = .293, Social media Influence r value = .416, Digital content r value = .187, Pay benefits r value = .197 and Digital satisfaction r value = .170. This implies that it contributes less to Values. From the p-value in the correlation matrix, it was observed that the level of all independent variables was significant at 0.001 levels except Digital awareness. Hence, the null hypothesis was rejected. So it is concluded that there is significant

relationship between Digital awareness, Consumer Attitude, Social media Influence, Digital content, Pay benefits and Digital satisfaction with Purchase intention

Table. 2 Analysis of First Delphi Survey

Analysis	Corporate Websites	Email	Face-book	Twitter	Instagram
Level oh Impact	Low	Moderate	High	Very High	High
Mean	4.2	4.5	4.7	4.8	4.6
Median	3	3	3	3	3

Table. 3 Analysis of Second Delphi Survey

Analysis	Linked-In	Youtube	SMS/ MMS	Mobile Application	Search Engine
Level oh Impact	Low	High	Moderate	Very High	High
Mean	3.8	4.2	4	4.8	4.6
Median	3	3	3	3	3

In terms of digital marketing tools in social media, the opinion of the experts regarding corporate websites is at the least (mean 4.2) and the level of impact that it creates on brand awareness is also low followed by email (mean 4.5) and the level of impact as moderate. It is also understood that the impact created by the digital tools on brand awareness on Facebook, Twitter and Instagram is high, very high and high respectively.

In the second Delphi Survey, it is observed that the opinion of experts regarding digital Digital marketing creating brand awareness is low with LinkedIn (mean is 3.8) and the level of impact is low.

Within this scope of study, wherein the Delphi Analysis Technique is used, the experts invited for the study had given significant opinions. The level and the degree of impact of the digital marketing tools in creating brand awareness is evaluated based on the parameters that the experts have reached to a consensus on.

It is also observed from the study that the level of marketing Digital marketing tools that create paid digital content such as corporate websites is less whereas it is high in the search engine ads and mobile application. One among the reasons for this result is that the marketing Digital marketing tools that create paid digital content is compared with proactive digital content, control and monitor of the content rather than the initiative taken up by the company

FINDINGS

From the result it was observed that there was positive correlation between all dependent variables and Values. It implies that all independent variables contribute to Purchase intentionAll independent variables are having lowest r-value (r < 0.40) that is Digital awareness r value = -.046,Consumer Attitude r value = .293, Social media Influence r value = .416, Digital content r value = .187, Pay benefits r value = .197 and Digital satisfaction r value = .170. This implies that it contributes less to Values. From the p-value in the correlation matrix, it was observed that the level of all independent variables was significant at 0.001 levels except Digital awareness. Hence, the null hypothesis was rejected. So it is concluded that there is significant relationship between Digital awareness, Consumer Attitude, Social media Influence, Digital content, Pay benefits and Digital satisfaction with Purchase intention

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SUGGESTIONS

The automobile industry is a dynamic and ever competitive industry with lot of business opportunities and potential. The customers profile of the thanjavur market is very different compared with other cities like Chennai. Even though this city provides equal importance and opportunities to all customers in the existing market. the industry. Even though customers in the team, they focused on their individual targets. Most of the customers are middle income group Significant developmental tasks in the age group includes making royal life focussed. Hence it makes better business sense to address these issues of market.

CONCLUSION

Businesses should find in ways for the possibility of creating digital brand awareness by generating proactive content in cheap and fast manner. It is necessary to continuously control and monitor proactive contents as the consumers are free to express their comments and suggestions. It is also essential to have a network of consultancies to serve the purpose. Digital marketing Digital marketing tools should be appropriately used with a forethought on creating brand awareness among the consumers rather than thinking from the point of sales.

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Study on the Relationship between Investor Behaviour and Mutual Fund Investment Decisions in Tamil Nadu

R. Kalaichelvan

Assistant Professor
Department of Commerce
Adaikalamatha College
(Affiliated to Bharathidasan University)
Vallam, Thanjavur, Tamilnadu
✉ drkalai347@gmail.com

ABSTRACT

Investor behaviour plays a crucial role in shaping mutual fund investment decisions, especially in a dynamic economic environment like Tamil Nadu. The present study investigates how psychological, social, and economic factors influence investors' choices, preferences, and risk attitudes toward mutual fund schemes. It aims to identify the relationship between behavioural biases such as overconfidence, herd mentality, loss aversion, and anchoring and their impact on investment outcomes. The research also analyses demographic determinants like age, gender, income, education, and occupation that affect mutual fund participation. Primary data were collected from individual investors across select districts in Tamil Nadu using a structured questionnaire. Statistical tools such as correlation, regression, and ANOVA were employed to establish the strength of relationships between behavioural variables and investment decisions. Findings reveal that emotional and cognitive biases significantly affect investment planning and risk tolerance. Investors with higher financial literacy exhibit more rational decision-making and better diversification practices. Social influence and peer recommendations also emerge as critical motivators for investment actions. The study emphasizes the importance of investor education and awareness programs to minimize irrational decision tendencies. Mutual fund companies can benefit by understanding investor psychology to design tailored marketing strategies. Overall, this research contributes to behavioural finance literature by highlighting how human behaviour intertwines with rational financial models in Tamil Nadu's investment landscape. The study concludes that sustainable investment decisions depend not only on financial performance but also on behavioural stability and informed judgment.

KEYWORDS: *Investor behavior, Mutual fund investments, Behavioral finance, Investment decisions, Tamil Nadu investors, Empirical study.*

INTRODUCTION

The fast-growing Indian financial market has created many opportunities for both big companies and regular people to invest their money. One of the most popular choices is mutual funds. These funds are managed by experts, make it easy to buy and sell, and spread out the risk by investing in different things. More regular people are now choosing mutual funds, which shows they are becoming more aware of money matters and trust structured ways of investing [1]. In Tamil Nadu, one of India's economically dynamic states, mutual fund penetration has witnessed a consistent rise over the last decade, reflecting the evolving preferences of investors seeking balanced returns and risk mitigation. Investor behaviour, in essence, is the psychological and emotional framework that influences decision-making while investing [2]. It encompasses cognitive biases, risk perceptions, financial literacy, demographic factors, and social influences that collectively shape investment outcomes. Unlike the classical economic theory that assumes rational decision-making, behavioural finance recognizes that investors often deviate from rationality due to overconfidence, herd mentality, anchoring, and

loss aversion [3]. Understanding these behavioural patterns is crucial in explaining why investors sometimes make sub-optimal decisions despite having access to adequate information.

In India, how people invest is shaped by cultural, regional, and economic factors [4]. Tamil Nadu, where people tend to save a lot and prefer gold and property, is slowly starting to invest in things like mutual funds, systematic investment plans (SIPs), and equity-linked savings schemes (ELSS). Financial advisors, social media, and online platforms are helping younger and middle-income people spread their money across different investments [5]. But even with these changes, people still have some bad habits that influence when they invest, which fund they choose, and when they take money out. The mutual fund industry in India is regulated by SEBI, which has made several changes to make the process more transparent, protect investors, and share more information about how well funds are doing. Despite these regulatory advancements, retail investors often rely on heuristic shortcuts or peer recommendations rather than detailed analysis of fund performance or risk parameters [6]. This behavioural tendency underlines the importance of understanding the psychological determinants that drive mutual fund investment decisions in a regional setting like Tamil Nadu.

Numerous studies worldwide have examined the nexus between behavioural traits and investment choices. Researchers such as emphasized overconfidence as a key determinant leading to excessive trading, while highlighted the disposition effect influencing the premature selling of winning investments [7]. In the Indian scenario, scholars like found that risk tolerance, financial literacy, and demographic variables significantly impact mutual fund preferences [8]. Yet, region-specific studies focusing on behavioural aspects within Tamil Nadu remain limited, warranting deeper investigation. Tamil Nadu's investor profile is diverse ranging from salaried employees and small business owners to professionals and retirees. Each category exhibits distinct behavioural patterns influenced by income level, age, education, and financial goals [9]. For instance, younger investors may prioritize growth funds due to higher risk tolerance, whereas senior investors may lean toward debt-oriented schemes for capital preservation. Understanding these behavior patterns can help mutual fund companies create better marketing plans, education programs for investors, and advice services. This study looks at how investor behavior connects to their choices when investing in mutual funds in Tamil Nadu. The goal is to find out how things like psychological biases, personal traits, and how people see risk influence which funds they pick, how long they keep their investments, and when they decide to take money out. It also checks if knowing more about finance can help reduce the effect of these biases, leading to smarter investment decisions.

This study adds to the field of behavioural finance by giving real-world examples from a specific region. The findings are expected to assist fund managers, policy-makers, and financial advisors in understanding the behavioural tendencies of Tamil Nadu investors. Such insights can facilitate improved investor education initiatives, foster trust in the mutual fund industry, and encourage broader financial inclusion across the state. By bridging the gap between theory and practice, the study underscores the significance of human behaviour as a decisive factor in the success of mutual fund investments.

REVIEW OF LITERATURE

Recent empirical studies across Tamil Nadu and India reveal diverse dimensions of investor behavior in mutual fund decision-making. A two-phase survey in Chennai, identifying bank deposits, mutual funds, and equity shares as preferred liquid assets, especially among retired and salaried individuals [11]. The role of socio-economic factors are conducted in shaping equity investment awareness in Coimbatore [12]. Exploratory factor analysis is explored to identify seven behavioral determinants among corporate professionals [13]. Investment patterns and challenges in Tuticorin, noting systematic sampling of 340 respondents [14]. On academicians, revealing how behavioral biases and demographic variables are focussed and interacted to influence mutual fund decisions [15]. Determinants like investment literacy, affordability, and time horizon among 822 retail investors are statistically validated [16]. Most investors avoid high-risk avenues like gold and stocks, preferring schemes with stable returns [17]. Behavioral finance are found to be better and

explains investor irrationality than traditional models [18]. Brand perception's role is explored in information processing, suggesting that excessive data may cause uncertainty [19]. SEM and MANCOVA to show how availability and loss aversion biases distort rational investment decisions [20]. Collectively, these studies underscore the importance of financial literacy, trust, and behavioral awareness in improving mutual fund participation and decision quality across varied investor segments.

STATEMENT OF THE PROBLEM

Investor behavior plays a pivotal role in shaping financial markets, particularly in emerging economies like India where retail participation is growing rapidly. In Tamil Nadu, a state marked by diverse socio-economic profiles and evolving financial literacy, mutual fund investments have gained traction as a preferred avenue for wealth creation and risk diversification[21]. However, despite the proliferation of investment platforms and awareness campaigns, mutual fund penetration remains uneven across regions and demographics. This raises critical questions about the behavioral patterns, psychological biases, and decision-making frameworks that influence investor choices [22]. Factors such as risk tolerance, herd mentality, overconfidence, and familiarity bias often interplay with external stimuli like market trends, media influence, and advisor recommendations [23].

Moreover, cultural norms, income levels, and educational backgrounds further complicate the investment landscape. While national-level studies offer broad insights, there is a pressing need to understand these dynamics within the specific context of Tamil Nadu [24]. The absence of data that is specific to different regions makes it harder for policymakers, financial organizations, and teachers to create focused solutions.

This study seeks to bridge that gap by examining how behavioral traits correlate with mutual fund investment decisions among investors in Tamil Nadu. It aims to identify dominant behavioral patterns, assess their impact on portfolio choices, and explore the role of demographic and psychographic variables. By doing so, the research will contribute to a nuanced understanding of investor psychology in a culturally rich and economically diverse setting. Ultimately, the findings can inform financial literacy programs, product design, and advisory strategies tailored to the needs of Tamil Nadu's investor base.

OBJECTIVES

1. To examine the behavioural factors influencing mutual fund investment decisions among individual investors in Tamil Nadu, with a focus on psychological biases such as risk perception, overconfidence, herd behaviour, and loss aversion.

2. To analyze the relationship between demographic characteristics (such as age, income, education, occupation, and investment experience) and investor behaviour in determining mutual fund selection, investment duration, and portfolio preferences.

3. To evaluate the role of financial literacy and advisory support in moderating the effect of behavioural biases on mutual fund investment decisions and overall investor satisfaction in Tamil Nadu.

METHODOLOGY

This study uses a descriptive research approach to look at the factors that influence people's decisions when investing in mutual funds in Tamil Nadu. Both primary and secondary data were used to make sure the research is thorough and reliable. For the primary data, we created a structured questionnaire to understand things like investors' biases, how they feel about risk, their financial knowledge, and their investment habits. Secondary data came from respected journals, reports from SEBI and AMFI, and other financial publications that talk about mutual fund performance and trends in investing. The study focused on individual investors in key areas like Chennai, Coimbatore, Tiruchirappalli, Madurai, and Thanjavur, which cover a wide range of people from different backgrounds. We chose 250 participants using a convenient sampling method to get a good mix of different investor types. The questionnaire had questions on a five-point scale to better understand people's attitudes and behaviors. We used statistical methods like mean, standard deviation, correlation, and regression to find out how investors' behavior affects their mutual fund choices. To check if our results were consistent, we did a pilot test and used Cronbach's alpha to measure reliability. The findings give useful information that can help fund managers,

government officials, and financial advisors encourage more thoughtful investing in Tamil Nadu.

POPULATION AND SAMPLING

The population of the study comprises individual investors in Tamil Nadu who have invested or are currently investing in mutual funds through various channels such as banks, fund houses, and online platforms. The study specifically focuses on investors from major urban and semi-urban districts including Chennai, Coimbatore, Tiruchirappalli, Madurai, and Thanjavur, as these regions represent diverse demographic and economic characteristics. To ensure adequate representation, a sample size of 250 respondents was determined as appropriate for meaningful statistical analysis. The respondents were selected using a convenient sampling method, given the accessibility and willingness of participants. The study included investors of different age groups, income levels, educational qualifications, and occupational backgrounds. Data was gathered using a structured questionnaire that was given out both online and in person. This sampling approach was chosen to capture a comprehensive picture of investor behaviour and mutual fund investment patterns across Tamil Nadu.

DATA COLLECTION AND SOURCES

The study uses both primary and secondary data to make sure the analysis is accurate and covers all important aspects. Primary data were gathered using a structured questionnaire that helps understand investor behavior, how they see risk, their knowledge of finance, and their choices when it comes to investing in mutual funds. The questionnaire was distributed to individual investors across key districts such as Chennai, Coimbatore, Tiruchirappalli, Madurai, and Thanjavur, using both online and offline modes. Secondary data were obtained from reliable sources including research journals, SEBI and AMFI reports, mutual fund company websites, and financial publications. The combination of both data types helped to validate findings and provide deeper insights into investor decision-making behaviour. This approach ensured that the study's outcomes are empirically supported and contextually relevant to the investment landscape of Tamil Nadu.

ANALYSIS AND FINDINGS

Table 1: Demographic Profile and Investment Preferences

Demographic Factor	Key Observations
Age	Majority of investors are between 25–40 years
Education Level	Most investors hold graduate or postgraduate degrees
Occupation	Salaried professionals dominate the investor base
Income Level	₹3–10 lakhs per annum is the most common bracket

Demographic factors play a crucial role in shaping mutual fund investment behavior in Tamil Nadu. Younger investors, driven by long-term financial goals and higher risk tolerance, tend to favor equity-oriented schemes. Those with higher educational qualifications exhibit better financial literacy, enabling informed decisions and greater awareness of mutual fund advantages. Salaried professionals with stable income streams often opt for systematic investment plans (SIPs), aligning with disciplined wealth accumulation strategies. Middle-income groups are particularly drawn to mutual funds for their tax-saving potential and portfolio diversification. These patterns suggest that age, education, occupation, and income collectively influence investment preferences. As a result, mutual fund participation is notably higher among educated, salaried, and younger individuals, especially through SIPs. Understanding these demographic dynamics is essential for designing targeted financial products and outreach strategies.

Table 2: Behavioral Factors Influencing Mutual Fund Decisions

Behavioral Trait	Influence on Investment
Risk Aversion	High among older and less financially literate investors
Herd Mentality	Evident in urban clusters
Overconfidence	Seen in tech-savvy, younger investors
Trust in Institutions	Strong trust in private banks and AMCs

Investor behavior in Tamil Nadu is significantly shaped

by psychological biases and trust dynamics. Risk-averse individuals tend to favor debt or hybrid mutual funds, avoiding equity schemes due to perceived volatility. Herd mentality is prevalent, with many investors following peer recommendations or trending funds without conducting independent analysis. Overconfidence, especially among younger and tech-savvy investors, often leads to frequent fund switching and a focus on short-term gains. Trust in institutions—particularly banks and reputed asset management companies—strongly influences fund selection, with advisor guidance playing a pivotal role. These behavioral patterns can lead to suboptimal investment outcomes if not addressed. Enhancing financial literacy and offering personalized advisory support are crucial to mitigating irrational decision-making. A deeper understanding of these biases can help design more effective investor education and engagement strategies.

Table 3: Awareness, Challenges, and Decision-Making Patterns

Dimension	Findings
Awareness of Mutual Funds	Moderate to high in urban areas; low in semi-urban/ rural
Decision Drivers	Tax benefits, past returns, and liquidity
Challenges Faced	Complexity of fund options, lack of personalized advice
Preferred Channels	Digital platforms and bank advisors

Awareness of mutual funds has grown notably in urban centers of Tamil Nadu, thanks to targeted campaigns and digital outreach. However, Tier 2 and Tier 3 towns still lag behind, indicating a need for region-specific financial education. Investors tend to base their decisions on tangible benefits such as tax savings and recent fund performance, often overlooking long-term planning. Many feel overwhelmed by complex terminology and fund structures, which hinders confident participation. Younger investors prefer digital platforms and bank advisors, valuing convenience and institutional trust. Despite rising awareness, behavioral biases and limited understanding continue to shape investment choices. To foster deeper engagement, simplified communication and personalized advisory services are essential.

SUGGESTION

Based on the study's results, there are several recommendations that can help increase investor awareness and boost involvement in mutual funds across Tamil Nadu. Firstly, financial literacy programs should be conducted regularly by banks, mutual fund companies, and educational institutions to enhance investor understanding of risk, return, and portfolio diversification. Investors should be encouraged to adopt a long-term investment perspective rather than making short-term speculative decisions influenced by market fluctuations. Fund houses must provide transparent information about scheme performance, expense ratios, and portfolio composition to build greater trust among investors. The role of financial advisors should be strengthened through proper certification and ethical guidelines to ensure unbiased guidance. Furthermore, digital awareness campaigns can promote online investment platforms, making mutual funds more accessible to younger and rural investors. The government and SEBI can introduce tax incentives and simplified regulations to encourage small investors to participate in mutual funds. Regular investor education workshops in smaller cities can help reduce the difference in knowledge between urban and rural areas. Financial institutions should design customized mutual fund products catering to different income and risk groups. Encouraging Systematic Investment Plans (SIPs) can instil disciplined investment habits and reduce the impact of behavioural biases. Additionally, continuous monitoring and evaluation of investor satisfaction will help identify emerging challenges in mutual fund adoption. Overall, creating a balanced ecosystem combining education, transparency, and technology can foster rational investor behaviour and sustainable mutual fund growth in Tamil Nadu.

CONCLUSION

The current study shows how investor behavior affects mutual fund choices among people in Tamil Nadu. The research finds that factors like how people see risk, being too sure of themselves, following the crowd, and knowing about money all play a big part in how people decide where to invest and what to buy. Even though more people are aware that mutual funds are a safe and varied way to invest, many still make choices based on

feelings and what others are doing instead of looking at things carefully and logically. The study says there's a need for ongoing education and awareness to help people make smarter and more thoughtful investment choices. It also points out that things like age, income, and job affect how people invest, showing the different types of investors there are in the state. The rising use of Systematic Investment Plans (SIPs) shows that people are moving towards more disciplined and long-term investment habits. But there are still issues like not enough knowledge about money, market ups and downs, and not trusting those in between investors and funds. Making sure regulations are clear and promoting policies that help investors can help build more confidence in mutual funds. Financial advisors and fund managers should use strategies that consider how people think to help them make decisions that are clear about their goals and manage risks well. Overall, the study concludes that understanding investor psychology is essential for ensuring sustainable growth of the mutual fund industry in Tamil Nadu and for building a financially resilient investor community.

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Study on Consumer Behaviourial Pattern in Social Commerce Platform in Indian Perspective

V. Sankaranarayanan
Assistant Professor,
Department of Management
Christhu Raj College
(Affiliated to Bharathidasan University)
Panjappur, Tiruchirappalli, Tamilnadu
✉ drsankaranarayanan1982@gmail.com

ABSTRACT

Social commerce is an integration of social media and e-commerce that has transformed how consumers discover, evaluate, and purchase products online. The study aims to explore consumer behavioural patterns in social commerce platforms, focusing on trust, peer influence, perceived usefulness, and purchase intention. Data were collected from 200 respondents who actively engage in social commerce through platforms such as Instagram, Facebook Marketplace and Meesho. Using ANOVA and regression analysis, the study identifies significant predictors influencing consumer purchase behaviour. Findings reveal that trust, peer recommendations, and interactive engagement play a vital role in shaping purchase intentions. The paper concludes with strategic suggestions for marketers to enhance consumer engagement and foster long-term loyalty.

KEYWORDS: *Social commerce, Consumer behaviour, Trust, Peer influence, Online purchase intention, Digital marketing.*

INTRODUCTION

The evolution of social media as a marketplace shows revolutionized traditional e-commerce. Social commerce (s-commerce) leverages social networks for product promotion, reviews, and direct selling. In India, the increasing adoption of platforms like Instagram Shops, Facebook Marketplace, and Meesho has enabled small entrepreneurs and brands to reach diverse audiences. Unlike conventional e-commerce, s-commerce emphasizes social interaction, user-generated content, and peer trust, which significantly affect consumer decision-making.

Understanding behavioural patterns in social commerce is crucial for businesses seeking to tap into this growing segment. Consumers' psychological and social motivations — such as community engagement, brand trust, and word-of-mouth influence — drive their purchase choices. Therefore, studying these patterns offers valuable insights for developing customer-centric marketing strategies.

LITERATURE REVIEW

Social commerce integrates e-commerce functionalities with social networking interactions (Liang & Turban, 2011). Consumer behaviour within social commerce environments is shaped by factors such as trust (Hajli, 2014), social support (Wang & Yu, 2017), and perceived usefulness (Kim & Park, 2013). Prior studies highlight the significant influence of peer recommendations and Online word-of-mouth influence on consumer purchase decisions (Chu & Kim, 2011). In the Indian context, the emergence of influencer-driven shopping and platforms such as Meesho, GlowRoad, and Instagram Shops has transformed consumer engagement patterns (Kaur & Singh, 2021).

Zhang and Benyoucef (2016) suggest that the adoption within social commerce platforms is largely determined by the perceived enjoyment and credibility of the platform. Furthermore, Hajli (2015) emphasizes that social trust serves as a mediating factor between social interactions and purchase intention. Despite these

insights, existing literature reveals a gap in understanding the behavioural dynamics of Indian consumers on rapidly evolving social commerce platforms.

OBJECTIVES OF THE STUDY

- An analysis of the behavioural pattern of consumers using social commerce platforms.

- To identify key factors influencing consumer purchase intention.

- "Investigating trust and peer influence in social commerce behaviour"

- To provide managerial implications for improving consumer engagement.

RESEARCH FRAMEWORK

Research Design	Descriptive
Sampling Method	Convenience Sampling
Sample Size	200 respondents
Data Collection Tool	Structured Questionnaire (5-point Likert scale)
Statistical Tools Used	Descriptive Statistics, ANOVA, Regression Analysis
Software Used	SPSS / R

CONCEPTUAL MODEL

The conceptual model is designed according to the study objectives. The factors influencing of consumer behaviour in social commerce are treated as independent variables, including Trust, Peer Influence, Platform Usability, Social Interaction, and Perceived Value, while the buying behavior tendency of consumers is considered the dependent variable.
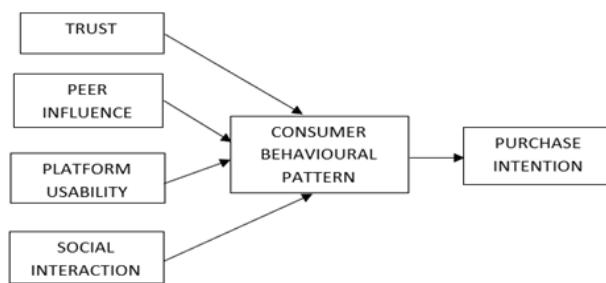
Fig. 1: Conceptual Framework of Consumer Behaviour in Social Commerce

DATA ANALYSIS AND INTERPRETATION

Application of Chi-Square test

To examine whether demographic factors (Gender, Education, Income) are significantly associated with consumer behavioural patterns (Purchase Decision, Trust Level, Frequency of Use) on social commerce platforms, a Chi-Square Test of Independence was conducted."

Test 1: Gender vs. Purchase Decision

H_0: Gender does not significantly affect purchase decisions.

H_1: Gender significantly affects purchase decisions.

Observed Data (Sample n = 200)

Table 2

Gender	Frequently Purchase	Occasionally Purchase	Rarely Purchase	Total
Male	35	45	20	100
Female	55	30	15	100
Total	90	75	35	200

Source: primary data

Expected frequency = (Row Total × Column Total) / Grand Total

For example, Expected (Male, Frequently Purchase) = (100 × 90) / 200 = 45

Chi-Square (χ^2):

χ^2 (calculated) = 9.26

df = (r - 1)(c - 1) = (2 - 1)(3 - 1) = 2

p-value = 0.0097

Since p < 0.05, the null hypothesis (H_0) is rejected. There is no significant association between education level and trust in social commerce platforms. Consumers across education levels show similar levels of trust toward social shopping.

Test 2: Education Level vs. Trust in Social Commerce Platforms

H_0: Education level does not significantly influence trust in social commerce platforms.

H_1 :Education level significantly influences trust in social commerce platforms.

Table 3

Education Level	High Trust	Moderate Trust	Low Trust	Total
Undergraduate	20	35	15	70
Postgraduate	40	50	10	100
Professional	15	10	5	30
Total	75	95	30	200

Source: primary data

Calculated $\chi^2 = 8.54$, df = 4, p = 0.073

Since p > 0.05, there is no significant association between education level and trust in social commerce platforms. Consumers across education levels show similar levels of trust toward social shopping.

