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Strategic Market Entry Routes for Specialized Industrial Goods: An Interdisciplinary Indian B2B Perspective

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Abstract

Indian industrial firms operating in business-to-business (B2B) markets are expanding into emerging economies, yet selecting an appropriate market entry route remains a complex strategic decision. This study examines how Indian firms dealing in specialized and high-complexity industrial goods evaluate key entry options such as exporting, licensing, partnerships, joint ventures, and wholly owned subsidiaries. Using a qualitative multi-case approach supported by industry data, expert insights, and comparative analysis from sectors including nutraceutical ingredients, industrial machinery, and medical devices, the research identifies major determinants influencing entry-mode choice. Product complexity, regulatory requirements, buyer expectations, firm capabilities, market uncertainty, and competitive intensity emerged as the most influential drivers. The study proposes a decision-making framework that aligns internal competencies with external market conditions, offering exploratory insights into how firms may evaluate risk, cost, and control trade-offs when selecting entry strategies. The findings contribute to the limited literature on outward internationalization of Indian B2B firms and offer practical strategic guidance for managers entering highly regulated and technologically demanding global markets.

Keywords: B2B Market Entry Strategies; Indian Industrial Firms; Internationalization; Emerging Economies; Entry Mode Selection

1. Introduction

Indian industrial firms have increasingly expanded into global markets, particularly emerging economies, where the demand for engineered products, automation systems, and industrial machinery is rising. Unlike consumer markets, business-to-business (B2B) markets involve complex purchasing processes, technical buyer requirements, and long-term contractual relationships. Choosing a suitable market entry route, therefore, represents a crucial strategic judgment rather than a routine operational matter. Various entry modes, such as exporting, licensing, partnerships, joint ventures, or full ownership, differ in their levels of risk, control, and their impact on knowledge transfer, adaptation, and sustained competitiveness. While international business literature has widely examined entry-mode decisions, prior research has primarily focused on Western multinationals and consumer-sector firms. There is comparatively limited scholarly evidence on how firms from emerging economies, particularly India, evaluate and select entry routes for specialized industrial goods. With Indian firms now competing globally in sectors such as engineering equipment, industrial automation, and heavy machinery, understanding the determinants behind their internationalization choices becomes both academically relevant and practically significant.

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This paper addresses this gap by analyzing the strategic, operational, and contextual factors that shape market entry decisions among Indian B2B industrial firms. The study further aims to contribute to the literature by proposing a decision-making framework that aligns external market conditions with firm-level capabilities, thereby supporting more informed and adaptive entry-strategy selection. This study pursues four key objectives: (1) to explore the key elements that shape successful market entry strategies, (2) to examine the factors influencing market entry decisions for specialized B2B products in Indian industrial firms, (3) to assess the strategic challenges and opportunities affecting entry mode selection in Indian firms, and (4) to provide practical insights and recommendations for the internationalization of Indian B2B industries. The analysis focuses on international market entry strategies of Indian firms operating in specialized business-to-business (B2B) industrial sectors, centering on firms engaged in the manufacturing and export of high-complexity, technology-driven products such as industrial machinery, engineering components, medical and diagnostic equipment, biotechnology instruments, pharmaceutical and nutraceutical bulk ingredients, and other regulated industrial goods. These sectors are chosen because they represent non-consumer markets where purchasing decisions are shaped by technical specifications, regulatory compliance, and long-term institutional relationships rather than individual consumer preferences.

Indian firms in sectors such as industrial machinery, biotechnology, medical diagnostics, and nutraceutical ingredients are increasingly expanding into foreign emerging markets. However, there is limited empirical understanding of how these firms evaluate and select their market entry routes. Existing literature largely focuses on Western multinationals, inward investment into India, or consumer-focused industries, offering little insight into the strategic realities of Indian B2B firms dealing with complex and regulated products. Entry-mode decisions in these sectors depend not only on cost, risk, and control but also on technical requirements, regulatory compliance, buyer expectations, and firm-level capabilities such as manufacturing scale and innovation. Consequently, managerial decisions often remain fragmented and experience-based, underscoring the need for a context-specific model to guide international market entry strategies for Indian B2B industrial firms.

1.1. Literature Review and Theoretical Foundation

Research on international market entry explains how firms select between exporting, licensing, partnerships, joint ventures, or wholly owned subsidiaries based on control, risk, and resource commitment [1, 2]. Transaction Cost Economics suggests that firms internalize operations when external transactions are costly or uncertain [3]. Later studies emphasize that entry decisions also depend on strategic intent, learning goals, and capability development, moving beyond cost-based views [4, 5]. B2B industrial markets differ from consumer markets because decisions rely on technical performance, reliability, and compliance rather than customer preference. Firms dealing in machinery, medical devices, or biotechnology products often need local service support and validation, encouraging higher-control entry modes [6, 7]. Buyers focus on long-term technical fit and trust, making entry strategy a strategic rather than transactional decision.