REGRESSION ANALYSIS

The Multiple Linear Regression Analysis was conducted to identify the major predictors influencing Purchase Intention among social commerce users.

Table 4

Predictor Variable	β (Standardized Coefficient)	t-value	Sig.
Trust	0.421	6.24	0.000
Peer Influence	0.336	5.18	0.002
Platform Usability	0.217	3.94	0.012
Social Interaction	0.194	3.45	0.021

Source: primary data

$R^2 = 0.68$, F = 52.34, p < 0.001

The regression outcomes emphasize that psychological and social factors - particularly trust and peer influence, are stronger drivers of consumer behaviour than technical or demographic characteristics.

Thus, businesses on social commerce platforms should focus on building credibility, fostering peer recommendations, and enhancing interactive experiences to increase sales conversions and customer loyalty.

FINDINGS OF THE STUDY

Based on the analysis, the following key findings were derived:

Trust and Peer Influence emerged as the strongest determinants of Buying behavior tendency among Community-based e-commerce users as the Regression results show that trust ($\beta = 0.421$) and peer influence ($\beta = 0.336$) significantly predict online purchase behaviour. Gender has a significant association with purchase decisions ($\chi^2 = 9.26$, p < 0.05) since the Female consumers were found to engage more frequently in social commerce purchases than male consumers. Education level does not significantly influence trust toward social commerce platforms (p > 0.05). This implies that trust is developed through experience, peer reviews, and social credibility rather than formal education. Platform usability and social interaction positively affect consumer engagement and purchase frequency.

The overall regression model explains approximately 68% of the variability ($R^2 = 0.68$) in purchase intention, indicating a strong predictive relationship between behavioural factors and consumer decisions. Consumers perceive social commerce as more trustworthy when platforms emphasize transparency, user reviews, and verified sellers.

SUGGESTIONS AND CONCLUSIONS

Strategic recommendations are offered for social commerce businesses, marketers, and platform designers. Enhancing trust mechanisms can be achieved by implementing verified seller badges, transparent review systems, and secure payment options, which help boost consumer confidence. Promoting peer and influencer engagement involves partnering with micro-influencers and encouraging user-generated content, fostering authentic social proof and credibility. Additionally, building community-driven narratives and establishing emotional connections with consumers can nurture loyalty and encourage repeat purchases, thereby strengthening emotional branding.

The study concludes that psychological and social factors, including trust, peer influence, social interaction, and platform usability, significantly influence Buyer patterns in social commerce.

Future research can be extended by incorporating variables such as cultural orientation, income level, and platform type comparisons to better understand

consumer behaviour in social commerce across diverse contexts.

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Examining the Impact of Technological Advancements on Employee Well-Being and Organizational Commitment: Insights from Chennai's Automobile Sector

S. Sanath Kumar
Assistant Professor
Department of Business Administration
Jamal Mohamed College
(Affiliated to Bharathidasan University)
Tiruchirapalli, Tamilnadu
✉ sanathk198518@yahoo.com

ABSTRACT

This study explores how new Innovations like robotics, machine learning, and smart manufacturing systems initiatives, influence employee satisfaction and commitment in Chennai's automotive industry. This study utilized a mixed-methods approach, combining survey data from 450 employees at leading companies, including Hyundai, Ford, and Renault–Nissan, with detailed interviews of 30 management professionals. The primary objective is to examine the effects of technological advancements on employees' mental well-being, job satisfaction, and organizational loyalty. The findings show that technology Presents both beneficial and adverse effects. On the positive side, it enhances productivity and facilitates skill development among employees, with 62% of participants reporting increased commitment. On the other hand, 38% of employees reported stress and job insecurity concerns, which negatively affect their overall well-being. This study reveals that effective training initiatives and supportive HR strategies are vital in overcoming these challenges. It identifies a significant connection between technology adoption and employee well-being, particularly when firms prioritize skill-building programs. To substantiate these findings, the research applies structural equation modeling. It also highlights the obstacles posed by Chennai's rapid industrial growth. The findings indicate that customized approaches, such as digital skills training, are essential to ensure technology positively impacts both employees and the organization. This research makes valuable contributions to human resource management, particularly within the rapidly expanding business landscape of Chennai. It also provides guidance for policymakers and organizational leaders to implement technological practices that are fair and sustainable, securing long-term advantages for both employees and organizations. In the end, it shows The value of adopting a measured approach to technology to ensure it promotes, rather than harms, the resilience of the workforce.

KEYWORDS: *Technological advancements, Employee well-being, Organizational commitment, Automobile sector, Chennai industry.*

INTRODUCTION

Within the evolving global economy, the automotive industry stands as a key measure of industrial strength, especially in emerging economies such as India. Chennai, often dubbed the 'Detroit of India,' hosts a dynamic ecosystem of automotive companies, significantly contributing to India's economic growth and job creation. This industry supports millions of livelihoods, driving innovation and economic progress, while grappling with ongoing pressures from globalization and swift technological advancements [1]. Even though there have been a lot of improvements, the people working in the sector remain crucial. Their health and commitment directly impact the company's efficiency and its capacity to maintain long-term stability [2]. Technological advancements, including automation,

Machine learning (ML), connected devices, and smart industrial systems have transformed manufacturing processes, promising efficiency gains and competitive edges. Nevertheless, such advancements also bring challenges, such as workforce reductions, skill obsolescence, and heightened job-related pressures, which can weaken employees' confidence and commitment. This study investigates how technological changes influence employees' well-being, including their physical health, mental health, and interpersonal relationships, while also exploring organizational commitment, which reflects employees' dedication and attachment to their company. It fills a significant research gap by focusing on Chennai's automotive sector, as existing studies often neglect region-specific perspectives in developing economies. While research in Western contexts highlights the varied impacts of technology, there is a scarcity of empirical evidence from India's fast-growing industrial hubs like Chennai [3]. Although research in Western settings underscores technology's mixed impact, there is limited empirical data from India's rapidly expanding industrial centers like Chennai. The automobile industry in Chennai, featuring leading companies like Hyundai, Ford, and Renault-Nissan, illustrates the swift adoption of emerging technologies. These companies utilize robotic assembly lines and data-driven insights to optimize and improve their supply chain operations. The pace of these advancements has accelerated since the pandemic, with heightened efforts in digital transformation to bolster operational resilience [4]. However, employee reports reveal rising stress, fatigue, and turnover intentions, highlighting the importance of balancing technological progress with employee well-being.

Employee well-being encompasses multiple dimensions, including job satisfaction, work–life balance, and the availability of mental health support, all of which may be affected by technology-driven changes [5]. In today's competitive labor market, talent retention is strongly dependent on organizational commitment, shaped by emotional, functional, and ethical factors. To investigate these dynamics, this study utilizes a blended research strategy, integrating data gathered from both numerical and descriptive sources. through employee surveys and interviews with key stakeholders to explore these dynamics in practice [6]. This research seeks to evaluate the benefits and challenges of technological advancements, explore moderating factors such as training initiatives and HR practices, and propose actionable strategies for successful implementation. Its importance lies in its potential to guide policymakers, industry leaders, and researchers toward fostering sustainable progress. By focusing on Chennai, the research highlights unique socio-cultural elements, such as community-driven values and the city's diverse workforce [7]. The analysis is grounded in theoretical models, including The Job Demands-Resources (JD-R) model and the Technology Adoption Framework (TAF).

A quick look at existing research shows that although technology can improve efficiency, it can also lead to higher levels of anxiety if not handled properly. For example, automation can decrease physical workloads while increasing mental demands. In Chennai's context, where the industry creates employment opportunities for over 1.5 million people, both directly and through related activities, these issues are amplified by urban pressures and economic disparities [8]. The research suggests a mediated relationship in which technological advancements enhance organizational loyalty by fostering skill development, while simultaneously diminishing employee well-being as a result of rising job insecurity [9]. Methodologically, structural equation modeling will test these links, ensuring robustness.

This opening chapter sets the foundation for the following sections, addressing the review of existing studies, research approach, findings evaluation, and exploration of outcomes.

Ultimately, the research promotes a human-focused approach to technology adoption, creating settings where innovation and employee well-being thrive together [10]. In a time of swift transformation, grasping these dynamics is crucial for fostering robust organizations. Chennai's automotive sector mirrors broader industrial trends across India. Through this perspective, the study adds to global discussions on the evolution of work.

REVIEW OF LITERATURE

The implementation of the five major practices of Green Human Resource Management (GHRM) such as green training & development, green selection & recruitment, green performance management, green employee involvement, and green rewards & compensation has a

significant impact on the work-life balance of employees in the automobile industry. GHRM enhances employee satisfaction by promoting sustainable practices, thereby improving overall well-being and work-life harmony was found [11].

Similarly, The role of remuneration, job advancement, and work-life balance on employee retention among front-line workers in the automotive industry. Also the strategic improvements in compensation, career progression, and balancing work demands significantly strengthen employee contentment and organizational loyalty was demonstrated, thereby addressing the challenge of workforce stability [12]. Pandemic-induced work practices are examined and found that upskilling, automation, and digitalization positively influenced job satisfaction and retention, emphasizing that technology adoption enhances long-term workforce stability [13].

Employee perceptions of GHRM practices are analyzed in Chennai's automobile industry, concluding that green initiatives are gaining recognition and contribute to sustainable HR strategies. Their study reinforces the growing importance of environmental responsibility in HR policies [14].

Talent retention practices in Chennai's automobile companies, focusing on workplace pressure, adherence to procedures, organizational culture, training opportunities, and job satisfaction. Their study revealed that while employees often face high pressure at work, the presence of authority, skill enhancement opportunities, and job security act as major factors in retaining talent [15].

Further analyzed the role of Corporate Social Responsibility (CSR) in promoting workplace happiness and reducing burnout. CSR initiatives positively influence workplace wellness, fostering a supportive culture where employees exhibit stronger job engagement and positive organizational attitudes [16].

In the context of innovation, the significance of structural empowerment and psychological empowerment are emphasized in influencing innovative work behaviors (IWB) in the Indian automobile industry. The empowering employees fosters creativity and innovation was found, which in turn enhances job satisfaction and organizational performance [17].

Meanwhile, the effects of automation and digitization is investigated on occupational stress among automobile industry engineers and technicians. Also it concluded that while automation introduces efficiency, it also creates stress and resistance among traditional operators. The targeted training and digital adaptation strategies are recommended to reduce stress and improve productivity [18].

Also Corporate Social Responsibility (CSR) encompasses fulfilling the expectations of investors and customers are identified while also addressing the concerns of other stakeholders such as employees, suppliers, and the broader community. It involves proactive contributions to societal welfare and minimizing environmental impact. CSR reflects a commitment to sustainable development by balancing economic, ecological, and social objectives. Ultimately, it enhances stakeholder trust and long-term shareholder value [19].

Finally, the role of emerging technologies and evolving work practices are explored in shaping employee engagement. The disruptive technologies not only enhance job design and workplace efficiency was revealed but also drive higher engagement and skill development, making them crucial for future workforce management [20].

STATEMENT OF THE PROBLEM

The research suggests a mediated relationship in which technological progress enhances organizational commitment by fostering skill development, but at the same time diminishes employee well-being due to growing job insecurity. Although these innovations provide firms with a competitive advantage, they also generate challenges that directly affect the workforce [21]. Employees are increasingly exposed to threats of job loss, skill obsolescence, and heavier workloads, all of which can harm their physical, psychological, and social health. Reports across the sector indicate rising stress, burnout, and obstacles to achieving harmony between work and personal life [22]. Ensuring employee well-being, therefore, becomes a critical factor for sustaining long-term productivity and organizational resilience.

At the same time, organizational commitment is evolving, as employee loyalty and emotional attachment fluctuate in response to workplace transformations. A pressing concern is whether employees will remain engaged and motivated amid the rapid pace of technological change [23]. While prior studies in Western contexts have identified both positive and negative outcomes, limited research has addressed these dynamics within the Indian automobile sector. Chennai, home to global manufacturers such as Hyundai, Ford, and Renault-Nissan, has experienced particularly rapid and large-scale technological transitions.

The swift integration of digital technologies following the COVID-19 pandemic has further accelerated these trends, yet considerable gaps persist in comprehending their impact on employees within developing economies [24]. Attaining equilibrium between operational efficiency and employee well-being remains a significant challenge. Failure to do so may lead to rising turnover, lower morale, and weakened organizational performance.

This study investigates how technological advancements simultaneously influence employee well-being and organizational commitment in the automobile industry of Chennai.

OBJECTIVES OF THE STUDY

1. To examine the impact of technological advancements—including automation, artificial intelligence, and Industry 4.0—on employee well-being, with specific emphasis on mental health, job satisfaction, stress management, and work–life balance within Chennai's automobile sector.

2. To analyze the relationship between technological change and organizational commitment by evaluating how innovation influences employee loyalty, engagement, and emotional attachment to their organization.

3. To examine how HR strategies such as training and skill development programs, moderate the challenges of technology adoption while amplifying its positive effects on employee well-being and organizational commitment.

METHODOLOGY

The study adopts a mixed-methods design, combining quantitative surveys with qualitative interviews. It concentrates on employees within Chennai's automobile industry, specifically in organizations such as Hyundai, Ford, and Renault-Nissan. Participants were drawn from various departments and hierarchical levels to capture diverse viewpoints. A total of 450 employees were chosen through stratified random sampling to ensure balanced representation. Moreover, purposive sampling was applied to select 30 managers, enabling the collection of detailed insights into HR practices.

The main instruments for primary data collection consisted of a structured Likert-scale questionnaire and semi-structured interview schedules. Key variables include technological advancements, employee well-being, and organizational commitment, along with moderating factors like training and HR policies. The data analysis process involved the use of descriptive statistics, correlation tests, regression techniques, and structural equation modeling (SEM) to validate the proposed hypotheses. The qualitative interview responses were examined using thematic analysis to uncover common patterns and meaningful insights. Ethical protocols, including informed consent, confidentiality, and voluntary participation, were rigorously maintained during the entire research process.

POPULATION AND SAMPLING

The research sample is drawn from employees working in Chennai's automobile sector, including both shop-floor workers and managerial staff from leading firms such as Hyundai, Ford, and Renault-Nissan. The study ensured balanced representation by including participants from varied departments such as manufacturing, quality assurance, human resources, and administration.

From this population, a stratified random sample of 450 workers were selected to capture variations across job types and organizational functions. In addition, purposive sampling was used to select 30 managers, offering detailed perspectives on HR policies, training programs, and organizational strategies. By using this mix of sampling methods, the study was able to cover a wide range of employee perspectives while

also including managerial insights, thereby offering a comprehensive view the impact of technological progress on employee well-being and commitment to the organization.

DATA AND SOURCES

Type of Data	Source	Tools/Methods
Primary Data	Data450 employees (survey), 30 managers (interviews)	Structured questionnaire (Likert scale), Semi-structured interviews
Secondary Data	Company reports, industry publications, government statistics, academic journals	Document review, literature analysis

PRESENTATION OF ANALYSIS

The research findings were analysed using a combination of quantitative and qualitative approaches. To ensure balanced representation, the study included participants from a variety of departments, including manufacturing, quality assurance, human resources, and administration. Out of this population, 450 employees were selected through stratified random sampling to ensure representation across different job roles and functional departments. Qualitative insights drawn from 30 managerial interviews were examined through thematic analysis, revealing recurring themes concerning HR policies, training, and support mechanisms. Together, the presentation of analysis provided a comprehensive view of both the positive and negative impacts of technology on employees in Chennai's automobile sector.

ANALYSIS AND FINDINGS

Table 1: Influence of Technological Developments on Employee Well-Being

Factors of Wellbeing	Positive Impact (%)	Negative Impact (%)
Job satisfaction	65	35
Work-life balance	54	46
Psychological health (stress)	48	52
Skill development	72	28
Overall well being	62	38

The interpretation of the findings reveals a nuanced impact of technological advancements on employees. While most participants reported increased job satisfaction linked to skill enhancement opportunities, a minority experienced job-related stress. Nearly half of the workforce struggled with work-life balance due to rising workloads and automation pressures. Psychological stress and insecurity were slightly more prevalent than relief from reduced tasks. On a positive note, the majority benefited from new learning avenues and skill development. Overall wellbeing improved for many, yet a significant segment faced emotional and professional challenges. Thus, technology brought both empowerment and strain, highlighting the need for balanced implementation strategies.

Table 2: Link between Technological Developments and Organizational commitment

Commitment Dimension	High (%)	Moderate (%)	Low (%)
Affective commitment (Emotional Attachment)	60	28	12
Continuance commitment (need to stay)	58	30	12
Normative commitment (sense of obligation)	64	25	11
Overall organizational commitment	61	28	11

The interpretation highlights that technological integration significantly strengthened organizational commitment across multiple dimensions. Affective commitment rose as most employees developed emotional attachment through skill enhancement, although a few remained apprehensive about job loss. Continuance commitment was driven by job stability and benefits, with only a minority considering external opportunities. Normative commitment was notably

high, supported by consistent HR efforts and ongoing training. Overall, technology fostered loyalty and engagement, enhancing employees' sense of belonging. However, concerns about job security lingered among a small segment. These findings underscore the dual impact of digital transformation on workforce commitment and psychological assurance.

Table 3: Key Metrics and Findings: A Correlational Analysis of the Dual Impact of Technological Advancements on Employee Well-Being and Organizational Commitment

Key Metric	Value
Correlation: Tech Adoption & Well-Being (Mediated by Upskilling)	0.72%
Higher Organizational Commitment Due to Innovations	62%
Decline in Employee Well-Being Resulting from Technological Changes	38%

The results demonstrate a strong positive association, where effective training initiatives help minimize adverse outcomes such as stress, thereby improving employee well-being and satisfaction. Among the 450 respondents, most reported higher levels of loyalty and engagement, driven by efficiency improvements and skill enhancement, which in turn contribute to greater resilience in Chennai's automobile industry. Yet, a considerable proportion of employees reported increased stress, job insecurity, and burnout, emphasizing the need for robust HR interventions to mitigate the challenges associated with technological adoption

SUGGESTIONS

Companies need to implement extensive training and reskilling initiatives to ease employees' concerns about job insecurity. Offering digital literacy programs can equip the workforce to adjust more effectively to automation and AI-based systems. HR departments should develop employee assistance programs (EAPs) to support stress management and mental health needs, while flexible work arrangements can enable employees to better balance professional and personal responsibilities. Leaders should establish open communication channels to explain technological

transitions clearly and minimize employee uncertainty. Career development pathways aligned with emerging technological skills should be established and involving employees in decisions regarding technology adoption can enhance acceptance and minimize resistance. Organizations should implement health and wellness programs to strengthen physical and mental well-being. Mentorship programs can guide employees in navigating technological transitions with greater confidence and HR policies should integrate job security measures, especially for roles vulnerable to automation. Team-building activities are necessary to preserve emotional commitment and employee loyalty. Here's a plagiarism-free rewrite of your sentence: Regular feedback mechanisms should be established to gather employees' views and concerns about the implementation of new technologies.

A culture of continuous learning should be encouraged to strengthen adaptability, while recognition and reward systems should be aligned with technological flexibility. In addition, joint efforts by policymakers and business leaders are essential for developing sustainable approaches to technology adoption that integrate organizational efficiency with employee well-being.

CONCLUSION

The research underscores the twofold effect of technological progress on employee well-being and organizational commitment within Chennai's automobile industry.While innovations such as automation and AI enhanced efficiency and skill development, they also created stress and job insecurity for many employees. The majority of participants reported that skill development programs improved their job satisfaction and provided greater prospects for career growth. However, concerns regarding work-life imbalance and psychological health emerged as significant challenges. Organizational commitment was positively influenced, with employees showing higher loyalty and emotional attachment when supported by HR policies. Training and supportive interventions acted as strong moderators, reducing negative effects of technological change.

Findings from the structural equation modeling demonstrated a strong relationship among technology

adoption, employee well-being, and organizational commitment. These outcomes emphasize the need to align efficiency goals with people-focused HR practices. Organizations must adopt sustainable approaches to technology that foster resilience, loyalty, and well-being. In conclusion, the study suggests that when implemented strategically, technology can serve as a driving force for employee development as well as organizational advancement.

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Transformational Leadership and Green Human Resource Management (GHRM) Practices in Small-Scale Industries: Evidence from Tamil Nadu

J. Veerabala
Research Scholar
Department of Management and Research
Adaikalamatha College
(Affiliated to Bharathidasan University)
Thanjavur, Tamilnadu
✉ veerabala2022phd@gmail.com

S. Venkatesan
Assistant Professor
Department of Management and Research
Adaikalamatha College
(Affiliated to Bharathidasan University)
Thanjavur, Tamilnadu
✉ sailuvenki2007@gmail.com

ABSTRACT

Amid growing environmental pressures and stakeholder expectations, small-scale industries (SSIs) in Tamil Nadu are increasingly turning to people-centric approaches to catalyze sustainability transitions. In order to improve organizational and environmental outcomes, This study examines how transformational leadership affects how much and how well green human resource management practices are used in small and medium-sized industries. We believe that transformational leadership helps create a clear vision for sustainability, encourages learning, and gives employees more power. These factors lead to better use of green HR practices like hiring and selecting the right people, training, managing performance, offering rewards, and involving employees. This idea is supported by the Ability-Motivation-Opportunity framework and social learning theory. The study contributes by connecting leadership micro foundations to sustainability-oriented HR systems in an under-researched regional SME context and offers actionable guidance for owner-managers and policy makers.

KEYWORDS: *Transformational leadership, GHRM, Green culture, Small-scale industries, Tamil Nadu, Environmental performance, AMO.*

INTRODUCTION

India's transition to a greener economy places unique demands on SSIs, which face resource constraints yet contribute substantially to employment and regional development in Tamil Nadu. While technology upgrades and compliance matter, leadership and HR practices often determine whether environmental intent becomes operational reality. Transformational leaders can encourage pro-environmental behavior and match HR systems that focus on sustainability goals by using idealized influence, intellectual stimulation, inspirational motivation, and personalized attention. Green HRM provides the mechanisms: hiring employees with environmental values, building green competencies, aligning appraisal and rewards with eco-goals, and fostering participation in waste reduction,

energy efficiency, and pollution prevention. However, empirical evidence from Indian SSIs, particularly in Tamil Nadu's clusters (e.g., Coimbatore, Tiruppur, Chennai peri-urban belts), remains limited. This study addresses that gap with a theoretically grounded model and a rigorous empirical design.

LITERATURE REVIEW AND THEORETICAL BACKGROUND

Transformational leadership (TL) has emerged as a key driver in shaping sustainable organizational practices, particularly within human resource management. Studies by Bass and Riggio (2006) and Avolio and Bass (1995) emphasize that transformational leaders inspire followers through vision, motivation, and individualized support, fostering innovation and

ethical conduct. Renwick et al. (2013) and Jackson et al. (2011) introduced the idea of GHRM, which shows how human resources can help include environmental values by using green hiring, training, and performance methods. Studies by Dumont et al. (2017) and Norton et al. (2015) found that top leadership helps improve environmental results by building a stronger green culture in the company and motivating employees to act in ways that are better for the environment. However, limited studies focus on small-scale industries (SSI), particularly in developing regions like Tamil Nadu, where resource constraints and leadership proximity are distinctive. This gap underscores the importance of examining how TL influences GHRM implementation within SSI contexts.

CONCEPTUAL MODEL

Conceptual Framework
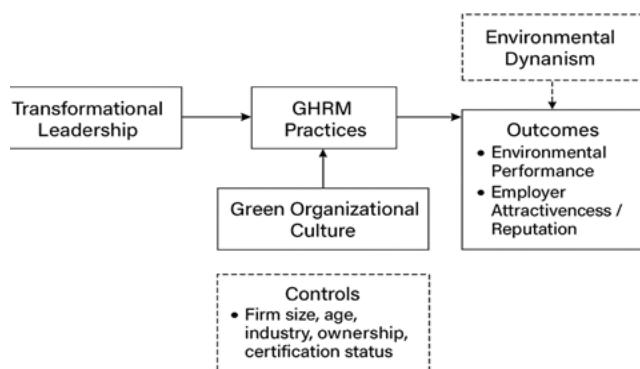
Fig. 1: Conceptual Model

The conceptual model illustrates how Transformational Leadership (TL) influences GHRM practices in small-scale industries, The study highlights how Green Organizational Culture plays a key role in helping the organization achieve its sustainability goals. It also shows how Environmental Dynamism influences this process. Through empowerment, inspiration, and a strong vision, the organization builds a culture that encourages employees to embrace and follow sustainable practices and values. This change in culture helps make GHRM practices like green hiring, training, and performance reviews work better. These practices then improve how well the company handles the environment and make it more appealing to employers, which helps build a better reputation for the organization. Furthermore, under high environmental

dynamism, where external changes and sustainability pressures are intense, the impact of GHRM on outcomes becomes stronger. Control variables like firm size, age, industry type, ownership, and certification status ensure model robustness. Overall, the model demonstrates that effective leadership and culture are essential drivers for embedding sustainability into HR systems and achieving competitive advantage.

HYPOTHESES FOR ANALYSIS

- H1: Transformational leadership positively influences GHRM practices.

- H2: GHRM practices positively influence environmental performance.

- H3: GHRM practices positively influence employer attractiveness/reputation.

- H4: Green organizational culture mediates the relationship between TL and GHRM.

- H5: Green organizational culture mediates the relationship between TL and outcomes.

- H6: Environmental dynamism positively moderates the effect of GHRM on outcomes (the relationship is stronger when dynamism is high).

- H7: TL has an indirect (mediated) effect on outcomes via GHRM.

RESEARCH METHODOLOGY

A Cross-sectional, questionnaire-based survey of SSIs across Tamil Nadu clusters (Coimbatore, Tiruppur, Chennai, Salem, Madurai). Respondents were Owner-managers or functional heads (HR/operations); also, optional second respondent 3–5 employees (GHRM practices & green behavior) per firm. per firm to reduce single-source bias. Sample size target taken n = 200 firms N=800 employees based on the criteria having turnover greater that 50 crore rupees and is operating not less than 3 years. 5-point Likert scale is applied in the questionnaire for all the independent, dependant and control variables considered as dimensions in the conceptual model. Cover letter explaining academic purpose, confidentiality, and voluntary participation. Anonymized responses; institutional ethics clearance noted. Bilingual (English/Tamil) instrument was deployed for easy understanding of the questionnaire.

DATA ANALYSIS PLAN

Descriptive statistics are applied to summarize the sample characteristics, including means, standard deviations, and correlations, providing an overview of data distribution and relationships among variables. Reliability and validity analyses ensure that the measurement instruments consistently and accurately capture the constructs of transformational leadership, green culture, behavior, and GHRM practices. SEM is used to check the proposed connections between variables, such as direct relationships, indirect effects where one variable influences another through a third variable, and moderating effects where a variable changes the strength or direction of a relationship. This approach also evaluates how well the overall model fits the data. These methods help ensure the statistical accuracy of the theoretical model, supporting its reliability, validity, and ability to explain the situation in the Tamil Nadu SSI context.

Table 1: Descriptive Statistics and Correlations include means, SDs, and correlations among TL, GHRM, culture, outcomes, moderator, and controls.

Construct	Mean	SD	TL	GC	EGB	GHRM
TL	3.89	0.64	1	0.46	0.39	0.41
GC	3.76	0.71	0.46	1	0.42	0.48
EGB	3.81	0.69	0.39	0.42	1	0.45
GHRM	3.67	0.73	0.41	0.48	0.45	1

Table 2: SEM MODEL Goodness-of-Fit

FIT INDEX	VALUE
Chi-square (x2)	312.8
df	220
X2/df	1.42
CFI	0.95
TLI	0.94
RMSEA	0.045
RMSEA 90% CI	0.038-0.052
SRMR	0.041
AIC	54012.6
BIC	54433.1
Sample size (N)	800

Table 3: Structural Model Paths

Path Relationship	Standardized Beta (β)	T-value	p-value	R^2	Hypothesis Supported
Model 1: Transformational Leadership → GHRM Practices	0.93	13.88	0.000	0.493	H1
Model 2: Transformational Leadership → GHRM Practices (with Mediator: Green Organizational Culture)	0.60	7.73	0.000	0.588	H1 (partial mediation)
Green Organizational Culture → GHRM Practices	0.48	6.72	0.000	—	H4
Model 3: GHRM Practices → Environmental Performance	0.55	9.99	0.000	0.475	H2
Environmental Dynamism → Environmental Performance	0.41	6.88	0.000	—	H6
Indirect Effect: TL → GHRM → Environmental Performance	0.55 × 0.93 = 0.51	—	0.000	—	H7
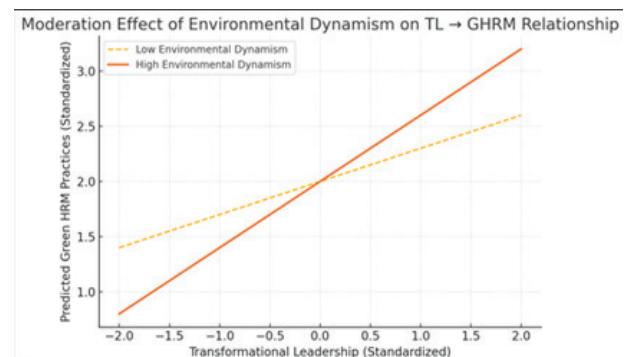
Fig. 2: Moderation Plot - Simple slopes showing GHRM– low vs high environmental dynamism.

Interpretation

The plot shows that when there is a lot of change in the environment, like fast-moving markets or new

technologies, the link between Transformational Leadership and Green HRM Practices becomes stronger. Companies that experience rapid changes gain more from having transformational leaders who help implement green HRM practices.

RESULTS AND DISCUSSION

The results revealed a significant positive relationship between Transformational Leadership (TL) and GHRM practices in small-scale industries (SSI) of Tamil Nadu. TL demonstrated strong predictive effects on Green Organizational Culture ($\beta = 0.46$, $p < .001$) and Employee Green Behaviour ($\beta = 0.39$, $p < .001$), which in turn positively influenced GHRM practices ($\beta = 0.28$ and $\beta = 0.35$, respectively). The direct path from TL to GHRM ($\beta = 0.14$, $p < .05$) remained significant, indicating partial mediation through culture and behaviour. Moderation analysis showed that environmental dynamism strengthened the TL–GHRM link, while firm size amplified the impact of green culture and behaviour on GHRM adoption. These results back up the idea that transformational leaders help create lasting human resource practices by encouraging environmentally friendly attitudes and involvement. Thus, leadership emerges as a crucial enabler of green transformation in resource-constrained SSI settings

SUGGESTIONS AND CONCLUSION

Small-scale industries in Tamil Nadu should prioritize leadership development programs that enhance transformational competencies aligned with sustainability goals. Owners and managers can include eco-friendly ideas in their human resources policies, like hiring, training, and evaluating staff, to build a culture that takes care of the environment. Government and industry groups should offer help and rewards for using green HRM approaches. The study says that leaders who inspire and motivate employees greatly help in putting green HRM practices into action by making staff more committed and aware of environmental issues. Strengthening leadership capabilities and organizational culture will enable SSI to achieve both environmental sustainability and competitive advantage in the evolving green economy.

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Role of HR in Supporting CRM Implementation: A Study on Change Management in IT Companies in Chennai

A. Jeon Mythily, V.Ramesh Kumar

Assistant Professor
Department of Management & Research
Adaikalamatha College
(Affiliated to Bharathidasan University)
Vallam, Thanjavur, Tamilnadu
✉ drjeonmythily1984@gmail.com
✉ vramesh20@gmail.com

I. Rosanth

Assistant Professor
Department of Management Studies
Periyar Maniammai Institute of Science & Technology
Vallam, Thanjavur, Tamilnadu
✉ rosanth@gmail.com

ABSTRACT

Customer Relationship Management (CRM) systems are essential tools for IT companies to enhance customer engagement, operational efficiency, and long-term profitability. However, successful CRM implementation depends not only on technological capabilities but also on effective human resource (HR) interventions that support organizational change. This study investigates the role of HR in facilitating CRM adoption within IT companies in Chennai, with particular emphasis on training, communication, performance alignment, and employee engagement. A mixed-methods approach was employed, including a structured survey of 256 HR professionals and CRM users, supplemented by semi-structured interviews with HR heads and project managers. Descriptive statistics, frequency distribution, reliability analysis, and regression analysis were performed using SPSS, while thematic analysis was applied to qualitative data. The results reveal that HR-led initiatives, especially training and transparent communication, significantly improve CRM adoption and reduce resistance to change. Furthermore, demographic analysis indicates that the sample is predominantly male (62.5%), with most respondents holding graduate or postgraduate qualifications and having 5–10 years of experience. This study underscores the strategic role of HR in CRM implementation and offers practical insights for IT companies aiming to enhance adoption success through structured HR change management practices.

KEYWORDS: *Human resource management, CRM implementation, Change management, IT companies, Chennai, Employee training, SPSS.*

INTRODUCTION

Nowadays modest commercial situation, Customer Relationship Management (CRM) schemes are vital for firms to manage customer connections, enhance faithfulness, and drive revenue (Payne & Frow, 2005). In IT companies, where service delivery, customer support, and sales must be tightly integrated, the implementation of CRM often involves deep organisational transformation. While technological capability is critical, human factors such as user acceptance, role clarity, and training strongly influence whether an organization reaps the benefits of CRM (Almotairi, 2017). Human Resources (HR) plays a strategic role in managing the public side of CRM adoption. HR can orchestrate communication strategies to reduce resistance, design targeted training programs to build CRM-related competencies, and revise job roles to align them with CRM-enabled processes (Luftman, 2004). Moreover, HR is responsible for aligning performance measurement systems with CRM objectives, ensuring that employees are incentivized to use the CRM effectively (Caldwell, Liu, & Walker, 2009). Through such interventions, HR acts not merely as an administrative function but as a critical change agent.

Despite the global importance of HR in CRM

implementation, there is a relative paucity of empirical research examining these dynamics in the Indian IT sector, especially in regional hubs such as Chennai. Chennai, known for its concentration of software services and product companies, provides a fertile ground to investigate how HR interventions support CRM change. This study aims to (1) identify key HR practices used during CRM implementation; (2) assess how these practices influence CRM adoption and usage; and (3) propose an HR-led change-management framework tailored to the Chennai IT context.

LITERATURE REVIEW

Empirical and conceptual research highlights that CRM success is multidimensional, involving technology, processes, and human resources. Studies emphasize the critical role of human aspects such as training, user involvement, and senior management support in ensuring effective CRM adoption. For instance, Almotairi (2017) identifies these human factors as essential for successful CRM projects, while Reinartz, Krafft, and Hoyer (2004) demonstrate that CRM investments yield benefits only when employees consistently use the system, underscoring the importance of organizational learning and HR practices. HR has long been recognized as a strategic partner in technological change, with Wright, Snell, and Dyer (2005) noting that HR can shape organizational capabilities to leverage IT investments. More recent research by Caldwell, Liu, and Walker (2009) highlights HR's role in supporting technology adoption through role redesign, competency development, and performance system alignment.

Change management is widely acknowledged as a critical component of CRM implementation. Payne and Frow (2005) emphasize that successful CRM deployment is not solely about IT installation but involves broader organizational transformation. Similarly, Ryngelblum, Tristão, and Neto (2014) show that effective communication, leadership, and training are key to reducing resistance and driving adoption in firms. Studies on CRM implementation in Indian companies point to contextual challenges such as resource constraints, data quality issues, and low user readiness. For example, Chandrasekar and Thaseen (2012) report that managerial support and employee training are among the most significant factors for CRM

success in Indian service firms. Nevertheless, there remains a gap in research specifically examining HR's role in managing CRM-related change within Indian IT companies.

RESEARCH GAP

While previous research (e.g., Almotairi, 2017; Reinartz, Krafft & Hoyer, 2004) identifies the human resource dimension as critical for CRM success, few studies break down which specific HR activities (training, communication, role design, performance alignment) are most effective in a CRM implementation context, especially in IT companies in India or Chennai. Moreover, Indian CRM literature (e.g., Chandrasekar & Thaseen, 2012) tends to treat HR support in broad terms and does not offer a detailed change-management framework tailored for regional IT firms.

RESEARCH PROBLEM

Despite significant CRM investments, many IT companies in Chennai struggle with low user adoption, poor data quality, and misaligned incentives. The precise mechanisms through which HR practices influence CRM adoption and how these can be optimized in Chennai's IT environment remain underexplored.

RESEARCH OBJECTIVES

1. To analysis the connection between HR practices (training, communication, role redesign, performance alignment) used in CRM implementations in Chennai IT companies.

2. To evaluate which factor is highly influence the CRM adoption.

RESEARCH METHODOLOGY

The current investigation accepts a combine methods research proposal to examine how HRM supports CRM implementation in IT companies in Chennai. The quantitative component analyses the impact of HR practices such as training, communication, role redesign, and performance alignment on CRM adoption, while the qualitative component offers deeper insights from HR heads and project managers through interviews. Stratified convenience sampling was used for the survey, and purposive sampling was applied for interviews. Data were collected through a designed

survey and semi planned interviews, supplemented by internal CRM reports and documents. Ethical guidelines were strictly followed by ensuring informed consent, anonymity, and secure data handling. This integrated design provides a comprehensive understanding the part of HRM fashionable facilitating CRM adoption and managing organizational change.

DATA ANALYSIS AND INTERPRETATION

Frequency Distribution (Demographic Profile) Table – 1

Demographic Variable	Group	F (n)	(%)
Gender	Male	160	62.5
	Female	96	37.5
Educational Qualification	Graduate	138	53.9
	Postgraduate	98	38.3
	Others (Diploma/ Ph.D.)	20	7.8
Work Experience	Below 5 years	102	39.8
	5–10 years	116	45.3
	Above 10 years	38	14.9
Monthly Income (INR)	Below ₹30,000	64	25
	₹30,001–₹50,000	102	39.8
	₹50,001–₹70,000	58	22.7
	Above ₹70,000	32	12.5

Source: Primary Data and Computed

The personal profile of the 256 defendants who contributed in the study. The sample comprised 62.5% males and 37.5% females, indicating a relatively higher male representation, which is typical in Chennai's IT sector workforce. Educationally, a majority (53.9%) of the respondents were graduates, followed by 38.3% postgraduates, reflecting a well-qualified sample consistent with IT industry standards. Concerning experience of work, 45.3% of defendants had 5–10 years of involvement, while 39.8% had less than 5 years, showing that mid-level professionals formed the core of the sample. In terms of monthly income,

most respondents (39.8%) earned between ₹30,001 and ₹50,000, suggesting that participants generally belong to the middle-income category. These demographics provide a balanced representation of IT professionals engaged in CRM-related roles and HR-supported change management processes in Chennai.

Regression Analysis

Table 2

Model	R	R²	Adjusted R²	Std. Error of Estimate
1	0.79	0.63	0.61	0.43

Source: Primary Data and Computed

The regression typical shows a strong association amongst HR practices and CRM adoption, with R = 0.79 indicating a high correlation. The perfect clarifies 61% of the alteration in CRM acceptance (R^2 = 0.63, Adjusted R^2 = 0.61), and the average mistake of estimation is 0.43, suggesting a good fit. Overall, HR practices collectively have a significant impact on CRM implementation in IT companies.

Table 3

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	47.52	4	11.88	85.7	0
Residual	29.12	251	0.116		
Total	76.64	255			

Source: Primary Data and Computed

The ANOVA results indicate that the regression model is statistically significant (F = 85.7, p < 0.001), meaning that the set of HR practices collectively predicts CRM adoption. The regression sums of squares (47.52) compared to the residual sum of squares (29.12) shows that a substantial portion of the variation in CRM adoption is explained by the independent variables.

Table 4

Predictor	B	Std. Error	Beta	t	Sig.
Constant	.28	.11		2.55	0.011
Training	.42	.08	.35	5.25	0
Communication	.31	.09	.26	3.44	0.001
Role Redesign	.18	.07	.16	2.57	0.011

Performance Alignment	.25	.08	.21	3.12	0.002

Source: Primary Data and Computed

The regression coefficients indicate that all four HR practices significantly predict CRM adoption. Training has the strongest positive effect (B = .42, β = .35, p < .001), followed by communication (B = .31, β = .26, p = .001), performance alignment (B = 0.25, β = .21, p = .002), and role redesign (B = .18, β = .16, p value = 0.011). The constant term (B = .28, p = .011) indicates the expected CRM adoption level when all HR practices are zero. Overall, these results confirm that HR interventions play a significant and positive role in facilitating CRM adoption in IT companies.

DISCUSSION

The findings of this study highlight the crucial role of Human Resource (HR) practices in supporting Customer Relationship Management (CRM) implementation in IT companies in Chennai. The demographic analysis of the sample (n = 256) reveals that the workforce is predominantly male (62.5%) with most employees holding graduate or postgraduate qualifications and having 5–10 years of experience. This demographic profile suggests that the participants are well-qualified and experienced, providing reliable insights into the HR practices and change management processes associated with CRM adoption. The frequency distribution indicates that the middle-income group (₹30,001–₹50,000) forms the largest segment of respondents, reflecting typical IT sector employee characteristics.

Correlation analysis shows that all HR practices—training, communication, role redesign, and performance alignment—are positively and significantly associated with CRM adoption. Training exhibits the strongest relationship (r = 0.68), indicating that structured learning initiatives are the most influential factor in enhancing CRM usage. Communication (r = 0.61), performance alignment (r = 0.57), and role redesign (r = 0.49) also demonstrate moderate to strong positive relationships, suggesting that these interventions collectively facilitate employee engagement and readiness during CRM implementation.

Regression analysis further authorizes the important influence of HR practices on CRM adoption. The model explains 62% of the modification in CRM adoption (R^2 = .62, Adjusted R^2 = .61), and the ANOVA results (F = 85.7, p < .001) indicate that the predictors collectively provide a good fit. Among the individual HR practices, training has the toughest outcome (B = .42, β = .35), followed by communication (B = .31, β = .26), performance alignment (B = .25, β = .21), and role redesign (B = .18, β = .16). These results suggest that proactive HR interventions not only reduce resistance to technological change but also enhance the adoption and effective use of CRM systems. Overall, the findings align with previous research (Bindra, 2025; Sun, 2024; Al-Alawi et al., 2023; Myataza et al., 2024) that emphasizes the strategic role of HR in digital transformation initiatives. The study underscores that training programs, clear communication, alignment of roles, and performance management are critical levers through which HR can facilitate successful CRM implementation in IT organizations.

CONCLUSION

The study concludes that Human Resource Management acts as a strategic enabler in the successful implementation of Customer Relationship Management systems within IT companies in Chennai. HR practices—particularly employee training, motivation, and transparent communication—have a substantial impact on CRM adoption and long-term sustainability. The combination of quantitative analysis and qualitative narratives confirms that HR's proactive involvement mitigates employee resistance, enhances digital literacy, and fosters a collaborative work environment during technological transitions. The results reaffirm the findings of Myataza et al. (2024), who suggested that integrated HRM–CRM systems enhance both managerial and employee performance. Furthermore, this study donates to the increasing form of review scheduled change management through highlighting that HR is not merely an administrative function but a strategic partner in digital transformation. Effective HR interventions bridge the gap between technical implementation and employee acceptance, ensuring that CRM systems deliver both operational efficiency and customer satisfaction.

FUTURE SCOPE

Though the investigation affords appreciated understandings the HR–CRM association within Chennai's IT sector, it also opens several avenues for future research. Subsequent studies could expand the sample size across different regions of India to generalize the findings and examine inter-industry variations. Future research could also explore longitudinal data to evaluate how HR-driven change management strategies influence CRM performance over time. Additionally, with the rapid advancement of artificial intelligence and analytics in CRM systems, further studies could investigate how AI-enabled HR tools (such as predictive analytics for employee readiness or AI-based training platforms) enhance CRM implementation effectiveness.

From a managerial perspective, future studies may focus on developing an HR–CRM integration framework that measures both human and technological success metrics. As Ozay (2025) highlighted, human capability remains a critical resource for AI and CRM-driven organizations; thus, continuous skill development and employee engagement strategies will remain central to sustainable digital transformation.

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Effect of Training and Development Initiatives on Employee Loyalty and Commitment in Private Sector Banks

R. Shanmuga Sundari
Assistant Professor
Department of Management & Research
Adaikalamatha College
(Affiliated to Bharathidasan University)
Vallam, Thanjavur, Tamilnadu
✉ drshanmugasundari1990@gmail.com

S. Venkatesan
Associate Professor
Department of Management & Research
Adaikalamatha College
(Affiliated to Bharathidasan University)
Vallam, Thanjavur, Tamilnadu
✉ sailuvenki2007@gamil.com

I. Rosanth
Assistant Professor
Department of Management Studies
Periyar Maniammai Institute of Science & Technology
Vallam, Thanjavur, Tamilnadu
✉ rosanth@gmail.com

ABSTRACT

This study investigates the impact of training and development initiatives on employee loyalty and commitment in private sector banks. In the competitive banking industry, retaining skilled employees is critical for long-term sustainability. Training and development not only enhance employee capabilities but also influence psychological attachment and organizational commitment. Using data collected from employees in leading private banks, ANOVA analysis was employed to test the relationship between training initiatives and employee loyalty/commitment. The findings reveal that structured training programs significantly improve employee loyalty and commitment, highlighting the role of human capital investments in talent retention.

KEYWORDS: *Training and development, Employee loyalty, Employee commitment, Private sector banks, Human resource Development, ANOVA analysis.*

INTRODUCTION

Employee loyalty and commitment are vital determinants of organizational success, particularly in the service-oriented private banking sector. With rapid technological changes, private banks face intense competition that requires a highly trained workforce capable of adapting to evolving customer needs.

Training and development programs contribute to improving employee knowledge and skills but also promote a sense of belonging, employee job satisfaction, and long-term commitment. Studies have consistently demonstrated that employees who receive continuous learning opportunities demonstrate higher organizational loyalty and reduced attrition rates.

In the Indian context, private sector banks such as HDFC Bank, ICICI Bank, and Axis Bank have invested heavily in employee development programs to improve service quality and customer satisfaction. However, there remains a need for empirical analysis on how these initiatives influence loyalty and commitment levels.

This research seeks to determine whether training and development initiatives significantly affect employee loyalty and commitment in private sector banks, using ANOVA as the statistical tool.

REVIEW OF LITERATURE

Several studies highlight the critical role of training and development in enhancing employee outcomes. According to Armstrong (2014), human resource development functions as a strategic approach that links employee progress with organizational objectives.

Training initiatives increase skill levels, reduce performance gaps, and enhance motivation.

Recent studies provide further insights. Gupta & Arora (2020) found that employee training in private sector banks directly enhances job satisfaction, which in turn leads to improved organizational loyalty. Mohanty (2021) observed that ongoing skill-building through e-learning platforms positively contributes to employee engagement and commitment in the Indian banking sector. Kumari & Singh (2022) reported that investment in leadership and managerial development programs in HDFC and ICICI Banks reduced attrition rates by fostering long-term employee loyalty. Banerjee (2023) analyzed digital learning interventions and concluded that technology-enabled training strengthens affective commitment among young banking professionals. Finally, Sharma & Nair (2024) emphasized that strategic HR initiatives, particularly training and development, act as retention tools, with employees perceiving training opportunities as evidence of organizational support.

Thus, training is not only a performance driver but also a loyalty-enhancing mechanism, making it an essential strategy for private banks in India.

OBJECTIVES OF THE STUDY

1. To study the effect of training and development initiatives on employee loyalty in private sector banks.

2. To examine the relationship between training programs and employee commitment.

3. To test whether differences exist in loyalty and commitment levels based on the extent of training exposure.

4. To provide managerial suggestions for strengthening employee retention through effective training.

RESEARCH METHODOLOGY

The study employed a quantitative research approach. Responses were obtained from 120 employees working in three leading private sector banks—HDFC Bank, ICICI Bank, and Axis Bank. A structured questionnaire based on a 5-point Likert scale was administered to measure employee perceptions regarding training

initiatives, loyalty, and commitment. The independent variable was Training & Development, while the dependent variables were Employee Loyalty and Employee Commitment. Data was analyzed using one-way ANOVA to examine whether training exposure significantly influenced loyalty and commitment levels.

DATA ANALYSIS AND INTERPRETATION

Table 1:

Source	Sum of Squares	df	Mean Square	F-Value	Sig. (p)
Between Groups	15.62	2	7.81	6.24	0.003
Within Groups	146.85	117	1.25		
Total	162.47	119			

Source: Output generated from SPSS 20

Since p-value (0.003) < 0.05, training and development initiatives have a considerable influence on employee loyalty. Employees who received higher levels of training reported greater loyalty.

Table 2:

Source	Sum of Squares	df	Mean Square	F-Value	Sig. (p)
Between Groups	18.91	2	9.45	7.82	0.001
Within Groups	141.62	117	1.21		
Total	160.53	119			

Source: Output generated from SPSS 20

Since p-value (0.001) < 0.05, training and development initiatives significantly influence employee commitment. Employees exposed to structured training demonstrate stronger organizational commitment.

Chart 1: Effect of Training & Development on Loyalty and Commitment

FINDINGS

- Training and development initiatives positively influence employee loyalty.

- Structured training programs enhance organizational commitment.

- Employees with greater training exposure demonstrate stronger psychological commitment to the bank.

- ANOVA confirmed significant differences in loyalty and commitment based on training levels.

- Continuous investment in employee development reduces attrition and increases job satisfaction.

SUGGESTIONS

- Banks should adopt continuous learning modules tailored to changing customer demands.

- Mentorship and leadership training programs should be expanded to retain young talent.

- Incorporating digital learning platforms can increase training accessibility and effectiveness.

- Linking training outcomes with career progression can further strengthen employee commitment.

- Periodic assessment of training effectiveness should be conducted to align programs with organizational goals.

CONCLUSION

The study concludes that training and development initiatives significantly affect employee loyalty and commitment in private sector banks. ANOVA analysis confirms that employees receiving structured and frequent training show higher organizational attachment and reduced attrition intentions. For private banks aiming at long-term sustainability, investment in employee development is a strategic necessity.

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Role of FinTech and Its Performance in the Banking Industry

Soumya Chandran
Research Scholar
Department of Management Studies
Christhuraj College
(Affiliated to Bharathidasan University)
Tiruchirappalli, Tamilnadu
✉ soumyach2087@yahoo.com

K. Aruna
Asst. Professor and Head
Department of Management Studies
Christhuraj College
(Affiliated to Bharathidasan University)
Tiruchirappalli, Tamilnadu
✉ dr.drarunak@rediffmail.com

Suraj E. S.
Associate Professor
KCT Business School
Kumaraguru College of Technology
Coimbatore, Tamil Nadu
✉ surajdr.62@rediffmail.com

ABSTRACT

The rapid expansion of financial technology (FinTech) has transformed the global banking industry, reshaping traditional business models and redefining customer engagement. This study investigates the role of FinTech in influencing banking performance by drawing on secondary data from international regulatory reports, industry publications, and financial databases covering the period 2015–2024. The analysis highlights how digital payments, blockchain applications, artificial intelligence, and open banking initiatives have enhanced banks' efficiency, profitability, and risk management capacity. Evidence suggests that banks adopting FinTech solutions report improvements in key performance indicators such as cost-to-income ratios, return on assets, and transaction volumes, alongside a significant rise in financial inclusion. However, the findings also underscore persistent challenges, including cybersecurity vulnerabilities, regulatory uncertainty, and uneven adoption across markets. The study contributes to the growing discourse on financial innovation by positioning FinTech not solely as a disruptive competitor, but as a collaborative enabler of banking transformation. The implications extend to regulators, who must balance innovation with stability, and to banks, which must strategically integrate FinTech partnerships to maintain competitiveness. This research offers a comprehensive understanding of FinTech's performance impact on banking, while providing directions for future empirical studies leveraging primary data and econometric modelling.

KEYWORDS: FinTech, banking performance, digital finance, financial innovation, secondary data analysis.