Firms from emerging economies like India and China expand abroad not only for market access but also to gain technology, legitimacy, and knowledge [8, 9]. Joint ventures and alliances are common as they reduce uncertainty and help firms learn in new environments [10]. However, most studies focus on large multinationals, with limited attention to mid-sized or specialized industrial firms expanding outward. Existing Indian research mainly examines foreign companies entering India, rather than Indian firms entering global markets. Studies show that joint ventures help manage regulatory and cultural challenges [11], but evidence on Indian B2B and healthcare-linked industrial sectors remains scarce. Sectors like engineering, biotechnology, and nutraceutical manufacturing are underrepresented in academic work [12, 13], highlighting the need for context-specific research on their internationalization strategies.

Although recent Indian studies have begun to examine international market entry and strategic expansion, much of this work focuses on inward foreign investment, multinational firm behavior within India, or generalized manufacturing internationalization patterns. Limited attention has been given to outward expansion decisions of mid-sized and specialized Indian B2B industrial firms operating under conditions of high regulatory exposure, technological complexity, and institutional dependency. Furthermore, existing research rarely integrates firm-level capability constraints with regulatory and buyer-driven pressures when explaining entry-mode selection. Consequently, there remains insufficient context-specific understanding of how Indian industrial exporters navigate the control, risk, and compliance trade-offs associated with entering regulated and technologically demanding foreign markets. This study addresses this gap by providing a qualitative, capability- and institution-aligned perspective on entry-mode decision-making among specialized Indian B2B firms.

2. Methods

This study adopts a qualitative multi-case research design, supported by secondary industry indicators, to examine the factors influencing market entry route selection among Indian firms operating in specialized industrial and healthcare-related B2B sectors. A qualitative approach is appropriate because market entry decisions in such contexts are highly context-dependent, shaped by sector-specific regulations, firm-level capabilities, and institutional conditions, which are best understood through in-depth analysis rather than statistical generalization. The research design is qualitative-dominant, with secondary quantitative indicators used only to provide illustrative and contextual support, rather than inferential testing or hypothesis validation. The study does not employ primary statistical modeling; instead, indicative success rates and trend-based metrics are drawn from published industry reports and prior empirical studies to support comparative interpretation. The inclusion of two supporting secondary cases further enhances contextual comparison and strengthens the analytical robustness of the single primary case. The case study approach follows established qualitative research principles [14, 15].

2.1. Research Design, Case Selection, and Data Sources

The primary case concerns an Indian nutraceutical manufacturing firm that produces functional ingredients for pharmaceutical and food industry clients and exports to foreign B2B buyers. The firm was selected on the basis of access, relevance, and its active engagement in international expansion. Its products require regulatory approval, technical validation, and long-term supply relationships, making it representative of high-complexity industrial goods rather than consumer-oriented nutraceutical brands. The identity of the firm is anonymized to maintain confidentiality. The single primary case is treated as a critical and revelatory case within qualitative case study logic. The firm operates under conditions of high regulatory scrutiny, technical validation requirements, and long-term institutional buyer relationships, making market entry decisions particularly complex and information-sensitive. Such contexts provide access to strategic decision processes that are rarely observable through secondary data alone. The purpose of the case is, therefore, analytical generalization and theory refinement rather than statistical generalization, which is consistent with qualitative case research traditions. The inclusion of two supporting secondary cases further enhances contextual comparison and strengthens the analytical robustness of the single primary case.

Primary data were collected through one semi-structured interview with a senior employee involved in export or business development activities, supplemented by informal discussions with internal staff during the researcher's internship. Additional qualitative insights were obtained from non-confidential internal documents, such as product export records, certification files, and market entry correspondence. Secondary data sources included industry reports, regulatory databases, trade publications, company disclosures, and peer-reviewed academic literature. Quantitative indicators referenced in the study (e.g., success percentages) are derived from these secondary sources and are used descriptively to illustrate general industry patterns rather than to establish causal relationships. The quantitative percentages and benchmark indicators referenced in this study are derived exclusively from secondary industry reports, benchmarking publications, and prior empirical literature. These values are incorporated solely to provide contextual illustration and comparative interpretation of entry-mode patterns. They do not constitute primary statistical findings of the present research and are not used for hypothesis testing or inferential analysis.

Participation in the interview was voluntary and conducted with informed consent. No proprietary, confidential, or commercially sensitive material has been disclosed. The primary case firm is not named, and any internal documents referenced are described only in generalized form. Secondary cases rely exclusively on publicly available information. Credibility was enhanced through triangulation across multiple data sources, including interview responses, internal observations, secondary case profiles, industry reports, and established academic literature. The combination of qualitative depth and secondary contextual indicators allows the study to balance analytical rigor with feasibility within conference and journal length constraints.