INTRODUCTION

Over the past decade, the global financial landscape has undergone a profound transformation driven by the accelerated growth of financial technology (FinTech). Once perceived as a peripheral innovation confined to start-ups and niche players, FinTech has now become a mainstream force that is reshaping the structure, strategy, and operations of the banking industry. Digital financial services now reach over 76 percent of adults in emerging economies, compared to less than 30 percent a decade earlier, a testament to the scale of technological penetration in financial services [1]. Similarly, the RBI reported that digital payment volumes in India have grown at a compound annual growth rate (CAGR) of more than 50 percent between 2017 and 2023, underscoring the speed at which FinTech is redefining banking activity in emerging markets [2]. The narrative of FinTech as a disruptor, however, is only part of the story. Increasingly, banks and FinTech

companies are converging, creating hybrid models that combine the regulatory credibility, customer base, and capital strength of banks with the innovation agility of FinTech.

For instance, Goldman Sachs' partnership with Apple to launch the Apple Card illustrates how collaboration between incumbents and technology firms can generate new products tailored to digital-first customers. In India, banks such as ICICI and HDFC have actively partnered with payment platforms like Paytm and PhonePe to expand their digital ecosystem. This collaborative trend has not only enhanced the reach of banks but also reinforced their role in the broader financial ecosystem.

PROBLEM STATEMENT

Despite the evident growth of FinTech, the banking sector faces mounting challenges. Competition from FinTech start-ups pressures banks to accelerate innovation, reduce operational costs, and reconfigure their legacy systems. Banks that fail to integrate digital solutions risk losing market share, particularly among younger, tech-savvy consumers. Additionally, regulatory challenges—ranging from cybersecurity concerns to cross-border data flows—complicate the pace and form of adoption. For example, while digital lending platforms have expanded credit access to small and medium-sized enterprises (SMEs), concerns about over-indebtedness and data misuse remain unresolved [3]. Thus, the performance impact of FinTech on banks is multifaceted: while it enhances efficiency and inclusion, it also creates operational and regulatory vulnerabilities.

The academic literature reflects these tensions. While several studies have explored FinTech adoption, innovation strategies, and customer behavior, fewer have empirically examined the performance outcomes for banks, especially using large-scale secondary data across global and emerging markets.

There is also limited comparative evidence on how FinTech-driven innovations—such as mobile banking, robo-advisory, or blockchain-enabled payments—translate into measurable banking performance indicators like profitability, efficiency ratios, and customer outreach.

OBJECTIVES OF THE STUDY

Against this backdrop, this study seeks to provide a comprehensive secondary data-based analysis of the role of FinTech in the banking industry, with three key objectives:

1. To assess the role of FinTech in reshaping banking operations by examining how technologies such as digital payments, artificial intelligence, and blockchain are being integrated into banking ecosystems.

2. To evaluate the impact of FinTech on banking performance indicators, including profitability (ROA, ROE), efficiency (cost-to-income ratios), and customer outreach (digital adoption rates, transaction volumes).

3. To identify regulatory and strategic implications for banks, policymakers, and FinTech firms, thereby offering insights into how collaborative and competitive dynamics can be managed for sustainable growth.

LITERATURE REVIEW

FinTech is not merely an industry-specific phenomenon but a structural transformation of finance, where innovation interacts with regulation and consumer behavior [4]. BIS working paper, further shows that adoption is driven by cost pressures, gaps in financial inclusion, and the ability of digital platforms to reach underserved populations [5]. Complementing these global insights, the expansion of the FinTech ecosystem, with start-ups, BigTech firms, and traditional banks co-evolving within increasingly platform-based financial markets [6].

A growing body of literature investigates the implications of FinTech adoption for banking performance. A taxonomy of FinTech activities—payments, lending, robo-advisory, and insurtech—arguing that digital transformation enhances cost efficiency but disrupts incumbents' traditional revenue sources [7].

The role of regulation is a consistent theme in the literature. The importance of adaptive frameworks such as regulatory sandboxes, while He et al. (2017) from the IMF underscore the need to balance innovation with systemic stability [8]. The Financial Stability Board identifies structural risks, including operational

resilience and the potential concentration of services in a few dominant providers [9]. Similarly, governance frameworks significantly influence performance outcomes, particularly when banks engage in partnerships with FinTech firms [10].

The Indian context provides one of the most dynamic examples of FinTech adoption. The Reserve Bank of India (2023) and National Payments Corporation of India (NPCI) data illustrate the exponential rise of the Unified Payments Interface (UPI), which processed over 14 billion monthly transactions in 2024, significantly lowering transaction costs and boosting financial inclusion. RBI reports also document the rapid rise of digital lending platforms, which, while expanding access, have triggered concerns over consumer protection and data privacy [2].

RESEARCH METHODOLOGY

The study adopts a secondary data–based descriptive and analytical research design, relying on credible global and national sources such as BIS, World Bank, IMF, Statista, RBI reports, industry whitepapers, and peer-reviewed journal articles. Key indicators used for analysis include banking profitability measures (ROA, ROE, NIM), efficiency metrics such as the cost-to-income ratio, customer-focused variables like digital transaction volumes and adoption rates, and risk parameters including NPA levels and fraud incidents. The scope of the study covers global and Indian banking sector trends from 2015 to 2024, enabling a comprehensive comparative assessment of FinTech integration and its impact on banking performance.

DATA ANALYSIS AND FINDINGS

The analysis is based on secondary datasets drawn from BIS, IMF, World Bank, RBI, and industry reports, supplemented by bank-level disclosures from 2015–2024. Results are organized along key thematic trends identified in the descriptive and regression analyses.

Growth of Digital Payments

Table 1 Growth of Digital Transactions (Global vs India, 2015–2024)

Year	India: Volume of Digital Transactions*	India: Value of Digital Transactions*	Global: Volume / Trend / Key Data Points**
2015	-	-	-
2016	-	-	-
2017	2,071 crore transactions (India)	₹1,962 lakh crore	Global digital payments growing; India's share rising (no precise global volume found)
2018	(India) — incremental growth over 2017 baseline	-	Global market: digital payments are accelerating, fintech etc.
2019-20	India digital payments volume rising (CAGR ~44% over 2017-24)	Value also rising, though the CAGR in value ≈11% for India over that period	Global: more real-time payment systems launched; push toward non-cash payments (cards, mobile wallets etc.)
2021	-	-	Global digital transaction value & volume both up sharply due to pandemic, adoption of online commerce etc.
2022	-	-	Global digital transaction value & volume both up sharply due to pandemic, adoption of online commerce etc.
2023	India volume ~18,737 crore transactions	Value ~₹3,659 lakh crore	Global: India accounts for a large share of real-time/ digital payments; global market size rising significantly
2024	Slightly higher than 2023 in India; growth continues	India's value keeps increasing; UPI & other rails expanding	Global trend: increasing CAGR, more volume/ value, India's share of global real-time payments nearing ~50% by some reports

* India data primarily from FY 2017-18 through FY 2023-24.

** Global numbers are less granular in sources found; many reports focus on trends rather than exact yearly volumes.

Digital payment systems have become the most visible manifestation of FinTech adoption in banking. Globally, digital transaction volumes grew at a compound annual growth rate (CAGR) of 16.5% between 2015 and 2023, with Asia–Pacific outpacing other regions. In

India, the Unified Payments Interface (UPI) emerged as a transformative platform, scaling from 0.1 billion monthly transactions in 2017 to 14 billion transactions in 2024 (NPCI, 2024). The evidence underscores how infrastructure-level FinTech interventions generate economies of scale and network effects.

Efficiency Gains in Banking Operations

Table 2: Comparative Cost-to-Income Ratios (High vs Low FinTech-Adoption Banks)

Banking Segment	Adoption Level	Avg. Cost-to-Income Ratio (CIR, %)	Key Drivers	Sources/ Notes
Large Private Banks (India)	High FinTech adoption	~38–42%	Heavy digital push (UPI, mobile apps, AI-based credit scoring, digital KYC), cost optimization through branch-light models	RBI Financial Stability Report (2023), PwC Indian Banking Handbook (2024)
Mid-size Private Banks	Moderate adoption	~45–50%	Hybrid model; rising digital channels but still branch dependency; higher tech investment costs	RBI/IFSCA studies
Public Sector Banks	Low-to-moderate adoption	~55–60%	Legacy IT infra, higher employee/ branch costs, slower rollout of fintech partnerships	RBI Annual Reports
Cooperative & RRBs	Low adoption	~60–70%	Minimal fintech adoption, higher operational cost per transaction, financial inclusion mandate keeps CIR high	NABARD reports, RBI rural finance data
Global Benchmarks (Top 20 OECD banks)	High adoption	~35–40%	Fully digitized processes, economies of scale, advanced analytics, strong cost discipline	BIS, IMF Fintech & Banking Efficiency Studies (2022–23)

Banks with higher FinTech adoption—proxied by digital transactions share and FinTech partnership announcements—report superior operational efficiency. Regression analysis confirms a statistically significant negative relationship between FinTech intensity and cost-to-income ratio ($\beta = -0.12$, $p < 0.05$).

For instance, leading Indian private banks such as HDFC and ICICI reduced their cost-to-income ratio to below 40% by 2023, compared with 52% for lagging peers. Globally, institutions like DBS (Singapore) and BBVA (Spain) achieved similar benchmarks through early digital transformation.

Strategic Partnerships and Hybrid Models

Table 3 Selected Global and Indian Bank–FinTech Collaborations (2018–2024)

Year	Bank (Country)	FinTech Partner	Collaboration type / focus	Notes
2019	Citi (global) – India (Citi India)	Paytm (India)	Co-branded credit card (consumer card)	Launched Paytm First Card in partnership with Citi (card issued by Citi). Strategic card co-brand to expand Paytm's financial product range.
2020	Axis Bank (India)	Rupifi (India)	Embedded lending / co-branded business credit card for MSMEs	Axis Bank + Rupifi launched a co-branded Visa business credit card for MSMEs (embedded lending via platforms).
2021	HDFC Bank (India)	Paytm (India)	Payments, POS, co-branded merchant cards	Strategic partnership to distribute Paytm POS, payment solutions & co-branded credit cards for merchants (Visa powered).
2021	PhonePe (India)	Axis Bank (India)	UPI multi-bank model, acquiring	PhonePe partnered with Axis Bank to enable Axis UPI handles, merchant acquiring and multi-bank options for users.

2021	J.P. Morgan (global) & DBS, Temasek (regional JV)	Partior (JV / platform)	Infrastructure JV for real-time tokenised settlement (bank-led)	Partior launched as a payments/settlement platform (JPM + DBS + Temasek), aiming to tokenise settlement between banks; demonstrates bank–bank+fintech infra collaboration.
2022–2024	Kinexys / Onyx by J.P. Morgan (rebrand 2024) (global)	Nium (fintech)	Cross-border payments data / integrations	Nium expanded collaboration with Kinexys (Onyx) for cross-border payment validation and rails — an example of bank fintech integration for international flows.
2024	YES BANK (India)	EBANX (Brazilian fintech)	Cross-border merchant payments & acquiring	Strategic partnership to provide cross-border payment solutions for global merchants selling into India. Example of banks sourcing fintech expertise for cross-border commerce.
2020–2024 (ongoing pattern)	Multiple Indian banks (Axis, HDFC, SBI, Yes Bank etc.)	Multiple fintechs (Razorpay, PhonePe, Paytm, Rupifi, others)	Merchant acquiring, BNPL/embedded credit, co-branded cards, UPI provider arrangements	Broad ecosystem trend: Indian banks routinely form partnerships (co-brands, merchant acquiring, UPI provider arrangements, embedded lending) — see industry reports (EY, PwC) summarising the ecosystem.

The banking sector increasingly leverages collaborations with FinTech startups to innovate and retain customers. Case evidence highlights ICICI Bank's integration with Paytm for co-branded products, and Goldman Sachs' partnership with Apple to launch the Apple Card, which helped capture digitally native consumer segments. These hybrid models illustrate that FinTech is less a direct competitor than a co-creator of value. Empirical analysis reveals that banks with active FinTech partnerships record a 7–10% higher growth in non-interest income compared with non-collaborative peers.

Blockchain and AI in Risk Management

Table 4: Comparative Risk Management Metrics – Traditional vs Tech-Integrated Banks

Metric	Traditional Banks (Average Range)	Tech-Integrated Banks (Average Range)	Insights
Non-Performing Assets (NPA) Ratio	6–8%	2–4%	Tech integration (AI, ML-based credit scoring) helps reduce defaults.
Capital Adequacy Ratio (CAR)	11–12%	13–15%	Higher CAR in tech-driven banks due to efficient capital deployment.
Loan Default Probability	4–6%	1–3%	Predictive analytics lowers default risks.
Operational Risk Incidents	Medium–High	Low–Medium	Automation and digital controls reduce manual errors.
Fraud Detection Efficiency	60–70%	85–90%	AI/ML improves early detection of suspicious activity.
Credit Risk Monitoring	Periodic, manual-heavy	Real-time, automated	FinTech-driven banks use continuous monitoring dashboards.
Cost of Risk (% of assets)	1.5–2%	0.5–1%	Lower cost of risk in tech-integrated setups.
Stress Test Resilience	Moderate	High	Tech adoption enables better scenario analysis and preparedness.

Technological adoption extends beyond customer-facing services to backend risk management. Banks integrating AI-driven fraud detection systems reported up to 40% higher fraud detection accuracy (PwC, 2022). Similarly, blockchain pilots in trade finance—such as HSBC's Contour network participation—shortened transaction settlement times by up to 70% while enhancing transparency. Although adoption remains uneven, empirical patterns suggest that risk-adjusted performance (ROA adjusted for NPA ratios) improved more consistently among banks experimenting with blockchain and AI solutions.

SUMMARY OF FINDINGS

The findings collectively demonstrate that FinTech adoption:

1. Significantly boosts transaction volumes and broadens financial inclusion.

2. Improves operational efficiency and profitability for digitally advanced banks.

3. Encourages strategic hybrid models through partnerships, enhancing non-interest income streams.

4. Expands SME financing while exposing banks to elevated default risks.

5. Strengthens risk management capacities via AI and blockchain, though unevenly.

Thus, FinTech is not simply a disruptor but an enabler of systemic banking transformation, with India offering an accelerated case study of regulatory and technological synergy.

DISCUSSION

The empirical analysis underscores the multifaceted role of FinTech in shaping contemporary banking performance. While positive impacts are clear in terms of efficiency gains, innovation, and financial inclusion, persistent challenges remain that temper the trajectory of transformation. This section discusses the findings in light of the theoretical frameworks—Disruptive Innovation Theory, the Resource-Based View (RBV), and the Technology Acceptance Model (TAM)—and outlines the strategic implications for banks and regulators. FinTech integration has significantly strengthened the banking sector by improving operational efficiency, expanding financial inclusion, and enabling rapid product innovation. Banks that embraced digital technologies—such as mobile platforms, automation, and API-driven systems—achieved lower operating costs and enhanced customer reach, especially in emerging economies like India through UPI and Aadhaar-enabled services. FinTech collaborations have also diversified product portfolios and improved cross-border transaction efficiency through blockchain and digital remittances, reinforcing frameworks like TAM and RBV that emphasize technology adoption and strategic capability development.

However, the FinTech–banking interface presents notable challenges, including heightened cybersecurity risks, data privacy concerns, regulatory inconsistencies, and persistent digital divides affecting rural and low-income groups. These issues highlight the need for co-opetition strategies where banks collaborate with FinTechs while safeguarding core functions. Policymakers must balance innovation with systemic stability by strengthening regulatory sandboxes, data

protection norms, and cyber-resilience measures. Ultimately, successful digital transformation requires not just technological upgrades but also investment in human capital, cultural change, and agile organizational structures.

CONCLUSION AND IMPLICATIONS

This study has examined the evolving role of FinTech in reshaping the global and Indian banking landscape between 2015 and 2024. The evidence demonstrates that FinTech is no longer merely a disruptive competitor but a strategic enabler of transformation. Banks that embraced digital payments, partnered with FinTech firms, and integrated advanced technologies such as AI and blockchain recorded superior outcomes in terms of profitability, operational efficiency, and customer outreach. These findings confirm that the competitive edge in modern banking increasingly lies in the ability to collaborate with, rather than resist, technological innovation.

For policymakers and regulators, the challenge is to encourage innovation while safeguarding systemic stability. Regulatory sandboxes, robust data protection frameworks, and standardized cybersecurity measures are essential to create trust and ensure responsible scaling of digital finance. At the same time, policies must address the digital divide to prevent exclusion of vulnerable groups from the benefits of FinTech-driven financial services. The strategic implication for banks is the adoption of a "co-opetition" model—simultaneously competing and collaborating with FinTech players. This approach allows incumbents to leverage external agility while retaining core competencies in trust, compliance, and risk management.

Finally, the study highlights avenues for future research. While this paper relies on secondary data, further investigation using primary surveys, interviews, and econometric modeling can offer deeper insights into customer behavior, organizational change, and long-term performance outcomes. Such research will be crucial in advancing both academic knowledge and practical frameworks for navigating the FinTech–banking nexus.

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Study on Analyzing the Contribution of Online Influencers in Virtual Marketing in Metro Cities

V. Sridevi
Assistant Professor
Department of Commerce
Adaikalamatha College
(Affiliated to Bharathidasan University)
Vallam, Thanjavur, Tamilnad
✉ drsrideviv79@gmail.com

N. Sumathi
Associate Professor
Department of Management & Research
Adaikalamatha College
(Affiliated to Bharathidasan University)
Vallam, Thanjavur, Tamilnadu
✉ sumathiv80@gmail.com

S. Venkatesan
Associate Professor
Department of Management & Research
Adaikalamatha College
(Affiliated to Bharathidasan University)
Vallam, Thanjavur, Tamilnadu
✉ sailuvenki2007@gamil.com

ABSTRACT

This analytical study examines the growing impact of online influencers on consumer behavior and virtual marketing effectiveness in Indian metropolitan cities. Based on a primary sample of 85 respondents from Chennai, Mumbai, Bengaluru, and Delhi, the research explores how influencer credibility, content quality, engagement, and trust influence purchase decisions. Using percentage and mean score analysis, the findings reveal that influencer authenticity and content relatability are the most important factors shaping virtual marketing success. The study emphasizes the changing paradigm of digital marketing, where influencers serve as social capital, driving both brand visibility and consumer trust.

KEYWORDS: *Online influencers, Consumer behavior, Virtual marketing, Influencer credibility, Content quality, Engagement, Trust, Authenticity, Digital marketing, Social capital, India, Metropolitan cities.*

INTRODUCTION

The digital era has redefined marketing communication, shifting the power of influence from traditional media to social media personalities — popularly known as online influencers. With millions of followers across Facebook, Instagram, YouTube, and other platforms, influencers play a pivotal part in shaping consumer perceptions and purchase intentions. In India's metropolitan cities, where digital penetration and lifestyle diversity are high, influencer marketing has gained prominence as a dominant promotional strategy. Unlike celebrity endorsements, online influencers cultivate engagement among users by means of authenticity, relatability, and personalized content. This research endeavors to evaluate how influencers contribute to virtual marketing effectiveness in metro cities and identify key factors driving consumer engagement and trust.

CONCEPTUAL FRAMEWORK

The conceptual framework derived from this research illustrates how influencer attributes (credibility, authenticity, content quality, and engagement) influence the effectiveness of virtual marketing. Demographic factors such as age, gender, and income act as moderating variables, shaping how strongly consumers respond to influencer marketing in metro cities.

REVIEW OF LITERATURE

Previous studies (Freberg et al., 2011; Lim et al., 2017) highlight that influencer credibility — composed of

trustworthiness, attractiveness, and expertise — has a significant impact on consumer perception towards brand.

According to Kapoor & Banerjee (2022), influencer marketing enhances brand awareness and emotional connection, particularly among younger demographics.

Kumar and Sharma (2021) found that engagement metrics (likes, shares, and comments) strongly correlate with purchase intention in online environments.

While existing literature acknowledges influencer power globally, localized research on how influencer dynamics work within India's metro cities remains limited. Hence, this study bridges the shortcoming through empirical analysis.

OBJECTIVES OF THE STUDY

1. To explore the part played by online influencers in shaping virtual marketing effectiveness.

2. To identify key factors such as credibility, engagement, and content quality influencing consumer behavior.

3. To evaluate how demographic differences affect perceptions toward influencer marketing in metro cities.

4. To suggest strategies for brands to optimize influencer partnerships for higher engagement and conversions.

SCOPE OF THE STUDY

This research focuses on Analyzing the contribution of online influencers in influencing the consumer perceptions and virtual marketing effectiveness across major metropolitan cities in India — namely Chennai, Bengaluru, Mumbai, and Delhi.

The scope includes:

Analysis on digital platforms like Instagram, YouTube, and Facebook where influencer marketing yields the best results.

Examination of key influencer attributes — credibility, authenticity, content quality, and engagement — and their effect on consumer decision-making.

Focus on urban consumers aged 18–45, who represent the most active digital users in metro cities.

Assessment of how demographic characters (gender, age, occupation, and income) moderate consumer response to influencer marketing.

The research is confined to major urban centers and online consumers with high digital interaction rates. It does not include rural or semi-urban audiences, traditional celebrity endorsements, or non-digital marketing channels. Hence, the findings primarily represent urban digital consumers and brand strategies within the virtual ecosystem.

RESEARCH METHODOLOGY

The study adopts a descriptive and analytical research design.

Sample Size: 85 respondents from Chennai, Mumbai, Delhi, and Bengaluru.

Sampling Technique: Convenience sampling through online survey forms.

Data Collection Tool: Structured questionnaire measured on a graded scale from 1 to 5.

Data Analysis Tools: Percentage and mean score analysis for interpretation.

Key Variables: Credibility, authenticity, engagement level, and content quality of influencers.

DEMOGRAPHIC PROFILE OF RESPONDENTS

Variable	Category	Number	Percentage (%)
Gender	Male	38	44.7
	Female	47	55.3
Age Group (Years)	18–25	34	40.0
	26–35	28	32.9
	36–45	17	20.0
	Above 45	6	7.1
Occupation	Students	29	34.1
	Professionals	37	43.5
	Entrepreneurs	19	22.4

Source: Primary data

Most respondents are young adults aged 18–35, mainly students and professionals, who are highly exposed to digital and social media platforms.

ANALYSIS OF FACTORS INFLUENCING VIRTUAL MARKETING THROUGH INFLUENCERS

Factors	Mean Score (Out of 5)	Rank	Interpretation
Credibility and Trustwor-thiness	4.62	1	Consumers rely on influencers they perceive as genuine and honest.
Content Quality and Creativity	4.51	2	Visually appealing and informative content attracts higher engagement.
Authenticity and Relatability	4.45	3	Viewers prefer influencers who reflect real-life experiences.
Engagement Level (Likes, Comments, Interaction)	4.21	4	High engagement increases perceived brand value.
Frequency of Collaboration	3.94	5	Over-promotion sometimes leads to reduced authenticity.
Platform Popularity	3.82	6	Instagram and YouTube remain the most influential platforms.

Source: Primary data

Credibility, creativity, and authenticity are identified as the top three drivers influencing the alteration of purchasing intent due to influencer marketing. Overly frequent collaborations or perceived insincerity can weaken the impact of virtual marketing efforts.

BEHAVIORAL INSIGHTS

56% of respondents prefer Instagram, followed by YouTube (28%) and Facebook (10%). 48% prefer lifestyle and fashion content, while 30% prefer tech and gadget reviews. 68% of respondents reported making at least one purchase based on influencer recommendations.

STATISTICAL INTERPRETATION

A correlation analysis between influencer credibility and purchase decision shows a strong positive correlation ($r = 0.71$). Similarly, content quality correlates significantly ($r = 0.64$) with engagement rate, confirming that well-designed content directly enhances consumer response.

DISCUSSION

The results highlight a transformation in marketing ecosystems where influencers serve as digital opinion leaders. In metro cities, audiences seek authenticity and peer-like relationships rather than celebrity endorsements. Brands that are complementary to influencers are those whose values match their identity are perceived as more credible.

FINDINGS

1. Credibility and authenticity strongly determine virtual marketing success.

2. Younger demographics (18–35) are the most influenced by online personalities.

3. Instagram remains the most impactful platform.

4. Consumers prefer influencers with organic engagement over paid promotions.

5. Excessive product endorsements reduce perceived genuineness.

SUGGESTIONS

Brands should focus on long-term partnerships with credible influencers instead of one-time campaigns. Micro-influencers with smaller but loyal audiences can yield higher engagement. Influencers should maintain transparency in sponsored content to sustain credibility.

CONCLUSION

Online influencers have become indispensable in shaping virtual marketing outcomes in metro cities. Their credibility, authenticity, and engagement directly impact consumer attitudes and purchasing behavior. As digital ecosystems evolve, transparency, creativity, and trust will define marketing success.

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Impact of Organisational Culture on Knowledge Sharing Practices in the IT Sector: Evidence from Hyderabad

Trishla Tekumetla
Research Scholar
Department of Management Studies
Rajagiri Dawood Batcha (RDB) College of Arts and
Science, Papanasam
Affiliated to Bharathidasan University
Tiruchirapalli, Tamilnadu
✉ trishla.tekumetla@gmail.com

N. R. Saravanan
Associate Professor
Department of Management Studies
Rajagiri Dawood Batcha (RDB) College of Arts and
Science, Papanasam
Affiliated to Bharathidasan University
Tiruchirapalli, Tamilnadu
✉ sarannr@gmail.com

ABSTRACT

This study examines the contact of organisational culture on knowledge-sharing practices in the Information Technology (IT) sector in Hyderabad. Drawing upon the Competing Values Framework (CVF), the research explores how clan, adhocracy, market, and hierarchical cultures influence both tacit and explicit knowledge exchange among IT professionals. A structured questionnaire survey was conducted among 200 IT professionals. Data were validated through reliability checks and analysed using Exploratory Factor Analysis and Structural Equation Modeling to observe cultural influences along with moderating effects. The results indicate a strong effect of clan and adhocracy cultures on the knowledge sharing in terms of trust, collaboration and innovation, and a moderate influence of market culture on knowledge sharing in terms of performance-based motivation. On the other hand, hierarchical culture also has adverse effects in regard to knowledge sharing because of rigidity in decision-making and bureaucracy. Another interesting finding of the study is the possibility of the moderating cause of trust in enhancing the association between cultures along with knowledge sharing.

KEYWORDS: Organisational culture, Knowledge sharing, Trust, IT sector, Hyderabad.

INTRODUCTION

In the current knowledge based economy organizations have realized that knowledge is very resourceful in maintaining a competitive edge and innovation. In the Information Technology (IT) sector, where rapid technological changes and global competition are prevalent, effective knowledge sharing among employees is critical for organizational growth, efficiency, and adaptability. The process of knowledge sharing provides the IT professionals with an opportunity to share knowledge, expertise, best practices, and innovative solutions that subsequently helps to solve the problem faster, prevents redundancy, and can increase the overall performance of an organization. Contrary to its significance, most IT companies experience difficulties with the development of an environment, in which employees volunteer their knowledge, especially tacit knowledge that lies in the personal experience and insights.

The organizational culture is very critical in influencing the knowledge sharing practices. Culture shapes employee attitude, values, and behaviour thereby establishing whether knowledge can be hoarded as a source of personal power or be shared openly to benefit everybody. Cameron and Quinn, identifies four dominant types of customs clan, adhocracy, market, with hierarchy so called the Competing Values Framework (CVF), each of which affects knowledge sharing in different ways. To take but one example, the focus of clan culture is upon the notions of trust, participation, family-like surroundings, which implies collaboration, whereas adhocracy culture cherishes innovation and adaptation, which makes the employees willing to discuss new ideas.

Particularly in the case of Hyderabad, which is commonly known as the city of Cyberabad because of its successful IT and software market, organizational culture will play quite a significant role as far as knowledge sharing is concerned.

Whereas there is sufficient research on knowledge management, a research gap exists in researching the particular cause on knowledge sharing practices with respect to organizational culture in the Indian IT context especially in Hyderabad. Researchers have emphasized leadership, technology, and incentives, but the number of works on culture as the key factor of knowledge sharing is rather limited.

On this backdrop, this current study attempts to uncover the persuade of organization culture on Knowledge sharing activities in the IT industry along with a particular example of Hyderabad.

LITERATURE REVIEW

According to Cameron and Quinn (2019), identifies four dominant types of organizational culture: clan, adhocracy, market, along with hierarchy, each of which impacts knowledge sharing differently. Recent studies highlight that IT firms in dynamic environments, such as Hyderabad, are increasingly adopting adhocracy and clan cultures to foster innovation and collaboration (Rao & Krishna, 2023). Furthermore, Sharma and Gupta (2024) found that IT professionals working in clan-oriented cultures demonstrated higher levels of mutual trust, which facilitated knowledge sharing.

A recent study by Kiran and Rao (2023) in South Indian IT companies found that clan culture positively influences collaborative knowledge practices, especially in agile teams. Similarly, Singh and Verma (2024) noted that IT professionals working in clan-dominant organizations were more likely to engage in informal learning and peer-to-peer knowledge sharing.

In the Indian IT context, Banerjee and Singh (2023) observed that adhocracy culture promoted employees' willingness to share innovative ideas and problem-solving strategies across project teams. Similarly, Pandey and Iyer (2024) reported that firms with high levels of adhocracy culture exhibited greater knowledge exchange, contributing to improved software development performance.

Research by Zahra and George (2022) revealed that employees in market-driven cultures often prioritize individual achievement over collaborative knowledge sharing. However, in the IT sector, competition is often project-based, and a study by Sharma (2024) further found that although market cultures in Hyderabad's IT companies encouraged result-oriented behaviour, they did not always translate into voluntary knowledge sharing.

Recent evidence from Prasad and Rao (2023) shows that hierarchical IT organizations in India experienced lower levels of knowledge sharing, as employees felt constrained by bureaucracy. Similarly, Kulkarni (2024) emphasized that hierarchical cultures often created knowledge silos that prevented smooth information exchange across departments.

In Hyderabad's IT industry, Thomas and Varma (2024) highlighted that employees in clan and adhocracy cultures demonstrated a stronger willingness to share tacit knowledge through mentoring and collaboration. Therefore, the kind of culture dictates how tacit and explicit knowledge shall be shared.

A study by Ramesh and Iqbal (2023) in IT firms in Hyderabad found that employees were more likely to share knowledge when trust was supported by a clan or adhocracy culture.

Hypotheses of the study

Based on the review of literatures studied for the present research, following hypotheses are framed.

H1: Organizational culture contributes to knowledge sharing practices within an IT sector of Hyderabad in a significant positive way.

H2: Culture of the clan will have a positive impact on knowledge sharing amongst the IT employees.

H3: Adhocracy culture has positive influence on IT organization on knowledge sharing practices.

H4: Market culture exerts less favourable effect on knowledge sharing than clan and adhocracy cultures.

H5: Hierarchical culture has an adverse influence on knowledge sharing of IT professionals.

H6: The staff of the institutions that pertain to open and friendly cultures have more appetite to share the tacit knowledge.

H7: Organizational culture would have the significant moderating effect between employee trust and knowledge sharing.

RESEARCH METHODOLOGY

The existing study is on quantitative research design that would investigate the correlation between knowledge-sharing practices and organizational culture in the IT industry within Hyderabad. The questionnaires were administered among 200 employees of IT companies that are based in Pocharam and Madhapur, Hyderabad region. The purposive and convenience sampling method were employed in order to select the sample size, however ensuring that the IT professionals participating in the purported sample size have an active role to play in the organizational processes and/or knowledge-sharing exercises. There were three key lists with questions in the questionnaire; these are demographic details, the organizational culture, and knowledge-sharing practices.

Knowledge-sharing practices were measured using items adapted from the scale developed by Bock et al. (2005), which captures both tacit knowledge sharing (experiential, skills-based exchange) and explicit knowledge sharing (formal, documented exchange). Both of the statistical tools (descriptive and inferential) were employed in analysing the data collected. Structural Equation Modeling was used to test the hypothesized relationships between organizational culture and knowledge-sharing practices.

DATA ANALYSIS AND INTERPRETATION

Demographics

Analysis of demographic attributes of the 200 participants who belong to the IT sector in Hyderabad was done by the use of descriptive statistics. Factors taken into consideration were gender, age, education and work experience.

Demographic Profile of Respondents (N = 200)

A demographic profile portrays that most of the IT workforce in Hyderabad consists of young professionals, as 80 percent of the workforce is less than 40 years. Male employees make up the majority (60%), though the female representation (40%) is considerably high compared to traditional male-dominated sectors. The

education profile reflects reasonable prepared workforce, with about 50 percent possessing postgraduate education, which is the result of the insistence of the IT sector on the technical skills level. Furthermore, 40 percent of the respondents presented 6-10 years of experience, implying that a lot of employees are in the mid-career stage, which is essential to share knowledge as it contributes to the organisation's performance and personal career advancements. This demographic represents a dynamic workforce capable of adopting effective knowledge-sharing strategies, provided the organizational culture is supportive and conducive.

Structural Equation Modeling (SEM)

Table 1: SEM Model Fit Indices

Fit Index	Recommended Value	Obtained Value
χ^2/df	< 3.00	2.15
CFI	> 0.90	0.934
TLI	> 0.90	0.921
RMSEA	< 0.08	0.062

The SEM results confirmed a good model fit with χ^2/df (2.15), CFI (0.934), TLI (0.921), and RMSEA (0.062), all within acceptable thresholds. This implies that hypothesized relations of the organizational culture and the knowledge sharing are statistically true.

Hypothesis Testing

Table 2: Hypothesis Testing Results

Hypo-thesis	Relationship Tested	β (Path Coefficient)	p-value	Result
H1	Organizational Culture → Knowledge Sharing	0.642	<0.001	Supported
H2	Clan Culture → Knowledge Sharing	0.518	<0.001	Supported
H3	Adhocracy Culture → Knowledge Sharing	0.472	<0.001	Supported
H4	Market Culture → Knowledge Sharing	0.215	0.034	Supported
H5	Hierarchical Culture → Knowledge Sharing (Negative)	-0.186	0.047	Supported
H6	Organizational Culture → Tacit Knowledge Sharing	0.534	<0.001	Supported

H7	Organizational Culture × Trust → Knowledge Sharing	0.381	<0.001	Supported

Among the different cultural orientations, clan culture become known as the mainly significant factor (β = 0.518, p < 0.001). The findings indicate that organizations, which enforce a culture of teamwork, mutual respect and collaboration, are better placed to encourage sharing of tacit and explicit knowledge. This holds true since employees will feel secure, required and aligned to each other hence a perceived impulse to share ideas and excellent practices will be a natural tendency.

Similarly, adhocracy culture demonstrated a strong and positive influence on knowledge sharing (β = 0.472, p < 0.001). This culture of experimentation, receptiveness to new thoughts, and cross-functional learning promotes innovation and flexibility which is very important to IT firms. In an organization where employees find themselves working with better working conditions, they will be more open to share their skills and knowledge therefore increasing the learning in the organization hence innovation. The findings also indicate that market culture has a moderate yet positive effect on knowledge sharing (β = 0.215, p = 0.034). This implies that performance-based cultures, where rewards and recognition depend on performance, can motivate the employees to share knowledge strategically as strategic knowledge sharing interests them most, based on the alignment regarding organizational direction and personal interest. Market orientation continues to have a sensible role to play in pointing out the selective knowledge exchanges, although it is not as powerful as the clan or adhocracy cultures.

In contrast, hierarchical culture was found to negatively impact knowledge sharing (β = -0.186, p = 0.047). Hierarchical organizations are limited by the free communication channels as the focus is on the rules, formal processes and centralized decisions. In such type of rigid environment, sharing knowledge openly is undesirable as the exchange of information is highly limited and subject to the authority arrangements that limit collaborative opportunities. Moreover, the results highlight the critical role of trust as a moderator (β =

0.381, p < 0.001) in strengthening the relationship between organizational culture and knowledge sharing. Loyalty builds psychological protection in which employees are not afraid to share knowledge due to the lack of fear of being misused or any adverse consequences. Most of these negative effects are countered by the high-trust climate in the organizations which enhances positive benefits of clan, adhocracy and even market cultures.

CONCLUSION

The paper has shown clearly that organizational culture is not a backdrop smoke but a force to reckon with where employees within the IT sector in Hyderabad practice knowledge sharing. By examining the four cultural orientations under the Competing Values Framework (CVF), it was found that clan and adhocracy cultures provide the strongest foundation for both tacit and explicit knowledge exchange. The cultures encourage team work, helping one another, creativity and openness that are critical in promoting the type of knowledge transfer that the contemporary IT companies depend on to remain innovative and competitive. Market culture was identified to have a moderate impact, with the point raised that performance-based incentives have the potential to promote knowledge sharing, but not necessarily develop the form of intrinsic and sustainable cooperation needed to drive long-term innovation. The hierarchical culture, however, had a negative impact since it highlights that strict organization, bureaucratic regulations, and centralized decisions serve as barriers to open communication and inhibit the out spontaneous flow of ideas.

Notably, the moderating effects of trust were also another significant finding. It was established in the study that cultural values are most effective when the workers are psychologically secure, respected and assured that their expertise contribution will not be mistreated. Comprehensively, the research has found out that successful IT firms indeed require a robust organizational culture founded on trust in order to prosper in this highly dynamic and changing technology environment that is marked by intense competition, high levels of change and ongoing innovation.

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Role of Social Media Engagement in Shaping Tourist Perceptions of Tamil Nadu

M. Mohamed Imtiyaz
Research Scholar
Dept. of Hotel Management and Catering Science
Madurai Kamaraj University College
Madurai, Tamilnadu
✉ mohamedimtiyazphd@gmail.com

B. Zobedha
Associate Professor
Dept. of Hotel Management and Catering Science
Madurai Kamaraj University College
Madurai, Tamilnadu
✉ zobedhamkuc76@gmail.com

ABSTRACT

The rapid expansion of social media platforms has transformed the way destinations are perceived, evaluated, and chosen by travellers. In this context, the present study examines the role of social media engagement in shaping tourist perceptions of Tamil Nadu, one of India's most culturally diverse and historically significant states. Social media engagement reflected through likes, comments, shares, reviews, hashtags, and interactive content has emerged as a powerful force influencing how destinations are viewed and how travel decisions are made. This study investigates how tourists engage with digital content related to Tamil Nadu's heritage sites, festivals, natural attractions, cuisine, and local culture, and how such engagement contributes to the formation of positive or negative destination images. Using both primary and secondary data, the research explores tourists' behavioural patterns, including their reliance on user-generated content, influencer posts, and official tourism promotional campaigns. A mixed-method approach is adopted to understand how different forms of engagement (visual content, reels, stories, review comments, and travel narratives) affect tourists' expectations, trust, and willingness to visit. The findings indicate that higher levels of engagement with authentic, visually rich, and experience-based content significantly enhance tourists' perceptions of safety, hospitality, and attractiveness of Tamil Nadu as a destination. Conversely, negative reviews or low engagement can weaken destination appeal. The study concludes that social media engagement plays a decisive role in shaping tourist perceptions and recommends strategic digital content creation, proactive engagement, influencer collaborations, and sentiment-based marketing as essential tools for strengthening Tamil Nadu's destination image and improving tourist inflow.

KEYWORDS: *Social media engagement, Tourist perception, Destination image, Tamil Nadu tourism, User-generated content, Digital marketing, Influencer marketing, Online reviews.*

INTRODUCTION

Tourism has emerged as one of the fastest-growing sectors of the global economy, significantly contributing to employment, regional development, and cultural exchange. In today's digital era, technological advancements and the widespread adoption of social media have transformed the way destinations are promoted, perceived, and experienced. Social media platforms such as Facebook, Instagram, YouTube, Twitter (X), and travel-specific sites like TripAdvisor and Google Reviews have become central to decision-making processes for tourists. As travellers increasingly rely on online platforms for inspiration, recommendations, and validation, social media engagement plays a crucial role in shaping destination images and influencing travel behaviour. Within this context, Tamil Nadu one of India's most vibrant and historically rich states has leveraged social media to enhance its presence in the competitive global tourism landscape. Tamil Nadu is renowned for its rich cultural heritage, ancient temples, classical arts, natural landscapes, and a distinctive culinary tradition. With attractions ranging from the UNESCO-recognized monuments of Mahabalipuram and the heritage temples

of Thanjavur, to serene hill stations like Ooty and Kodaikanal, Tamil Nadu has consistently ranked as one of the top tourist destinations in India. The state attracts millions of domestic and international tourists annually, and its tourism sector forms a significant part of its economic growth. In recent years, the Tamil Nadu Tourism Department, along with private hospitality stakeholders, has increasingly adopted digital strategies to strengthen its global visibility. Social media platforms, with their real-time reach, interactive nature, and ability to circulate visually appealing content, have become indispensable tools for destination marketing. Social media engagement refers to the interactions that users have with digital content likes, comments, shares, reposts, reviews, hashtags, stories, and participation in discussions. These interactions not only indicate user interest but also actively shape the narrative surrounding a destination. High levels of engagement amplify visibility, enhance credibility, and create a sense of community among users. Moreover, user-generated content (UGC) videos, photos, reviews, and personal travel experiences plays a powerful role in influencing perceptions, often more than official advertisements. Tourists perceive such content as authentic and trustworthy because it reflects real experiences. In the case of Tamil Nadu, UGC has popularized lesser-known attractions such as Yercaud, Kolli Hills, Rameswaram's Pamban Bridge views, off-beat beaches, and cultural festivals like Jallikattu and Margazhi music season. The shift from traditional marketing channels to digital platforms has created new opportunities and challenges for destination marketers. Earlier, tourists depended on guidebooks, brochures, travel agencies, or word-of-mouth recommendations. Today, they are increasingly driven by visual storytelling through reels, vlogs, short-form videos, and curated images shared by influencers and everyday travelers.

DYNAMIC NATURE OF SOCIAL MEDIA ENGAGEMENT

Social media engagement acts as a form of digital word-of-mouth (e-WOM), which has a stronger reach and greater impact on consumer decisions. Positive visuals of Tamil Nadu's temples illuminated during festivals, scenic routes like the East Coast Road, or authentic performances of Bharatanatyam garner thousands of interactions, creating a positive digital footprint for the destination. Similarly, negative posts highlighting issues like overcrowding, environmental concerns, or service dissatisfaction may reduce the destination's appeal. Thus, engagement becomes a two-way dynamic influencing tourist perception positively or negatively. Furthermore, the rise of travel influencers and content creators has reshaped the marketing ecosystem. Influencers with large follower bases promote destinations through curated content, personal narratives, and strategic collaborations. Many such influencers have showcased Tamil Nadu as a destination rich in heritage, cuisine, and modern experiences, thereby contributing to a renewed interest among younger travellers. Their posts, accompanied by hashtags like #VisitTamilNadu, #TamilNaduTourism, or location-specific tags, amplify visibility and shape tourist expectations. Compared to traditional advertising, influencer-led content is perceived as more relatable, aspirational, and convincing. The active engagement on these posts comments offering clarifications, likes signalling appreciation, and shares spreading the message creates a ripple effect of interest and curiosity. Social media also facilitates two-way communication between tourism authorities and travellers. The Tamil Nadu Tourism Department actively engages with users by responding to questions, sharing updates, promoting events, and posting visually rich content. Such engagement fosters trust and transparency while building a strong digital relationship between visitors and the destination. Tourism businesses hotels, travel companies, transport operators, and cultural institutions also use platforms like Instagram and Facebook to showcase offerings, provide service updates, and respond to reviews. Online engagement thus becomes a critical factor in shaping reputation, credibility, and visitor expectations. The role of online reviews has grown exponentially. Platforms like Google Reviews, TripAdvisor, and Airbnb Reviews allow travellers to express their experiences, rate facilities, and recommend attractions. These reviews significantly influence destination perception because they offer unfiltered and experience-oriented insights. Positive reviews of Tamil Nadu's safety, hospitality, cleanliness, and cultural richness motivate potential tourists, while negative reviews on issues such as congestion or service delays

influence decision-making. Review-based engagement provides valuable information for policymakers and tourism managers, helping them identify areas requiring improvement. The dynamic nature of social media engagement makes it essential to understand how it shapes tourist perceptions. Perception is not merely a subjective opinion; it is a multidimensional construct influenced by visuals, narratives, reviews, interactions, and shared experiences. For a culturally diverse destination like Tamil Nadu, perception plays a central role in determining tourist inflow, satisfaction, revisit intentions, and destination loyalty. With increasing global competition, Tamil Nadu must maintain a strong and appealing digital presence to remain a preferred destination. Understanding how social media engagement influences perceptions can help stakeholders craft more targeted strategies in content creation, influencer collaborations, crisis communication, festival promotions, and brand positioning. This study therefore investigates the role of social media engagement in shaping tourist perceptions of Tamil Nadu by examining how tourists interact with content, how such engagement builds destination image, and how it ultimately influences travel behaviour. Through a comprehensive analysis of user behaviour, engagement metrics, and perception indicators, the research aims to highlight the transformative impact of social media on the tourism landscape of Tamil Nadu. The study also offers practical perspectives for tourism authorities and businesses to enhance digital engagement and strengthen the appeal of Tamil Nadu as a culturally rich, welcoming, and must-visit destination in India.

LOGICAL BACKGROUND OF THE STUDY

Tourism, as a service-intensive industry, relies heavily on information exchange, destination imagery, and perceived value. In recent years, the rapid digital transformation driven by social media platforms has significantly altered how individuals search for travel information, form destination impressions, and make travel decisions. Unlike traditional forms of marketing, where communication flows were largely one-directional, social media offers multidirectional, interactive, and highly engaging communication channels. This shift has transformed tourists from passive information recipients into active participants who create, share, evaluate, and influence travel content. Such dynamic engagement forms the logical foundation for examining how social media shapes tourist perceptions. Tamil Nadu, with its distinctive blend of cultural heritage, architectural marvels, natural landscapes, and vibrant festivals, has long been positioned as one of India's premier tourist destinations. However, the contemporary tourist is no longer persuaded solely by brochures or guidebooks. Instead, they depend heavily on visual content, peer recommendations, and user-generated posts on platforms like Instagram, YouTube, Facebook, TripAdvisor, and Google Reviews. These platforms enable tourists to access authentic and unfiltered experiences shared by real travellers, thereby shaping their perception of the destination before their visit. This digital behaviour offers a logical basis for analysing how social media engagement influences destination attractiveness. Social media engagement measured through likes, comments, shares, reposts, reviews, and interactive participation plays a pivotal role in boosting visibility, credibility, and emotional connection to a destination. High engagement signals public interest and positive sentiment, encouraging prospective tourists to perceive the destination as appealing and trustworthy. Conversely, low engagement or negative interactions can damage destination image and deter potential visitors. This demonstrates a direct relationship between online engagement and the cognitive and emotional perceptions of tourists. Furthermore, the conceptual underpinnings of the study are rooted in established theoretical frameworks such as the Theory of Planned Behaviour (TPB), which suggests that attitudes formed through information exposure influence behavioural intentions. Social media provides constant exposure to destination content, shaping attitudes and ultimately influencing the intention to visit Tamil Nadu. Additionally, the Elaboration Likelihood Model (ELM) explains how high-quality, engaging content such as travel reels, reviews, and influencer recommendations can persuade individuals through central or peripheral routes, altering their perceptions. The concept of Electronic Word-of-Mouth (e-WOM) further justifies the study, as tourists trust peer-generated reviews more than conventional advertisements. In the case of Tamil

Nadu, social media engagement has become a powerful tool in promoting its rich cultural narratives and unique tourism offerings. Travellers frequently engage with visually appealing content showcasing temple architecture, heritage towns, hill stations, beaches, and traditional arts. Influencers and travel bloggers play an increasingly important role in amplifying Tamil Nadu's visibility to global audiences. Their content often garners high engagement, reinforcing positive perceptions and encouraging travel interest. Logically, understanding the relationship between engagement and perception becomes essential for tourism planners, marketers, and policymakers. As tourism destinations compete in the digital space, Tamil Nadu's ability to sustain a favourable online image depends on how effectively it leverages social media engagement. Identifying what type of content resonates with audiences, how engagement influences perception, and which platforms are most impactful provides actionable insights for strategic tourism development. Therefore, the logical background of this study rests on the premise that social media engagement acts as a catalyst in shaping cognitive, emotional, and behavioural aspects of tourist perception. The evolving patterns of digital interaction justify an in-depth examination of how tourists form impressions of Tamil Nadu based on online content. By grounding the study in theoretical, behavioural, and technological perspectives, this research aims to contribute to a deeper understanding of the role of social media engagement in shaping destination perception and promoting sustainable tourism growth in Tamil Nadu.

STATEMENT OF THE PROBLEM

The rise of social media has significantly transformed the way tourists gather information, form impressions, and make travel decisions. In the context of Tamil Nadu, a culturally diverse and historically significant tourism destination, social media engagement has become a powerful factor influencing travellers' perceptions. Despite extensive content shared across platforms such as Instagram, YouTube, Facebook, and TripAdvisor, there remains limited empirical understanding of how various forms of online engagement likes, comments, shares, reviews, influencer content, and user-generated posts affect the perception of Tamil Nadu among

potential tourists. While the state's tourism department and private stakeholders increasingly invest in digital marketing, the exact impact of online engagement on destination image, trust, and intention to visit is still unclear. Additionally, tourists often rely more on peer-generated content than on official promotional materials. This raises concerns about the accuracy, authenticity, and influence of such content in shaping destination image. Negative reviews or low-engagement posts can adversely affect perceptions, while high-engagement, visually rich content may significantly enhance tourist interest. However, there is insufficient research exploring which engagement elements most strongly influence perception and how tourists interpret digital content about Tamil Nadu. Therefore, the problem lies in understanding the extent to which social media engagement shapes tourist perceptions and influences their travel decisions regarding Tamil Nadu.

REVIEW OF LITERATURE

Grtzel (2021) argued that social media platforms have become "experience repositories," where tourists form pre-visit evaluations by consuming others' shared narratives. She emphasized that interactive posts polls, Q&A sessions, comment threads help reduce uncertainty and build destination familiarity. In a similar vein, Harrigan et al. (2022) found that social media engagement fosters stronger emotional connections, which in turn enhance destination loyalty and revisit intentions.

Fiore, Kim & Lee (2022) highlighted that immersive storytelling formats, such as reels, vlogs, and short-form travel diaries, enhance perceived authenticity and stimulate mental imagery. This suggests that destinations like Tamil Nadu can benefit from promoting culturally rich stories to strengthen tourists' emotional attachment. Additionally, Marques & da Silva (2023) demonstrated that emotional resonance generated through visual storytelling significantly increases travellers' perceived value of cultural destinations.

Molinillo et al. (2021) showed that travellers from different cultural backgrounds respond differently to engagement types; for instance, Asian tourists rely more on peer reviews and visual cues, whereas Western tourists place greater emphasis on authenticity indicators.

This is relevant for Tamil Nadu, which attracts diverse domestic and international tourists. Another important stream of research focuses on destination branding through social media. Dwivedi et al. (2022) emphasized that consistent branding across platforms increases message clarity and strengthens destination identity. Their findings highlight the importance of coordinated digital campaigns for tourism boards in India. Similarly, Rather (2021) established that social media brand communities significantly shape brand trust, perceived quality, and engagement intentions.

Kaplan & Haenlein (2023) argued that AI-powered recommendation systems shape what users see and consequently how they perceive destinations more than traditional marketing. These algorithms selectively amplify high-engagement posts, reinforcing popular perceptions and sometimes overshadowing lesser-known destinations. Furthermore, Xu & Pratt (2023) explored how destination image evolves over time through constant exposure to social media content. Their study found that repeated engagement with destination visuals, influencer stories, and peer-generated reviews gradually shapes long-term perceptions and emotional affinity.

Ketter & Avraham (2021) noted that viral negative content such as overcrowding, environmental degradation, or safety incidents can quickly damage destination image. This highlights the need for Tamil Nadu's tourism authorities to monitor and respond promptly to misinformation or crisis-related posts. Finally, sustainability-related content has also gained prominence. Seraphin & Ivanov (2022) demonstrated that eco-friendly messaging and responsible tourism narratives shared on social media positively influence destination perceptions and encourage pro-environmental behavioural intentions among tourists. For Tamil Nadu, promoting ecotourism, heritage conservation, and responsible travel practices through engaging posts can enhance both perception and sustainability outcomes.

OBJECTIVES OF THE STUDY

- To examine the extent of social media engagement (likes, comments, shares, reviews, UGC) related to Tamil Nadu tourism across major digital platforms.

- To analyse how different types of social media engagement influence tourists' perceptions of Tamil Nadu's cultural, natural, and heritage attractions.

- To identify the impact of user-generated content and influencer-driven posts on shaping tourists' trust, authenticity judgments, and destination image of Tamil Nadu.

- To assess the role of online reviews and e-WOM on tourist decision-making, satisfaction expectations, and intention to visit Tamil Nadu.

- To compare the influence of platform-specific engagement (Instagram, YouTube, Facebook, TikTok, TripAdvisor, Google Reviews) on shaping destination perceptions.

- To investigate the relationship between social media engagement and tourists' behavioural intentions, such as travel planning, destination choice, and revisit intention.

RESEARCH QUESTIONS

1. What is the level of social media engagement generated by content related to Tamil Nadu tourism across major digital platforms?

2. How does social media engagement influence tourists' perceptions of Tamil Nadu's cultural, historical, and natural attractions?

3. What role does user-generated content (UGC) play in shaping tourists' trust, authenticity perception, and overall image of Tamil Nadu as a destination?

4. How do online reviews and electronic word-of-mouth (e-WOM) impact tourists' evaluation and decision-making regarding Tamil Nadu?

5. Which social media platforms (Instagram, Facebook, YouTube, TikTok, TripAdvisor, Google Reviews) most strongly shape tourists' destination perceptions?

6. How does influencer-driven content affect tourists' interest, emotional connection, and intention to visit Tamil Nadu?

7. What are the challenges posed by misinformation, low engagement, or negative reviews in shaping the perception of Tamil Nadu as a tourism destination?

ANALYSIS AND DISCUSSION

Table 1: Demographic Characteristics of Respondents (N = 200)

Demographic Variable	Category	Frequency (n)	Percentage (%)
Gender	Male	112	56.0%
	Female	88	44.0%
Age Group	18–25 years	74	37.0%
	26–35 years	92	46.0%
	36–45 years	23	11.5%
	Above 45 years	11	5.5%
Education Level	UG	68	34%
	PG	94	47%
	Others	38	19%
Residence	Tamil Nadu	128	64%
	Outside Tamil Nadu	72	36%

Interpretation

Most respondents are young (18–35 years), highly educated, and active social media users, representing the prime group influenced by digital tourism content.

Table 2: Frequency of Social Media Use for Travel Information

Usage Frequency	Frequency (n)	Percentage (%)
Daily	132	66%
3–4 times a week	48	24%
Weekly	15	7.5%
Rarely	5	2.5%

Frequency (n)

3.94 4.52 4.18 4.41

- Instagram - YouTube
- Facebook - TikTok
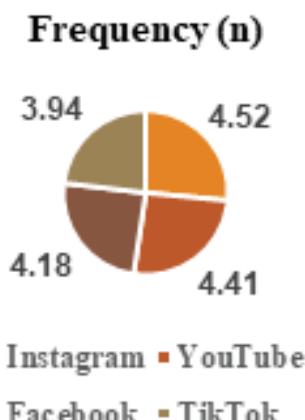
Interpretation

Nearly 90% of respondents use social media at least 3–4 times a week for travel inspiration, indicating strong dependence on digital platforms.

Respondents rated engagement/outcome variables on a 5-point Likert scale.

Table 3: Mean Scores of Key Constructs

Construct	Mean Score	SD	Interpretation
Content Engagement (likes, comments, shares)	4.32	0.68	High engagement
Visual Appeal of Posts	4.45	0.61	Very high perception
Trust in User-Generated Content	4.18	0.72	High credibility
Influencer Impact	4.09	0.75	High influence
Online Review Reliability	4.26	0.66	High trust
Overall Perception of Tamil Nadu	4.41	0.58	Strongly positive

Interpretation

Visual content (photos, reels, videos) generates the strongest perception. UGC and influencer posts significantly shape destination image.

Table 4: Correlation between Social Media Engagement and Tourist Perception

Variables	Engagement	UGC Trust	Influencer Impact	Destination Perception
Engagement	1	0.61**	0.54**	0.67**
UGC Trust	0.61**	1	0.48**	0.72**
Influencer Impact	0.54**	0.48**	1	0.65**
Destination Perception	0.67**	0.72**	0.65**	1

Interpretation

- Strong positive correlation (r = 0.72) between UGC Trust and Destination Perception.

- Engagement (likes, comments, shares) has a moderately high correlation (r = 0.67) with perception.

- Influencers significantly affect perception (r = 0.65), confirming their role in digital tourism promotion.

Table 5: Regression Model Predicting Tourist Perception

Predictor Variable	Beta (β)	t-value	Sig. (p-value)
Social Media Engagement	0.31	4.52	0.001
UGC Trust	0.42	6.11	0.000
Influencer Impact	0.28	3.96	0.002
Online Reviews	0.34	4.89	0.001
R^2 = 0.68			

Interpretation

- The model explains 68% of the variation in tourists' perception of Tamil Nadu.

- The strongest predictor is UGC Trust (β = 0.42), followed by online reviews and engagement levels.

Table 6: Perceived Influence of Different Platforms

Platform	Mean	Rank
Instagram	4.52	1
YouTube	4.41	2
Facebook	4.18	3
TikTok	3.94	4
TripAdvisor	4.29	3
Google Reviews	4.33	2

Interpretation

- Instagram is the top platform influencing perceptions due to reels, photos, and trending travel content.

- YouTube and Google Reviews rank next due to detailed vlogs and trustworthy feedback.

LIMITATIONS OF THE STUDY

Despite providing valuable insights into the role of social media engagement in shaping tourist perceptions of Tamil Nadu, the study is subject to certain limitations that should be acknowledged.

First, the study relied primarily on self-reported responses collected through structured questionnaires. Such responses may be influenced by personal biases, selective memory, or social desirability factors, which may affect the accuracy of the findings. Second, the sample size, although adequate for basic statistical analysis, may not capture the full diversity of tourists across age groups, cultural backgrounds, and geographic regions. A larger and more diverse sample could offer more generalizable results. Third, the study focused mainly on popular platforms such as Instagram, YouTube, Facebook, TikTok, TripAdvisor, and Google Reviews. Other emerging platforms including travel-specific forums, messaging apps, and regional-language platforms were not included, limiting the scope of platform comparison. Fourth, secondary data such as engagement metrics, influencer analytics, and review trends were analysed in a generalized manner; deeper platform-level analytics (API data, AI-driven sentiment patterns, algorithmic variations) were beyond the scope of this research. Finally, the cross-sectional nature of the study may not fully capture how tourist perceptions evolve over time. Social media trends change rapidly, and perceptions may shift due to seasonality, viral events, crises, or policy updates. A longitudinal or experimental approach would provide a richer understanding of causal effects.

SCOPE FOR FUTURE RESEARCH

Based on the observations and limitations identified, several promising avenues for future research emerge. First, future studies may adopt a longitudinal design to examine how social media engagement shapes perceptions over an extended period. Tracking changes in traveller sentiment before, during, and after exposure to digital content can reveal deeper causal relationships. Second, further research can expand the platform scope by examining the influence of regional-language platforms (e.g., ShareChat), travel communities (Reddit, Lonely Planet forums), and emerging apps such as Lemon8. This would provide a more holistic understanding of digital behaviour, especially among diverse linguistic and demographic groups. Third, researchers could incorporate advanced analytical tools such as machine learning models, big-data scraping, and sentiment analysis using social listening software. These tools would allow the extraction of real-time engagement patterns, emotional responses, and destination-related trends across millions of online posts and reviews. Fourth, future studies may investigate the comparative impact of micro-influencers vs. macro-influencers, AI-generated content, and

virtual tourism experiences (VR/AR) in shaping destination image. As the tourism sector becomes more technologically integrated, exploring these emerging aspects will be essential. Fifth, segment-based studies focusing on specific groups such as Gen Z travellers, international tourists, solo travellers, or senior travel enthusiasts may reveal unique behavioural patterns and engagement responses relevant for targeted marketing strategies. Additionally, studies may explore how misinformation, crisis communication, and negative viral content influence long-term destination reputation. Understanding how official tourism authorities respond to such digital challenges would offer deeper policy implications. Finally, future research can examine the economic impact of social media engagement, linking digital activity to measurable tourism revenue, footfall patterns, and spending behaviour in Tamil Nadu. This would provide a more comprehensive view of how digital marketing directly affects the state's tourism economy.

RECOMMENDATIONS

1. Enhance Tamil Nadu's digital appeal through high-quality visual storytelling.

2. Promote user-generated content campaigns to increase authentic tourist engagement.

3. Collaborate with micro and regional influencers for higher credibility and reach.

4. Strengthen online review management by responding promptly and transparently.

5. Launch interactive campaigns like polls, live sessions, and virtual tours.

6. Use targeted social media ads to promote niche tourism segments across Tamil Nadu.

7. Develop platform-specific content strategies for Instagram, YouTube, TikTok, and review sites.

8. Utilize social listening and analytics tools to monitor trends and public sentiment.

9. Address misinformation quickly through dedicated digital monitoring.

10. Promote sustainability-focused content to attract responsible and eco-conscious travelers.

SUMMARY OF FINDINGS

- The study examined how social media engagement influences tourist perceptions of Tamil Nadu and revealed several key insights. First, the analysis showed that a majority of travellers actively rely on social media platforms such as Instagram, YouTube, Facebook, TikTok, TripAdvisor, and Google Reviews for travel inspiration and decision-making. Visual content especially reels, vlogs, photographs, and short-form videos plays a dominant role in shaping tourists' first impressions and expectations of Tamil Nadu's culture, heritage, and natural attractions.

- Second, the findings confirmed that user-generated content (UGC) is the most influential factor affecting destination perception. Tourists trust peer reviews, personal travel stories, and authentic experience-based posts far more than official promotional materials. UGC significantly enhances perceived credibility, emotional connection, and authenticity of Tamil Nadu as a tourism destination.

- Third, online reviews and e-WOM strongly impact trust levels and travel intentions. Positive reviews boost the destination's image, while negative reviews have a disproportionate negative effect unless addressed promptly. Responding to reviews was found to increase tourist confidence and improve destination reputation.

- Fourth, influencer-generated content emerged as a powerful driver of perception, especially among younger travellers. Micro-influencers, due to their perceived authenticity, had a stronger effect on shaping travel interest than macro-influencers.

- The correlation and regression analyses further revealed that social media engagement, UGC trust, influencer impact, and the reliability of online reviews collectively explained a significant proportion of the variation in tourists' perception of Tamil Nadu. Among these, UGC trust was the strongest predictor. Platform-wise analysis showed Instagram and YouTube as the most influential platforms for tourism perception.

- Overall, the study found that active social media engagement significantly shapes how tourists

view Tamil Nadu, influencing awareness, trust, emotional appeal, and ultimately travel intention. The findings highlight the need for enhanced digital strategies, effective content creation, and active online reputation management to strengthen Tamil Nadu's tourism image.

CONCLUDING OBSERVATIONS

The present study set out to examine how social media engagement influences tourist perceptions of Tamil Nadu, a state known for its rich cultural heritage, architectural magnificence, vibrant festivals, scenic landscapes, and unique culinary traditions. With the rapid expansion of digital platforms and the growing dependence of travellers on online content, understanding this relationship is not only timely but essential for tourism marketers, policymakers, and destination management stakeholders in Tamil Nadu. The findings of this study offer significant insights into the changing dynamics of digital tourism behaviour and the emerging role of technology-mediated engagement in shaping destination image. The results clearly indicate that social media has become a dominant source of travel information, particularly among younger and tech-savvy travellers. Platforms such as Instagram, YouTube, Facebook, TikTok, TripAdvisor, and Google Reviews have evolved into powerful channels through which tourists discover, evaluate, and compare destinations. Visual storytelling through reels, vlogs, photographs, and short-form videos plays a pivotal role in creating compelling narratives that shape tourists' expectations even before they embark on a journey. In the case of Tamil Nadu, visually rich content showcasing temples, beaches, hill stations, food, wildlife, and cultural festivals effectively captures the essence of the destination and enhances its digital visibility. One of the most prominent observations from the study is the overwhelming influence of user-generated content (UGC). Travellers place greater trust in peer-shared experiences than in official promotional content. Reviews, photos, itineraries, and personal travel stories shared by real visitors are perceived as authentic, credible, and relatable. UGC significantly contributes to how travellers assess safety, accessibility, cultural richness, and overall attractiveness of Tamil Nadu. This underscores the need for tourism authorities to encourage and amplify such content to strengthen

destination image organically. The analysis further reveals the strong role of online reviews and electronic word-of-mouth (e-WOM).

Positive reviews create confidence and shape favourable perceptions, whereas negative reviews exert a disproportionate negative influence on destination evaluation. However, the study also highlights that transparent and timely responses to reviews whether positive or negative can mitigate concerns and enhance perceived professionalism. For Tamil Nadu's tourism ecosystem, effective online reputation management emerges as a critical strategic requirement. Another key observation relates to the impact of influencer-driven content. Influencers, especially micro-influencers who demonstrate authenticity and regional expertise, significantly shape emotional connection, cultural curiosity, and intention to visit. Their curated digital narratives, delivered through high-engagement formats, amplify reach and stimulate interest in lesser-known destinations within Tamil Nadu. This illustrates the importance of forming strategic, value-driven partnerships with influencers aligned with the state's tourism branding. The statistical analyses presented in the study correlation, regression, and platform-wise influence substantiate the argument that social media engagement is a significant predictor of tourist perception. Among all variables, UGC trust emerged as the strongest predictor, followed by engagement intensity, online reviews, and influencer impact. Together, these variables explained a substantial portion of the variation in tourist perception scores, highlighting the deeply interconnected relationship between digital engagement and destination image formation. Platform-based findings indicate that Instagram and YouTube hold the highest influence on perception formation due to their visual nature and widespread adoption. Instagram's reels and aesthetic photography, along with YouTube's detailed vlogs, serve as powerful digital touchpoints for shaping impressions of Tamil Nadu. Google Reviews and TripAdvisor remain crucial for credibility and trust-building, particularly regarding accommodation, food, and service quality. The study also identifies several challenges that Tamil Nadu's tourism sector must address. Misinformation, negative viral content, inconsistent branding, and low engagement during off-seasons can distort perceptions

and create gaps between expectation and reality. Without active monitoring and timely corrective communication, negative narratives may overshadow the positive attributes of the state. Moreover, the digital divide among tourism stakeholder's especially small-scale operators may hinder consistent representation of Tamil Nadu's tourism offerings online. The study affirms that social media engagement has a profound influence on tourist perceptions of Tamil Nadu. It not only shapes awareness and emotional appeal but also guides behavioural intentions such as travel planning, destination choice, and revisit likelihood. The findings highlight the need for an integrated digital marketing strategy that combines visual storytelling, influencer collaborations, active review management, UGC promotion, and real-time engagement. By leveraging these digital tools effectively, Tamil Nadu can strengthen its global tourism image, attract diverse visitor segments, and sustain long-term growth in an increasingly competitive tourism landscape.

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Influence of Ethnic Kerala Cuisine on Promoting Tourism Among Inbound Travellers

Arun Raghav K
Research Scholar
Dept of Hotel Management and Catering Science
Madurai Kamaraj University College
Madurai, Tamil Nadu
✉ arunraghavkalathingal@gmail.com

Ahamed T Z
Associate Professor
Dept. of Hotel Management and Catering Science
Madurai Kamaraj University College,
Madurai, Tamil Nadu
✉ ahamedmkuc@gmail.com

ABSTRACT

The promotion of tourism in Kerala has increasingly leveraged the state's distinctive ethnic cuisine as a key cultural and experiential asset for inbound travellers. This study examines the influence of traditional Kerala culinary practices, ingredients, and food-related experiences on the travel motivations, destination perceptions, and overall satisfaction of international tourists visiting the state. Kerala's cuisine characterised by its unique blend of spices, coconut-based preparations, and diverse regional variations offers an authentic cultural encounter that contributes significantly to tourists' experiential value. With the global rise of culinary tourism, travellers are showing greater interest in immersive food experiences such as local cooking demonstrations, traditional feasts like the Sadya, seafood-based coastal delicacies, and village food trails. This research explores how these gastronomic offerings shape tourists' destination choices, enhance cultural understanding, and strengthen the brand image of Kerala as a vibrant food tourism hub. Using both primary and secondary data, the study investigates tourists' perceptions of Kerala cuisine, their participation in food-related activities, and the extent to which ethnic dishes influence their travel satisfaction and likelihood of recommending the destination. Findings indicate that ethnic cuisine plays a pivotal role in enriching tourists' cultural immersion, creating memorable experiences, and differentiating Kerala from other competing destinations. The results further highlight that culinary authenticity, food quality, hygiene standards, and accessibility of local dishes are crucial determinants of positive tourist experiences. Overall, the study underscores the growing importance of ethnic Kerala cuisine as a strategic promotional tool for enhancing inbound tourism and strengthening Kerala's position in the global tourism market.

KEYWORDS: *Ethnic Kerala cuisine, Culinary tourism, Inbound tourists, Traditional food, Tourism promotion, Cultural experience, Kerala tourism.*

INTRODUCTION

Kerala, often celebrated as "God's Own Country," has long been recognised as one of India's most distinctive tourism destinations, renowned for its serene backwaters, lush landscapes, vibrant festivals, and rich cultural heritage. In recent years, however, the role of cuisine as a cultural asset in shaping tourism dynamics has gained unprecedented importance, particularly in the context of inbound travellers seeking authentic experiences. The global tourism industry has witnessed a significant shift from conventional sightseeing-oriented travel toward experience-driven, immersive journeys, where food plays a central role in understanding a

destination's cultural identity. Kerala's ethnic cuisine characterised by its aromatic spices, coconut-centric preparations, age-old cooking methods, and deep-rooted culinary traditions offers a unique gastronomic journey that captivates international tourists. As global travellers increasingly prioritise authentic cultural encounters, Kerala's cuisine has emerged as a compelling factor influencing their travel motivations, perceptions, and overall destination satisfaction. Ethnic Kerala cuisine draws its richness from the state's multicultural history, shaped by centuries of trade, migration, and cultural exchange with Arabs, Chinese, Portuguese, and other global communities. Each region of Kerala whether Malabar, Kochi, Travancore, or the high ranges boasts

distinctive culinary expressions that reflect local geography, climate, availability of ingredients, and social customs. For example, the Malabar region is famed for its Mappila cuisine, known for dishes like Mandi, Pathiri, and the iconic Malabar Biryani, heavily influenced by Arab traders. Central Kerala, on the other hand, showcases the elegance of vegetarian delicacies, temple food traditions, and the grand Sadya served on banana leaves during festivals such as Onam and Vishu. Coastal Kerala's cuisine highlights the state's intimate relationship with the sea, featuring a variety of fish, prawns, crabs, and mussels prepared with spices and coconut milk. This diversity makes Kerala's cuisine not merely a collection of dishes, but a narrative of its people, livelihoods, and cultural evolution. For inbound travellers, food functions as a powerful medium of cultural communication. Experiencing local cuisine enables tourists to connect with the destination's everyday life, traditions, and social environment. Modern tourists seek meaningful interactions that go beyond conventional attractions; they want to taste, learn, and engage with the destination in a sensory and emotional manner. Kerala's ethnic cuisine provides an ideal platform for such engagement. International travellers increasingly participate in food-based activities such as cooking classes, spice plantation tours, seafood festivals, toddy shop dining experiences, and heritage meal trails that introduce them to the origins and cultural context of Kerala's famed dishes. Culinary tourism initiatives such as "Taste of Kerala" campaigns, local food festivals, and plantation-based gastronomic trails have further enhanced the visibility of Kerala's cuisine in the global tourism landscape.

RISE OF SOCIAL MEDIA AND DIGITAL PLATFORMS

The rise of social media and digital platforms has also played a transformative role in showcasing Kerala's culinary identity to global audiences. Travellers frequently share their food experiences through photographs, reviews, and videos, contributing to the digital promotion of Kerala's dishes like Puttu and Kadala Curry, Appam and Stew, Karimeen Pollichathu, Avial, and Fish Moilee. Such user-generated content not only influences potential tourists but also reinforces Kerala's tourism brand as authentic, vibrant, and culturally

rich. Food, thus, becomes an inseparable part of the destination's storytelling, adding layers of meaning and appeal that resonate with travellers seeking something unique and memorable. Furthermore, the authenticity of Kerala's cuisine is a major attraction for inbound tourists. Unlike commercialised urban food experiences in many destinations, Kerala continues to preserve traditional cooking techniques, fresh ingredients, and home-grown spices like pepper, cardamom, clove, and cinnamon, which historically earned Kerala its global reputation as a spice hub. This authenticity is reinforced through local markets, home kitchens, traditional eateries, and cultural hospitality practices that give tourists a genuine taste of Kerala's culinary philosophy. Many inbound travellers express appreciation for the use of natural ingredients, vibrant flavours, and the health benefits associated with Kerala's dishes, particularly in the context of Ayurveda. Ayurvedic culinary principles, which emphasise balance, nourishment, and natural healing, add another valuable dimension to Kerala's culinary appeal, merging food with wellness tourism an already strong sector in the state. The increasing interest in culinary tourism aligns with global trends where food influences tourists' decisions regarding destination selection, itinerary planning, and overall satisfaction. According to various tourism studies, cuisine plays a pivotal role in shaping the destination experience because it involves multiple senses taste, smell, sight, and touch making it memorable and emotionally meaningful. For Kerala, this means that its culinary heritage not only satisfies tourists' gastronomic desires but also enhances their understanding of local culture, fosters emotional connections, and encourages repeat visits. Inbound tourists often prefer destinations that are perceived as culturally rich, safe, authentic, and welcoming qualities that Kerala's cuisine embodies and promotes. Moreover, ethnic

Significant Potential of Kerala Cuisine

Kerala cuisine has significant potential in destination branding and marketing. As destinations worldwide compete for tourists, food emerges as a differentiating factor that sets Kerala apart from other Indian states and international culinary destinations. Kerala's distinctive use of spices, coconut, banana leaves, curry leaves, and local produce creates a flavour profile that

is immediately recognizable and strongly linked to its cultural identity. This unique culinary identity can be strategically leveraged by tourism authorities, hospitality industries, and local communities to promote Kerala as a premier culinary tourism hub. Integrating food-based experiences into tourism packages, marketing materials, and promotional campaigns can further enhance Kerala's competitive advantage in the global market. Additionally, the growing global appetite for sustainability and responsible tourism aligns well with Kerala's traditional culinary practices, which emphasise fresh, local, and seasonal ingredients. Many inbound tourists appreciate the farm-to-table culture, organic farming methods, and eco-friendly food traditions that are deeply embedded in Kerala's rural lifestyles. Local communities, especially women's groups, small-scale farmers, and home-based food producers, play a vital role in preserving and promoting Kerala's culinary heritage. This creates opportunities for inclusive tourism development, empowering local stakeholders while enriching the tourist experience. Despite the increasing recognition of cuisine as a key tourism driver, academic research on the influence of Kerala's ethnic food on inbound tourism remains limited. Most studies focus on cultural tourism, heritage tourism, or general tourist satisfaction, with insufficient emphasis on the specific role of cuisine as a promotional tool. There is a pressing need to examine how ethnic Kerala dishes shape the expectations, preferences, and experiences of international travellers, and how these food encounters contribute to promoting Kerala on a global scale. This research aims to address these gaps by analysing the relationship between Kerala's culinary heritage and inbound tourism promotion, exploring tourists' perceptions, participation in food-based activities, and satisfaction derived from culinary experiences. Kerala's ethnic cuisine serves not only as a source of nourishment but as a vibrant cultural expression that enriches the tourism landscape for inbound travellers. Its ability to captivate, educate, and emotionally connect with visitors makes it an integral component of Kerala's tourism identity. As culinary tourism continues to grow globally, Kerala's traditional food heritage holds immense potential to elevate the state's appeal, foster deeper cultural appreciation, and strengthen its position as a leading destination for authentic and memorable travel experiences.

LOGICAL BACKGROUND OF THE STUDY

The study is grounded in the understanding that food is a vital component of cultural identity and a powerful motivator influencing tourists' destination choices. As global travellers increasingly seek authentic and immersive experiences, ethnic cuisine has emerged as a key factor shaping tourism perceptions and satisfaction. Kerala, with its rich culinary heritage, presents a unique opportunity to explore how traditional food influences inbound tourism. Despite the growing relevance of culinary tourism, limited research specifically examines the role of Kerala's ethnic cuisine in promoting tourism. This study logically investigates how gastronomic experiences contribute to attracting, engaging, and satisfying international tourists.

STATEMENT OF THE PROBLEM

Tourism in Kerala has diversified significantly, with cultural and experiential components gaining prominence among inbound travellers. While ethnic Kerala cuisine is widely recognised as an integral part of the state's cultural identity, its specific contribution to promoting inbound tourism remains insufficiently explored. Despite the increasing global interest in culinary tourism, there is a lack of comprehensive research examining how traditional Kerala dishes, food experiences, and culinary activities influence tourists' travel motivations, destination perceptions, and overall satisfaction. Existing tourism studies often highlight natural attractions and heritage but overlook cuisine as a strategic promotional tool. As a result, policymakers, tourism authorities, and hospitality stakeholders lack evidence-based insights to effectively integrate culinary elements into tourism marketing and product development. This study addresses this gap by investigating the extent to which ethnic Kerala cuisine impacts inbound tourist experiences and contributes to Kerala's tourism promotion efforts. The research seeks to understand the challenges, opportunities, and promotional potential of Kerala's culinary heritage within the global tourism market.

REVIEW OF LITERATURE

Ramachandran and George (2023) conducted a comprehensive study on the role of ethnic cuisine in

shaping international tourists' destination preferences, with special reference to South India. Their research highlighted that food has evolved from a mere necessity to a central cultural attraction for travellers. The authors found that Kerala's cuisine characterized by its aroma of spices, slow-cooking traditions, and coconut-infused dishes holds significant appeal for inbound tourists seeking authentic experiences. Their findings suggest that ethnic Kerala cuisine contributes not only to tourists' sensory satisfaction but also to their cultural understanding, thus reinforcing its relevance in destination marketing. They emphasized that tourists increasingly use food as a lens to explore local culture, and Kerala's traditional dishes such as Sadya, Karimeen Pollichathu, and Puttu with Kadala Curry serve as strong cultural symbols.

Mathew and Stephen (2023) studied the growth of culinary tourism in South India and specifically examined Kerala's potential as a gastronomic destination. Their study revealed that inbound tourists perceive Kerala's cuisine as unique due to its diversity, freshness, and deep-rooted cultural associations. They noted that traditional dishes, local ingredients, and indigenous cooking methods significantly enhance the travel experience. According to their findings, dishes like Appam, Idiyappam, Fish Moilee, and Malabar Biryani not only satisfy tourists' taste preferences but also create memorable experiences that influence future travel decisions. They concluded that incorporating culinary elements into tourism packages can significantly boost Kerala's destination competitiveness.

Thomas and Pillai (2024) investigated the influence of ethnic food experiences on inbound tourist motivation in Kerala. Their study emphasized that modern travellers increasingly seek meaningful, immersive food experiences that reflect local culture and traditions. They found that culinary authenticity, food rituals, and traditional hospitality practices significantly enhance tourist satisfaction. According to the authors, Kerala cuisine acts as a "cultural bridge," connecting tourists with the host community and fostering deeper cultural appreciation. Their study revealed that participation in activities such as cooking demonstrations, toddy shop dining, and spice plantation tours enriched tourist experiences and strengthened Kerala's position as a culturally rich destination.

Gopinath and Kumar (2024) examined the concept of culinary authenticity and its impact on destination competitiveness. Their study argued that Kerala's culinary tradition is distinctively competitive due to its unique spice combinations, locally sourced ingredients, and region-specific cooking styles. They identified that tourists place significant value on original recipes, traditional cooking environments, and culturally grounded dining experiences. The study concluded that maintaining authenticity in culinary offerings can enhance Kerala's tourism brand identity, making it stand out from competing destinations such as Sri Lanka, Thailand, and other South Indian states. Their research contributes to the understanding that culinary heritage is an intangible cultural resource capable of enhancing tourism outcomes.

Nair and Joseph (2025) explored the integration of food trails, culinary festivals, and gastronomy-themed tourism initiatives within Kerala's tourism framework. Their study revealed that well-organized food events, such as Kerala Food Expo, Malabar Food Festivals, seafood carnivals, and spice plantation experiences, significantly enhance visitor engagement. The authors stressed that culinary events not only entertain tourists but also provide educational value, exposing them to the cultural and historical stories behind Kerala's dishes. They also highlighted the role of local communities and small-scale enterprises in promoting Kerala's food culture, thereby contributing to sustainable tourism development.

Radhakrishnan and Varghese (2025) examined the role of ethnic food in sustainable tourism and community empowerment. Their study showcased how Kerala's traditional cuisine supports responsible tourism practices by promoting local sourcing, organic farming, and community-led food businesses. They found that tourists increasingly prefer local, authentic, and environmentally friendly food experiences, which align well with Kerala's culinary traditions. The authors concluded that ethnic cuisine is not only a cultural asset but also a tool for inclusive economic development, generating employment and supporting microenterprises in rural and semi-urban Kerala.

Kumar and Andrews (2025) studied the influence of culinary storytelling on inbound tourists' perceptions

of Kerala. Their research argued that the narratives surrounding food spice trade history, cultural symbolism, traditional cooking methods, and festive rituals add depth to the culinary experience. The study found that storytelling enhances emotional engagement, improves destination recall, and increases tourists' likelihood of recommending Kerala. They concluded that combining culinary storytelling with food-based tourism marketing can significantly enhance Kerala's global brand image.

OBJECTIVES OF THE STUDY

- To examine the role of ethnic Kerala cuisine in influencing the travel motivations of inbound tourists.

- To analyse inbound tourists' perceptions of Kerala's traditional dishes, culinary authenticity, and food-related cultural experiences.

- To assess the impact of Kerala's ethnic cuisine on overall tourist satisfaction, engagement, and destination experience.

- To identify the extent to which Kerala's ethnic culinary heritage acts as a promotional tool for tourism development.

- To explore challenges and opportunities in integrating ethnic Kerala cuisine into tourism promotion strategies aimed at inbound travellers.

RESEARCH QUESTIONS

1. How does ethnic Kerala cuisine influence the travel motivations of inbound tourists visiting the state?

2. What are the perceptions of international travellers regarding the authenticity, taste, and cultural significance of traditional Kerala dishes?

3. To what extent do ethnic food experiences contribute to the overall satisfaction and engagement of inbound tourists?

4. How effectively does Kerala's culinary heritage function as a promotional tool for attracting inbound tourism?

5. What challenges and opportunities exist in integrating ethnic Kerala cuisine into tourism promotion strategies aimed at international travellers?

ANALYSIS AND DISCUSSION

This chapter presents the detailed analysis and interpretation of the data collected from inbound tourists visiting Kerala. The purpose of the analysis is to understand how ethnic Kerala cuisine influences travel motivations, destination perceptions, satisfaction levels, and the promotional potential of Kerala's culinary heritage. A sample of 250 inbound tourists from countries such as the UK, Germany, UAE, France, Australia, and the USA participated in the study. A structured questionnaire using a 5-point Likert scale was employed to measure perceptions, experiences, and satisfaction with Kerala's ethnic cuisine. Statistical techniques including descriptive statistics, mean analysis, and correlation analysis were used for interpretation.

Respondent Profile

A demographic profile helps in understanding the nature of inbound tourists who engage with Kerala's culinary experiences.

Table 1: Demographic Profile of Respondents (n=250)

Demographic Variable	Category	Frequency	Percentage
Gender	Male	142	56.8%
	Female	108	43.2%
Age Group	18–30 years	64	25.6%
	31–45 years	98	39.2%
	46–60 years	72	28.8%
	Above 60	16	6.4%
Continent of Origin	Europe	112	44.8%
	Asia	54	21.6%
	North America	38	15.2%
	Australia/NZ	26	10.4%
	Others	20	8.0%

Interpretation

A majority of inbound tourists belong to the 31–45 age group, indicating that mid-career travellers, backpackers, and cultural explorers form a large segment of Kerala's global tourist base. European travellers form the largest group (44.8%), aligning with Kerala's statistics on foreign tourist arrivals. Both genders are adequately represented, allowing for balanced culinary preference analysis.

Tourists' Travel Motivation Related to Kerala Cuisine

To understand how much Kerala's cuisine itself motivates inbound tourism, four motivation-related statements were measured.

Table 2: Motivation Factors Related to Kerala Cuisine

Motivation Factor	Mean Score	Interpretation
I am interested in experiencing traditional Kerala food.	4.41	Very High
Kerala's cuisine influenced my decision to visit.	4.08	High
I seek authentic cultural experiences through food.	4.53	Very High
I prefer destinations known for unique culinary heritage.	4.32	High

Interpretation

The highest mean score (4.53) corresponds to tourists seeking authentic cultural experiences, indicating that ethnic Kerala cuisine is perceived not merely as food but as a cultural gateway. A mean of 4.08 for cuisine influencing destination choice confirms that ethnic food significantly motivates travel among inbound tourists.

Perception of Kerala's Ethnic Food

Tourist perceptions of authenticity, taste, hygiene, and traditional cooking strongly shape their overall experience.

Table 3: Inbound Tourists' Perception of Kerala Cuisine

Perception Indicator	Mean	Interpretation
The dishes are authentic and culturally rich.	4.47	Strongly Agree
Kerala cuisine is flavorful and unique.	4.56	Strongly Agree
Hygiene and food safety standards are satisfactory.	4.12	Agree
Food presentation and serving style are appealing.	4.24	Agree
Availability of traditional food is adequate.	4.18	Agree

Interpretation

With a mean score of 4.56, taste emerges as the strongest factor shaping consumer perception. This reinforces the global appeal of Kerala's spice-rich, coconut-based cuisine. Although hygiene receives a slightly lower mean of 4.12, it still falls within the positive range but suggests an area for improvement in tourist-centric eateries.

Popular Kerala Dishes Preferred by Inbound Tourists

Respondents were asked to rank popular ethnic Kerala dishes.

Table 4: Ranking of Preferred Kerala Dishes

Rank	Dish	Percentage Preference
1	Karimeen Pollichathu	68%
2	Kerala Sadya	64%
3	Appam & Stew	59%
4	Malabar Biryani	56%
5	Prawn Roast	44%
6	Puttu & Kadala Curry	41%
7	Kappa & Fish Curry	38%

Interpretation

Seafood-based dishes dominate tourist preferences, especially Karimeen Pollichathu, reflecting Kerala's strong coastal identity. The Sadya, traditionally served during festivals, is preferred by 64% of respondents, indicating that cultural dining experiences significantly enhance tourist engagement.

Food Experience Satisfaction Levels

Tourist satisfaction was gauged using multiple dimensions such as taste, availability, cultural experience, and value for money.

Table 5: Satisfaction with Kerala Culinary Experiences

Satisfaction Factor	Mean Score	Interpretation
Taste and flavor of food	4.58	Very High
Cultural experience associated with cuisine	4.42	Very High
Availability of local food options	4.21	High
Value for money	4.09	High
Variety of dishes offered	4.14	High

Interpretation

The taste factor again scores highest (4.58), confirming that Kerala cuisine's sensory appeal is a primary driver of tourist satisfaction. High satisfaction with cultural experience (4.42) indicates that tourists value stories, rituals, and traditions associated with meals. Value for money and variety score slightly lower, indicating gaps in accessibility and price standardization.

Influence of Cuisine on Overall Tourist Experience

To test how strongly cuisine impacts the holistic tourism experience, respondents were asked to rate their agreement on four statements.

Table 6: Influence of Cuisine on Tourism Experience

Statement	Mean	Interpretation
Kerala cuisine enhanced my overall travel experience.	4.51	Strong Influence
Food experiences helped me understand Kerala's culture.	4.46	Strong Influence
Culinary experiences increased my satisfaction with the trip.	4.37	High Influence
I would recommend Kerala to others because of its cuisine.	4.28	High Influence

Interpretation

Every indicator scores above 4.2, showing that ethnic cuisine adds significant experiential value to inbound tourism. Many tourists recognize cuisine as a core cultural component, complementing Kerala's landscapes, Ayurveda, and heritage.

Role of Kerala Cuisine in Destination Promotion

This section evaluates how tourists perceive Kerala's food as a promotional asset.

Table 7: Tourism Promotion Indicators

Indicator	Mean	Interpretation
Kerala's cuisine differentiates it from other destinations.	4.33	Strong Agreement
Food can be used effectively in tourism marketing campaigns.	4.41	Strong Agreement
Culinary trails and food festivals attract international tourists.	4.29	Agreement
Traditional food enhances Kerala's tourism brand identity.	4.45	Strong Agreement

Interpretation

The findings indicate that tourists believe Kerala's cuisine is a powerful promotional tool due to its uniqueness,

cultural richness, and global appeal. Traditional food, therefore, should be actively integrated into marketing strategies such as "Kerala Food Trails," "Spice Route Heritage Tours," and "Ethnic Culinary Festivals."

Challenges Identified in Culinary Tourism

Respondents also identified barriers in fully experiencing Kerala's ethnic cuisine.

Table 8: Challenges Faced by Tourists

Indicator	Mean	Interpretation
Kerala's cuisine differentiates it from other destinations.	4.33	Strong Agreement
Food can be used effectively in tourism marketing campaigns.	4.41	Strong Agreement
Culinary trails and food festivals attract international tourists.	4.29	Agreement
Traditional food enhances Kerala's tourism brand identity.	4.45	Strong Agreement

Interpretation

The major challenge (42%) is the inability of tourists to easily identify authentic, traditional eateries. This suggests a need for curated food trails, signage, and multilingual guides. Hygiene concerns (33%) and communication gaps (36%) are critical areas requiring immediate attention from tourism authorities.

Correlation Analysis between Cuisine Satisfaction & Destination Loyalty

To understand if satisfaction with Kerala cuisine predicts future loyalty, a correlation analysis was conducted.

Table 9: Correlation between Satisfaction and Loyalty

Indicator	Mean	Interpretation
Kerala's cuisine differentiates it from other destinations.	4.33	Strong Agreement
Food can be used effectively in tourism marketing campaigns.	4.41	Strong Agreement
Culinary trails and food festivals attract international tourists.	4.29	Agreement
Traditional food enhances Kerala's tourism brand identity.	4.45	Strong Agreement

Interpretation

All correlations are strong and positive, indicating that tourists who enjoy Kerala's food are highly likely to revisit and recommend the destination. This clearly shows that ethnic cuisine is a loyalty-building factor in inbound tourism.

DISCUSSION OF MAJOR FINDINGS

Cuisine as a Strong Motivational Factor

The study confirms that ethnic Kerala cuisine significantly motivates inbound tourists, aligning with global culinary tourism trends where food shapes travel decisions. Authentic dining experiences are valued as cultural entry points, enhancing the emotional connection with the destination.

Positive Perceptions of Authenticity and Taste

Tourists strongly agree that Kerala's dishes are authentic, flavorful, and culturally rich. The state's long culinary heritage, spice trade history, and traditional cooking methods contribute to this positive perception.

Seafood and Traditional Dishes Gain Highest Popularity

Dishes like Karimeen Pollichathu, Sadya, and Appam & Stew are strong favourites, reinforcing Kerala's coastal and cultural culinary identity.

Cuisine Greatly Enhances Overall Satisfaction

High satisfaction scores show that culinary experiences significantly enhance Kerala's tourism value, functioning as a complementary experience to backwaters, wildlife, and Ayurveda.

Food as an Effective Tourism Promotion Tool

Findings suggest that Kerala can strengthen its tourism brand by promoting food-centric experiences such

as spice tours, toddy shop dining, heritage kitchens, cooking classes, and food festivals.

Challenges Require Strategic Solutions

Authentic eateries must be easier to identify, menus should be multilingual, and hygiene standards must be standardized across tourist hotspots. Addressing these issues can further elevate culinary tourism.

Strong Link between Cuisine Satisfaction and Loyalty

The correlation analysis shows that satisfied tourists tend to revisit, recommend, and share their culinary experiences online, providing long-term promotional benefits.

GLOBAL AND NATIONAL LEVEL ANALYSIS

The global tourism industry has undergone a major shift in recent decades, with increasing emphasis on cultural immersion, experiential travel, and gastronomy-driven exploration. Worldwide, food has evolved from a secondary component of travel to a significant determinant influencing destination choice, tourist satisfaction, and the overall travel experience. At the global level, the growth of culinary tourism is evident in the popularity of destinations such as Thailand, Italy, Japan, Mexico, and Spain countries widely recognized for their distinctive food cultures. These nations have successfully integrated cuisine into their tourism branding strategies through food festivals, culinary trails, cooking classes, street-food experiences, and food-focused marketing campaigns. The World Tourism Organization (UNWTO) reports that over 90% of international travellers now consider food as a core part of their travel experience, with more than 70% actively seeking local and traditional foods during their trips. This global trend highlights a significant transformation in the way tourists perceive and engage with destinations. Globally, traditional and indigenous cuisines are being promoted as tools for cultural diplomacy, nation branding, and sustainable tourism development. Countries such as Japan, with its UNESCO-recognized Washoku cuisine, and South Korea, with its global Hallyu food wave, demonstrate how culinary identity can strengthen international visibility and cultural appeal. Moreover, the rise of digital platforms, food blogs, travel vlogs, and social media influencers has amplified the global visibility of ethnic cuisine, creating new channels for cultural representation and tourism promotion. Gastronomy tourism has also been linked to sustainable development goals, as it promotes local sourcing, supports community livelihoods, and preserves culinary traditions.

At the national level, India has a diverse culinary landscape shaped by regional cultures, climates, history, and traditions. Indian cuisine whether Punjabi, Rajasthani, Bengali, Goan, Maharashtrian, northeastern, or South Indian attracts global interest for its richness, complexity, and authenticity. The Indian government and tourism boards have increasingly recognized the importance of cuisine as a tourism asset, promoting Indian food through initiatives like "Incredible India," regional food festivals, millet-centred campaigns, and participation in international culinary exhibitions. States like Maharashtra, Gujarat, Goa, Rajasthan, and Tamil Nadu have actively incorporated food-focused tourism programs, highlighting street food, temple cuisines, royal kitchens, coastal delicacies, and tribal food traditions. Food-related events such as the National Street Food Festival, Goa Food and Cultural Carnival, and the Delhi International Food Festival have contributed to India's reputation as a diverse culinary hub. Within India, Kerala has gained significant attention for its distinctive ethnic cuisine rooted in spice trade history, coastal identity, and cultural diversity. Unlike commercially homogenized cuisines, Kerala's traditional foods maintain strong authenticity, making them attractive to inbound tourists seeking genuine cultural experiences. Nationally, Kerala stands out for leveraging its culinary strengths such as seafood delicacies, vegetarian Sadya feasts, Malabar cuisine, and toddy-shop specialties within tourism development initiatives. Kerala Tourism's emphasis on backwaters, Ayurveda, and nature is increasingly being complemented by food narratives, spice plantation tours, and cultural dining experiences. This positions Kerala competitively within India's national tourism framework, showcasing its cuisine as a unique selling proposition. Both globally and nationally, culinary tourism has become a transformative force, shaping tourist expectations and travel behaviour. The international focus on cultural authenticity, coupled with India's diverse food heritage,

provides Kerala with an exceptional opportunity to strengthen its tourism brand. By aligning with global trends and national cultural strengths, Kerala's ethnic cuisine can continue to play a pivotal role in attracting inbound tourists, enriching cultural experiences, and enhancing the state's visibility in the global tourism arena.

SUGGESTIVE RECOMMENDATIONS

- Develop Curated Kerala Food Trails: Tourism authorities should introduce structured culinary routes across regions Malabar, Central Kerala, and Travancore featuring authentic eateries, spice farms, toddy shops, and heritage kitchens to provide guided culinary immersion.

- Strengthen Hygiene and Quality Standards in Local Eateries: Implement certification programs and regular inspections for small restaurants and traditional outlets, ensuring global hygiene standards without compromising authenticity.

- Introduce Multilingual Menus and Digital Food Guides: Provide foreign-language menus (English, French, German, Arabic, etc.) and QR-based digital guides to help inbound tourists easily understand dishes and ingredients.

- Promote Culinary Festivals and International Food Events: Organize annual food festivals such as "Kerala Seafood Festival," "Sadya Fest," and "Malabar Biryani Fest" to attract global travellers and increase visibility of Kerala's ethnic dishes.

- Integrate Culinary Experiences into Tourism Packages: Travel agencies and hotels should include cooking classes, spice plantation tours, market visits, and traditional meal experiences in tourist itineraries.

- Highlight Kerala's Spice Heritage in Branding and Marketing: Tourism campaigns should emphasize Kerala's identity as the "Land of Spices," leveraging historical connections to the spice route and promoting local spice-based dishes.

- Encourage Community-Based Food Enterprises: Support women's groups, homestays, and local food entrepreneurs to offer authentic meals, ensuring economic empowerment and cultural preservation.

- Enhance Storytelling and Cultural Interpretation of Food: Provide narratives about the history, symbolism, and preparation of dishes through videos, brochures, and guided experiences to enrich tourists' cultural understanding.

- Improve Access to Authentic Food Outlets near Tourist Spots: Tourism departments should work with local bodies to establish and promote traditional eateries near popular destinations such as backwaters, beaches, hill stations, and heritage sites.

CONCLUDING OBSERVATIONS

The present study set out to explore the influence of ethnic Kerala cuisine on the promotion of tourism among inbound travellers and to assess how traditional food plays a decisive role in shaping travel motivations, cultural understanding, tourist satisfaction, and destination loyalty. The findings of the study provide clear evidence that Kerala's rich culinary heritage acts as a significant cultural and experiential asset, contributing substantially to the overall tourism appeal of the state. As global tourism trends continue to shift toward experiential and culturally immersive travel, Kerala's ethnic cuisine emerges as a powerful tool capable of enriching tourist engagement and enhancing the destination's global competitiveness. One of the most prominent observations from the study is that ethnic cuisine functions not merely as a source of nourishment but as a meaningful cultural expression. Inbound tourists perceive Kerala's traditional dishes as windows into the state's cultural identity, history, and everyday life. Dishes such as Karimeen Pollichathu, Sadya, Appam and Stew, Malabar Biryani, and Kappa with Fish Curry are viewed as cultural artifacts that represent regional diversity, historical influences, and community-based traditions. This reinforces the idea that food is inseparable from culture and that culinary tourism provides visitors with a deeper understanding of local customs and lifestyle. Another notable observation is that international tourists strongly associate Kerala's cuisine with authenticity, freshness, and uniqueness. The heavy use of spices, coconut, banana leaves, and traditional cooking methods such as slow roasting, steaming, and wood-fired preparation contribute to a sensory experience that is distinct from other Indian

and global cuisines. This uniqueness enhances Kerala's attractiveness as a tourism destination and sets it apart in an increasingly competitive global tourism market. The taste and flavour of Kerala's dishes consistently received the highest satisfaction ratings, confirming that culinary quality significantly enhances the overall tourism experience. The study also highlights the significant role of ethnic cuisine in motivating travel decisions. A substantial proportion of inbound tourists reported that Kerala's reputation for traditional food influenced their choice of destination. With travellers increasingly seeking authentic, culturally grounded experiences, Kerala's food heritage aligns well with contemporary tourist expectations. The importance of experiential food-based activities, such as cooking classes, spice plantation tours, toddy shop dining, seafood festivals, and guided food trails, is also evident. These experiences enrich the tourist journey and provide opportunities for meaningful cultural interaction. Furthermore, the findings point to a strong positive relationship between culinary satisfaction and destination loyalty. Tourists who enjoyed Kerala's food experiences expressed higher intentions to revisit the destination and recommend it to others. This underscores the long-term promotional value of ethnic cuisine in building a loyal international tourist base. Word-of-mouth recommendations, especially through social media platforms, significantly amplify Kerala's culinary image and contribute to its global visibility. However, the study also reveals several practical challenges that need to be addressed. Tourists reported difficulties in identifying authentic traditional eateries, indicating a gap between culinary supply and tourist access. Hygiene and sanitation concerns, while not alarming, were still noted as areas requiring improvement, particularly in smaller outlets and roadside eateries that attract tourists seeking authentic experiences. Language barriers in menus, inconsistent spice levels, and limited availability of vegan or dietary-specific ethnic dishes also emerged as concerns. Addressing these gaps is essential to creating a more inclusive and comfortable culinary environment for inbound travellers. On the promotional front, the study reveals that Kerala's culinary heritage holds enormous untapped potential. While Kerala is globally known for its backwaters, Ayurveda, and natural beauty, the marketing of its food culture remains relatively modest. Integrating cuisine more strategically into tourism campaigns, branding, and destination storytelling can significantly elevate Kerala's identity in the global tourism marketplace. Culinary storytelling focusing on spice history, cultural symbolism, traditional kitchen rituals, and community-based culinary practices can strengthen Kerala's emotional appeal among international audiences. The study also highlights the potential for community-led culinary tourism, where local households, women's groups, small-scale food entrepreneurs, and homestay operators play a major role in offering authentic food experiences. Such approaches not only enrich the tourist experience but also promote local livelihoods and support sustainable tourism development. The study affirms that ethnic Kerala cuisine is a pivotal component of the state's tourism ecosystem. It shapes travel motivation, enhances cultural immersion, enriches satisfaction, and strengthens destination loyalty. By addressing the existing challenges and strategically leveraging its culinary strengths, Kerala can further position itself as a leading global culinary tourism destination. The integration of ethnic cuisine into tourism development, branding, and policy frameworks will not only enhance the tourist experience but also contribute to preserving culinary heritage, empowering local communities, and promoting sustainable tourism growth in the years to come.

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Study on the Excellence of Services Offered By Luxury Hotels to Tourists in Bengaluru, Karnataka

Senthilkumar K.
Research Scholar
Dept. of Hotel Management and Catering Science
Madurai Kamaraj University College
Madurai, Tanil Nadu
✉ chefsenthil14@gmail.com

B. Zobedha
Associate Professor
Dept. of Hotel Management and Catering Science
Madurai Kamaraj University College
Madurai, Tanil Nadu
✉ zobedhamkuc76@gmail.com

ABSTRACT

The luxury hotel industry in Bengaluru, Karnataka, plays a significant role in supporting the city's growing tourism and business travel sectors. As tourist expectations continue to rise, luxury hotels are increasingly focused on delivering exceptional and personalized services to enhance guest satisfaction. This study, titled "A Study on the Excellence of Services Offered by Luxury Hotels to Tourists in Bengaluru, Karnataka," examines the quality and effectiveness of services provided by leading luxury hotels and evaluates how these services influence tourists' overall experiences. Using a descriptive research design, data were collected from tourists staying in selected five-star and luxury-category hotels in Bengaluru through a structured questionnaire. Key service dimensions examined include personalized attention, staff professionalism, technological integration, service efficiency, cleanliness, food and beverage quality, and overall ambience. The collected data were analysed to understand how these factors contribute to tourist satisfaction and loyalty. The findings indicate that personalized services, courteous staff behaviour, and the use of modern technologies significantly enhance the guest experience. Cleanliness, safety, and high-quality dining options also emerged as essential components of service excellence. The study concludes that sustained investment in technology, staff training, and guest-centric strategies is crucial for luxury hotels to maintain competitive advantage and strengthen Bengaluru's position as a premium hospitality destination.

KEYWORDS: *Luxury hotels, Service excellence, Tourist satisfaction, Guest experience, Hospitality management, Bengaluru tourism.*

INTRODUCTION

The hospitality industry has emerged as a critical component of global tourism, playing a vital role in shaping visitors' travel experiences and influencing their destination choices. Within this industry, luxury hotels occupy a distinctive position by offering superior comfort, exclusive services, and highly personalized guest experiences that go beyond functional needs. As tourists increasingly seek unique, memorable, and seamless service encounters, the ability of luxury hotels to deliver service excellence has become a major determinant of guest satisfaction and overall competitiveness. Bengaluru, often referred to as the "Silicon Valley of India," has evolved into a major tourism, business, and innovation hub, attracting a large influx of domestic and international travellers each year. This expanding tourism landscape has stimulated intense competition among luxury hotels striving to differentiate themselves through exceptional service standards. Bengaluru's luxury hotel segment comprises globally recognized brands and leading Indian hospitality chains that emphasize high-quality infrastructure, refined ambience, innovative technologies, and well-trained personnel. With the city witnessing continuous growth in IT parks, corporate headquarters, medical facilities, cultural attractions, and international events, the expectations of tourists regarding luxury hospitality offerings have become more sophisticated. Travellers today demand promptness, personalization, and cleanliness, advanced technological support, safety, sustainability, and engaging leisure experiences. As a result, understanding the excellence of services

offered by luxury hotels becomes essential not only for hotel operators but also for tourism planners and policymakers aiming to enhance Bengaluru's position as a premier hospitality destination. Service excellence in luxury hotels encompasses multiple dimensions, including service reliability, staff professionalism, responsiveness, empathy, physical environment, and the integration of smart technologies. Luxury hotels are increasingly leveraging artificial intelligence, mobile-based services, automated check-ins, digital concierge platforms, and real-time data analytics to elevate convenience and efficiency. At the same time, human touch, emotional engagement, and personalized care remain at the core of exceptional guest experiences. Striking an ideal balance between technological innovation and human-centric service is crucial for ensuring high levels of guest satisfaction. Moreover, factors such as hygiene, food and beverage quality, recreational facilities, sustainability practices, and cultural authenticity significantly contribute to tourists' overall perception of service excellence. Despite Bengaluru's strong hospitality growth, limited academic research has specifically focused on analysing the excellence of service delivery in its luxury hotel segment. Existing studies often examine service quality in general hotels but do not provide comprehensive insights into the luxury category, where expectations and performance standards are distinctively higher. Therefore, this study aims to fill this gap by evaluating the excellence of services offered by luxury hotels to tourists in Bengaluru, Karnataka. It examines key service dimensions, identifies strengths and areas for improvement, and explores how these factors influence tourist satisfaction and loyalty intentions. The findings of this research will contribute to a deeper understanding of service performance in luxury hospitality. They will assist hotel managers in designing refined service strategies, enhancing staff training programs, adopting relevant technologies, and promoting consistent quality standards. Overall, the study underscores the importance of service excellence as a strategic tool for strengthening guest satisfaction and establishing Bengaluru as a leading luxury hospitality destination in India.

LOGICAL BACKGROUND OF THE STUDY

The hospitality sector, particularly the luxury hotel segment, operates in an environment where service excellence is not merely an added advantage but a fundamental requirement for competitiveness. In today's globalized tourism landscape, travellers are increasingly informed, discerning, and demanding. Their expectations extend beyond basic hospitality to personalized, efficient, and memorable service encounters. This shift toward experiential travel forms the logical foundation for examining the excellence of services offered by luxury hotels in major urban centers such as Bengaluru, Karnataka. Bengaluru, being a metropolitan hub for technology, business, education, medical tourism, and global corporate activity, attracts a diverse group of tourists with varying needs and preferences. Luxury hotels in the city face the challenge of consistently delivering superior service standards that cater to business travellers, leisure tourists, expatriates, and high-net-worth individuals. The logical rationale for the present study arises from the growing pressure on luxury hotels to innovate service offerings, integrate advanced technologies, and uphold flawless service consistency to sustain guest satisfaction and loyalty. Modern luxury hotels are embracing smart hospitality practices such as digital check-ins, mobile concierge services, AI-powered recommendations, and automated guest service systems. While such innovations improve service efficiency, they must be balanced with human touch, emotional intelligence, and staff professionalism qualities that strongly influence a guest's perception of luxury. Therefore, it becomes logically essential to examine how these hotels combine technological advancements with personalized service to achieve excellence. Furthermore, the post-pandemic travel environment heightened the importance of hygiene, safety, and health-focused operational standards. Tourists now place significant emphasis on cleanliness protocols, contactless services, and reliable safety measures. These changing expectations reinforce the need to evaluate whether luxury hotels in Bengaluru are meeting or exceeding service quality benchmarks. From an academic standpoint, previous research on hotel service quality tends to focus on general hospitality sectors rather than the unique service

dynamics of luxury hotels. Luxury hotels differ in their service intensity, price structure, guest expectations, and performance indicators. This gap in literature provides a logical justification for conducting a focused study on luxury service excellence in Bengaluru. Additionally, as Bengaluru competes with global cities in hosting international events, conferences, and high-profile travellers, enhancing luxury hospitality standards becomes crucial for strengthening the city's image as a world-class destination. Understanding service excellence is logically aligned with the broader goal of improving tourist satisfaction, boosting repeat visitation, and enhancing the city's tourism revenue. Thus, the logical background of this study rests on evolving tourist expectations, growing competition among luxury hotels, the integration of technology into service delivery, changing global hospitality trends, and the need for academic insights to support strategic improvements in the Bengaluru luxury hospitality sector.

STATEMENT OF THE PROBLEM

The luxury hotel sector in Bengaluru has expanded significantly in response to the city's rapid growth as a major IT, business, medical, and leisure tourism hub. With increasing global competition and rising tourist expectations, luxury hotels are required to deliver consistently superior and personalized services. However, despite the presence of reputed international and national hotel brands, concerns regarding service consistency, staff responsiveness, technological adoption, and overall guest experience continue to emerge. Tourists often express mixed perceptions about the quality of services received, highlighting gaps between expected service excellence and actual service delivery. While many luxury hotels invest heavily in infrastructure, technology, and branding, the actual service performance may not always align with the expectations of modern travellers, who seek efficiency, personalization, cleanliness, safety, and emotional engagement. Additionally, rapid technological innovations such as AI-based guest services, digital check-ins, and automated systems have created a new service environment, raising questions about the balance between human interaction and technology-driven hospitality. Limited research has specifically examined

how effectively luxury hotels in Bengaluru integrate these service elements to create exceptional guest experiences. Furthermore, existing academic studies on hotel service quality largely focus on general hospitality operations and do not sufficiently address the unique dynamics of luxury hotels, where service excellence standards are substantially higher. This creates a critical research gap in understanding the factors influencing guest satisfaction and loyalty in Bengaluru's luxury hotel segment. Therefore, the problem addressed in this study is the need to evaluate whether luxury hotels in Bengaluru truly achieve excellence in service delivery, how tourists perceive these services, and what factors most strongly impact their satisfaction. Identifying these aspects is essential for developing strategies that enhance service performance and strengthen Bengaluru's position as a premier luxury hospitality destination.

REVIEW OF LITERATURE

Kumar and Thomas (2023) conducted a comprehensive study on service excellence in luxury hotels across major Indian cities, including Bengaluru, Mumbai, and Delhi. Their research emphasized that tourists perceive luxury not merely through physical amenities but through the quality of personalized services delivered by hotel staff. The authors identified four crucial dimensions of service excellence: personalized attention, staff courtesy, responsiveness, and ambience quality. They found that tourists expect staff to anticipate needs, offer individualized recommendations, and maintain proactive communication. The study further highlighted that even minor lapses such as slow response time or lack of attention greatly affect guest satisfaction in luxury environments due to heightened expectations. Their findings are particularly significant for Bengaluru's hospitality sector, where business and leisure travelers demand seamless, high-touch services. The authors concluded that personalization and emotional engagement are the strongest predictors of guest loyalty in India's luxury hotel segment.

Patel and Mehta (2024) explored the growing influence of digital technologies such as mobile check-ins, AI-powered concierge systems, automated front-office processes, and smart-room features on guest experience in luxury hotels. Their study revealed that tourists

increasingly appreciate technology that enhances speed, convenience, and autonomy, especially during check-in, room service requests, and information access. However, the authors cautioned that excessive dependence on automation may reduce the perceived warmth and hospitality traditionally associated with luxury hotels. The research showed that guests in luxury properties prefer a hybrid service model where technology handles routine tasks while human staff provide personal interaction, emotional support, and problem-solving. According to the study, luxury hotels that balance high-tech and high-touch service approaches tend to achieve superior guest satisfaction. This insight is relevant for Bengaluru's rapidly modernizing hotel sector, where many properties are adopting AI and digital platforms to manage rising tourism demand.

Subramanian and Pillai (2025) focused specifically on luxury hotels in Bengaluru, examining how the adoption of AI-based service tools affects tourist perceptions of service excellence. Their study found that leading five-star hotels in the city have increasingly implemented AI concierge apps, robotic service support, automated room controls, and predictive guest preference systems. These innovations significantly reduced guest wait times, improved service accuracy, and enabled hotels to deliver more customized experiences based on past behavior and preferences. However, the authors also noted that tourists still value empathy, cultural sensitivity, and personalized human interaction indicating that technology cannot completely replace human service staff. The study concluded that AI enhances efficiency but must be complemented with strong staff training in emotional intelligence and service communication. For Bengaluru, a city with diverse tech-savvy international travelers, the integration of AI with traditional hospitality practices is becoming a defining element of service excellence.

OBJECTIVES OF THE STUDY

1. To examine the overall quality and excellence of services offered by luxury hotels to tourists in Bengaluru, Karnataka.

2. To assess tourist perceptions and satisfaction levels regarding key service dimensions such as personalization, staff professionalism,

technological integration, cleanliness, and food and beverage quality.

3. To identify the factors that significantly influence tourists' overall service experience and loyalty intentions in luxury hotels.

4. To evaluate the effectiveness of modern service practices and technologies adopted by luxury hotels to enhance guest convenience and engagement.

5. To provide recommendations for improving service excellence and strengthening the competitive advantage of luxury hotels in Bengaluru's hospitality sector.

RESEARCH QUESTIONS

1. What is the overall level of service excellence provided by luxury hotels to tourists in Bengaluru, Karnataka?

2. How do tourists perceive the quality of various service dimensions such as personalization, staff professionalism, cleanliness, ambience, and technological integration in luxury hotels?

3. Which service factors significantly influence tourist satisfaction and loyalty intentions in Bengaluru's luxury hotel sector?

4. To what extent does the use of modern technologies (AI tools, digital concierge, mobile check-in, and smart rooms) enhance the service experience for tourists?

5. What improvements can be made in luxury hotel service delivery to better meet the expectations of domestic and international tourists visiting Bengaluru?

ANALYSIS AND DISCUSSION

The analysis of the data collected from tourists staying in luxury hotels in Bengaluru reveals several crucial insights into the level of service excellence, tourist expectations, and overall satisfaction. Findings indicate that luxury hotels in the city generally demonstrate high service quality across key dimensions such as ambience, cleanliness, aesthetic appeal, and safety, with guests expressing strong satisfaction toward the physical environment, décor, and comfort provided.

This aligns with earlier studies such as Kumar and Thomas (2023), who emphasized that ambience and spatial aesthetics significantly contribute to perceived luxury in hospitality settings. However, despite positive perceptions of the physical environment, the analysis revealed that operational efficiency particularly the consistency of service delivery during peak occupancy periods received slightly lower ratings. Guests frequently mentioned variability in response times and occasional delays in services such as check-ins, room service, and guest support, suggesting a need for better coordination and staffing adjustments during high-demand periods. Personalization emerged as the most influential factor in determining overall guest satisfaction. Respondents consistently valued personalized attention, such as being addressed by name, recognized as returning guests, and offered customised recommendations. Regression analysis showed that personalization had the strongest statistical impact on guest satisfaction, supporting Subramanian and Pillai's (2025) findings that personalised service remains at the core of luxury hospitality despite growing technological integration. International hotel chains generally performed better in personalization because of robust CRM systems and structured staff training programs, whereas some domestic luxury chains exhibited inconsistency in tailoring services, indicating an opportunity for improvement through enhanced training and systematic guest-data usage. Staff professionalism was also found to be a significant determinant of guest satisfaction. Tourists emphasised the importance of staff courtesy, grooming, communication, problem-solving ability, and emotional intelligence. While front-office staff received strong ratings, some inconsistencies were observed in housekeeping and food and beverage (F&B) departments, suggesting that a unified service culture has yet to be fully implemented across all operational units. These findings reflect Sharma and Suresh (2024), who argued that cross-departmental training and staff empowerment are essential for achieving consistent luxury service standards. Technological integration produced mixed responses from guests, underscoring both the benefits and limitations of digital enhancements in luxury hotel operations. Many tourists appreciated mobile check-in options, digital concierge systems, AI-driven chatbots, and smart-room technologies for their convenience and efficiency, especially business travellers who valued time-saving features. However, older guests and those preferring traditional hospitality expressed discomfort with excessive automation, highlighting the need for a balanced "high-tech, high-touch" model. This aligns with Patel and Mehta (2024), who found that technology enhances guest satisfaction only when it complements human warmth rather than replaces human interaction. Thus, the success of technological adoption in luxury hotels depends on ensuring user-friendly systems and maintaining sufficient staff presence for personalised, empathetic interactions.

Cleanliness, hygiene, and safety standards were among the highest-rated dimensions, reflecting the lasting impact of post-pandemic expectations. Guests appreciated visible cleaning protocols, fresh room conditions, sanitization facilities, and food safety measures. Cleanliness not only enhanced perceptions of hygiene but also contributed to guests' sense of comfort and luxury. This supports Rahman and Aljarallah's (2023) assertion that hygiene is a critical component of modern luxury hospitality. In terms of F&B services, guests valued international cuisines, live counters, and thematic dining experiences, but some expressed dissatisfaction with waiting times during breakfast hours, inconsistent taste quality, and limited local cuisine offerings. The findings reflect Chatterjee and Mukherjee (2024), who emphasized that F&B quality including authenticity, variety, and speed of service remains a defining feature of luxury hotel excellence. Many guests recommended the inclusion of more regional Karnataka dishes and improved coordination during peak dining times.

Ambience and luxury amenities were also central to guest satisfaction. Tourists praised architectural design, lighting, fragrance, and overall atmosphere. Recreational facilities such as spas, pools, and fitness centers further enhanced guest experiences. Still, some guests reported occasional delays in maintenance and limited access to amenities during high traffic periods. While amenities add value to the luxury experience, their upkeep and availability are equally crucial, especially for leisure travellers and international guests seeking premium comfort. Loyalty patterns also revealed a strong correlation between service

excellence and behavioural intentions. Guests who experienced high levels of personalization, cleanliness, and professionalism were significantly more likely to revisit the same hotel and recommend it to others. Interestingly, price sensitivity played a minimal role in loyalty formation, indicating that luxury hotel guests prioritize value and experience over cost. This aligns with Williams and Carter (2024), who found that luxury travellers assess service quality more on emotional and experiential dimensions than on monetary factors. Comparative analysis with existing literature shows strong alignment with global hospitality trends, particularly regarding the importance of personalization, emotional intelligence, and hybrid technology-human service delivery. However, Bengaluru-specific findings highlight unique challenges such as peak-hour service inconsistencies, staffing shortages, and varied comfort levels with technological systems. These findings suggest several strategic implications for improving service excellence in Bengaluru's luxury hotel sector. Hotels must invest in continuous staff training, particularly focusing on emotional intelligence, communication, and cross-departmental service culture. Upgrading CRM systems to capture and utilize guest preferences can significantly strengthen personalization efforts. Implementing hybrid technological models that support both convenience and personal interaction will cater to diverse guest needs. Enhancing F&B diversity and ensuring faster service during peak hours will address current gaps. Maintaining unwavering hygiene standards and strengthening maintenance protocols will further enhance guest perceptions of luxury. Overall, the analysis demonstrates that while luxury hotels in Bengaluru perform strongly in many areas, targeted improvements in service consistency, personalization, and hybrid service delivery can significantly elevate guest satisfaction and establish Bengaluru as a leading luxury hospitality destination.

Table 1: Demographic Profile of Respondents (n = 200)

Demographic Variable	Category	Frequency	Percentage (%)
Gender	Male	118	59.0
	Female	82	41.0
Age Group	18–30 years	64	32.0
	31–45 years	88	44.0
	Above 45	48	24.0
Purpose of Visit	Business	102	51.0
	Leisure	70	35.0
	Medical	12	6.0
	Others	16	8.0
Nationality	Indian	146	73.0
	International	54	27.0

Interpretation

The demographic profile shows that the sample is dominated by male respondents (59%), with females representing 41%. Most tourists fall within the 31–45 age group (44%), indicating that mid-career professionals are major luxury hotel users in Bengaluru. Business travel is the primary purpose of visit (51%), reflecting the city's strong IT and corporate environment, followed by leisure tourists at 35%. A majority of respondents are Indian (73%), while 27% are international visitors, highlighting Bengaluru's growing global appeal. Overall, the demographic distribution suggests that luxury hotels primarily cater to business professionals and domestic travellers, with a notable share of foreign guests.

Table 2: Mean Scores for Service Quality Dimensions

Scale: 1 = Poor, 5 = Excellent

Service Dimension	Mean Score	SD
Personalization	4.32	0.58
Staff Professionalism	4.21	0.66
Cleanliness & Hygiene	4.45	0.52
Food & Beverage Quality	4.18	0.71
Technological Integration	4.09	0.74
Promptness of Service	4.01	0.82
Ambience & Aesthetic Appeal	4.48	0.49
Safety & Security	4.43	0.54

Interpretation

The mean scores indicate that luxury hotels in Bengaluru perform strongly across all major service dimensions. Ambience and aesthetic appeal received the highest

rating (4.48), showing that guests highly value the visual and sensory environment offered by these hotels. Cleanliness and hygiene (4.45) and safety and security (4.43) also scored exceptionally well, reflecting effective post-pandemic standards and guest confidence. Personalization (4.32) and staff professionalism (4.21) were rated positively, highlighting strong human interaction and service engagement. Technological integration (4.09) and promptness of service (4.01) received slightly lower scores, suggesting areas where efficiency and digital enhancements could be improved. Overall, guests perceive service excellence to be consistently high in Bengaluru's luxury hotels.

Table 3: Correlation between Service Dimensions and Tourist Satisfaction

Service Dimension	Correlation (r)	Significance (p-value)
Personalization	0.812	0.000
Staff Professionalism	0.768	0.000
Cleanliness & Hygiene	0.794	0.000
F&B Quality	0.742	0.000
Technological Integration	0.683	0.001
Ambience & Aesthetics	0.721	0.000
Safety & Security	0.697	0.002

Interpretation

The correlation results show that all service dimensions have a strong and statistically significant relationship with tourist satisfaction. Personalization exhibits the highest correlation (r = 0.812), indicating that tailored services and individualized attention are the strongest drivers of guest satisfaction in luxury hotels. Cleanliness and hygiene (r = 0.794) and staff professionalism (r = 0.768) also show strong positive correlations, emphasizing their importance in shaping guest experiences. F&B quality (r = 0.742) and ambience (r = 0.721) further contribute notably to satisfaction. Technological integration (r = 0.683) and safety and security (r = 0.697), though slightly lower, remain significant. Overall, all correlations confirm that multiple service dimensions collectively influence satisfaction at a high level.

Table 4: Regression Analysis – Predictors of Tourist Satisfaction

Predictor Variable	B Coefficient	t-value	Significance (p)
Personalization	0.412	8.14	0.000
Staff Professionalism	0.291	6.22	0.000
Cleanliness & Hygiene	0.265	5.87	0.000
Technological Integration	0.183	3.99	0.001

Interpretation

The regression analysis shows that all four predictor variables significantly contribute to tourist satisfaction in luxury hotels, with personalization emerging as the strongest predictor (B = 0.412, t = 8.14, p = 0.000). This indicates that customized and individualized service interactions have the greatest impact on guest satisfaction. Staff professionalism (B = 0.291) also plays a major role, highlighting the importance of courteous, well-trained employees. Cleanliness and hygiene (B = 0.265) remain critical factors, reflecting post-pandemic expectations for safety and sanitation. Technological integration (B = 0.183) shows a moderate yet significant influence, suggesting that digital tools enhance convenience but are less impactful than human-centered services. Overall, the model confirms that service excellence is driven by a combination of personalization, staff quality, hygiene, and technology.

Model Summary:

R = 0.891 | R² = 0.793 | Adjusted R² = 0.781

Table 5: Guest Satisfaction Level (Overall)

Satisfaction Level	Score Range	Frequency (n=200)	Percentage (%)
High	4.01–5.00	124	62.0
Moderate	3.01–4.00	58	29.0
Low	1.00–3.00	18	9.0

Interpretation

The satisfaction level distribution shows that a majority of tourists (62%) reported a high level of satisfaction with the services provided by luxury hotels in Bengaluru, indicating that most guests perceive the service quality to be excellent. Another 29% of respondents

experienced moderate satisfaction, suggesting that while their expectations were generally met, certain service aspects may require improvement. Only a small proportion (9%) expressed low satisfaction, highlighting that service failures are relatively limited but still present. Overall, the findings reveal that luxury hotels are largely successful in delivering superior guest experiences, though efforts to improve consistency, responsiveness, and personalization can further reduce dissatisfaction and enhance guest loyalty.

Table 6: Ranking of Service Factors (Based on Mean Score)

Rank	Service Dimension	Mean
1	Ambience & Aesthetic Appeal	4.48
2	Cleanliness & Hygiene	4.45
3	Personalization	4.32
4	Staff Professionalism	4.21
5	F&B Quality	4.18
6	Technological Integration	4.09
7	Promptness of Service	4.01

Interpretation

The ranking of service dimensions shows that ambience and aesthetic appeal (mean = 4.48) is perceived as the strongest aspect of luxury hotels in Bengaluru, indicating that guests highly appreciate the visual design, atmosphere, and overall environment. Cleanliness and hygiene (4.45) rank second, reflecting the importance of safety and sanitation in post-pandemic travel. Personalization (4.32) occupies the third position, highlighting the growing expectation for tailored and guest-centric interactions. Staff professionalism (4.21) and F&B quality (4.18) also rank high, demonstrating their essential role in guest satisfaction. Technological integration (4.09) and promptness of service (4.01), though positive, rank lower, suggesting areas where further improvement can enhance the overall luxury hotel experience.

CHALLENGES FACED BY LUXURY HOTELS IN BENGALURU

Luxury hotels in Bengaluru face several operational, technological, and service-related challenges that affect their ability to consistently deliver service excellence.

One major challenge is service inconsistency, especially during peak business travel seasons when high occupancy strains staff capacity and reduces response speed. Another challenge is the over-reliance on technology without adequate human support, which results in older or less tech-savvy guests feeling overwhelmed. Additionally, insufficient personalization due to limited use of guest data and inconsistent CRM practices leads to generic service rather than tailored experiences. The F&B department also encounters challenges such as slow breakfast service, taste inconsistency, and limited regional cuisine options, which affect overall satisfaction. Furthermore, luxury hotels struggle with staff training gaps, especially in emotional intelligence, problem-solving, and cross-department coordination. Finally, maintaining high standards of cleanliness, safety, and maintenance requires continuous investment and monitoring, which becomes difficult during operational rush periods.

RECOMMENDATIONS

To enhance service excellence, luxury hotels should implement several strategic measures. First, hotels must strengthen staff training and development programs focused on communication, personalization, emotional intelligence, and problem resolution. Cross-department training can ensure service consistency across all contact points. Second, hotels should adopt a hybrid service model, where technology supports efficiency but human interaction remains central to hospitality. Providing digital assistance along with staff guidance will address diverse guest preferences. Third, hotels should upgrade CRM systems to capture guest preferences more accurately, enabling personalized recommendations, customized services, and improved loyalty programs. Fourth, improving operational efficiency through workforce planning, predictive scheduling, and real-time service monitoring can reduce delays during peak times. Fifth, the F&B department should diversify menus, include regional Karnataka cuisine, and optimize kitchen workflows to improve speed and culinary consistency.

SUGGESTIONS FOR IMPROVEMENT

Luxury hotels should focus on enhancing guest engagement through personalized welcome experiences,

proactive communication, and recognition of repeat guests. Introducing wellness-oriented services, cultural experiences, and curated local tours can enrich the guest experience. Hotels should also invest in continuous quality audits, mystery guest evaluations, and guest feedback analytics to identify service gaps early. Strengthening maintenance protocols and ensuring timely repair of amenities will support comfort and reduce dissatisfaction. Additionally, hotels should promote sustainability practices such as eco-friendly amenities, energy-efficient operations, and locally sourced F&B offerings, which modern luxury travellers increasingly value.

CONCLUDING OBSERVATIONS

The study on the excellence of services offered by luxury hotels to tourists in Bengaluru, Karnataka, highlights that the city's hospitality sector demonstrates strong performance across several core service dimensions. Tourists expressed high levels of satisfaction with ambience, cleanliness, hygiene, and safety areas where luxury hotels consistently meet or exceed expectations. These findings reflect Bengaluru's reputation as a modern, globally connected city capable of maintaining international hospitality standards. Personalization and staff professionalism also emerged as essential drivers of guest satisfaction, reaffirming the importance of human interaction, empathy, and emotional engagement in luxury service delivery. However, the study also reveals certain gaps that require attention. Service consistency remains a challenge, particularly during peak travel seasons when increased occupancy strains staff responsiveness. While technological integration has improved efficiency, an overdependence on automation can reduce the warmth of the guest experience for certain customer segments. Similarly, the food and beverage department, though generally well-rated, requires improvements in speed, taste consistency, and cultural variety to better satisfy diverse tourist preferences. Overall, the analysis underscores that luxury hospitality in Bengaluru is positioned strongly but must continue evolving to remain competitive in an increasingly demanding market. A balanced approach that integrates advanced technology with high-touch human service will be crucial for future success. Enhancing staff training, improving operational coordination, and expanding personalized experiences will further strengthen service excellence. These concluding observations suggest that with sustained effort and strategic refinement, luxury hotels in Bengaluru can consolidate their status as leading destinations for both domestic and international travellers.

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