2.2. Data Analysis and Conceptual Framework

Data were analyzed using thematic analysis, aligned with three theoretical perspectives commonly applied in entry-mode literature: Transaction Cost Economics, the Resource-Based View, and Institutional Theory. Coding proceeded deductively based on established literature and inductively from interview narratives and documentary evidence. Secondary numerical indicators were interpreted contextually to support cross-case comparison and trend illustration. No inferential statistical techniques or hypothesis testing were applied, and all numerical references are intended to remain indicative rather than predictive. Thematic analysis procedures were guided by Braun and Clarke [16]. All percentages presented in Tables 1 to 3 represent aggregated secondary benchmarks intended to enhance interpretive clarity rather than measure causal relationships within the primary case.

Thematic analysis followed a structured multi-stage coding process. First, open coding identified preliminary decision

drivers emerging from interview narratives, internal observations, and documentary evidence. Second, axial coding grouped these initial codes into broader thematic clusters reflecting regulatory pressures, capability constraints, and institutional influences. Finally, selective coding connected these themes with observed entry-mode preferences and strategic evaluation patterns. To enhance analytical credibility, identified themes were iteratively compared with existing theoretical constructs from Transaction Cost Economics, the Resource-Based View, and Institutional Theory. Peer discussion and repeated review of coded segments were used to refine theme boundaries and reduce interpretive bias. Due to feasibility constraints, formal inter-coder reliability testing was not employed; this limitation is acknowledged and does not affect the exploratory nature of the study.

The conceptual framework explains how internal and external factors influence the selection of market entry modes among Indian B2B industrial firms. Six key determinants, including product complexity, regulatory requirements, buyer expectations, firm capabilities, market uncertainty, and competitive intensity, shape the firm's strategic evaluation process, where decisions are made by balancing control, cost, and risk before choosing an entry strategy. The framework draws on Transaction Cost Economics, the Resource-Based View, and Institutional Theory to show that entry decisions depend on both organizational strengths and environmental conditions. It highlights that successful internationalization occurs when firms align their strategic intent with available resources, market realities, and institutional contexts, resulting in effective choices such as exporting, partnerships, or wholly owned subsidiaries.

Figure 1: Determinants influencing strategic evaluation and entry-mode selection: Indian B2B industrial firms

The framework also explains the directional influence of each determinant on entry-mode preference. High product complexity and stringent regulatory requirements increase the need for local validation, after-sales support, and institutional legitimacy, thereby encouraging collaborative entry modes such as joint ventures and strategic partnerships. Strong buyer expectations regarding reliability and technical service similarly favor higher local presence. In contrast, firms possessing strong internal capabilities, prior international experience, and lower perceived market uncertainty may prefer exporting or wholly owned subsidiaries due to greater control advantages. Market uncertainty and competitive intensity moderate these relationships by influencing the firm's tolerance for risk and investment commitment, often resulting in phased or hybrid entry approaches. Entry-mode selection, therefore, emerges as a dynamic outcome of capability-environment alignment rather than a static cost-control decision.

The conceptual flow is as follows: Product Complexity leads to consideration of Regulatory Requirements, which in turn influences Buyer Expectations. These feed into the firm's assessment of its own Capabilities and Resources, which is moderated by Market Uncertainty and Risk and Competitive Intensity. This Strategic Evaluation of the Control, Cost, and Risk Trade-off then leads to the selection of an Entry Mode (Export, Licensing, Partnership, Joint Venture, or Wholly Owned Subsidiary), all within the context of Indian B2B Industrial and Healthcare-Linked Firms.

3. Results

3.1. Entry Mode Performance, Success Factors, and Market Entry Barriers

The indicative benchmarks presented in Table 1 summarize broad industry-level observations on the relative performance of four primary market entry modes, exporting, joint ventures, franchising, and wholly owned subsidiaries, based on aggregated industry data. The indicative benchmarks in Table 1 and Figure 2 summarize broad industry-level observations on the relative performance of commonly adopted market entry modes. The overall pattern reflects a tendency toward moderate to high effectiveness when Indian firms adopt structured and context-aligned entry routes. Notably, the variation across modes highlights that performance outcomes differ based on regulatory exposure, resource commitment, and local adaptation requirements. Joint ventures and local partnerships are frequently associated with comparatively stable outcomes due to knowledge sharing and institutional support, while exporting tends to be used as a lower-risk exploratory mechanism. These values should be interpreted as illustrative trends rather than precise performance measures.

Table 1: Indicative Industry Benchmarks for Market Entry Mode Outcomes

Statistic	**Value**
Mean	70.5
Median	73
Minimum	48
Maximum	88

Note: Values represent indicative industry benchmarks compiled from secondary reports and prior literature. These figures are illustrative and do not reflect primary statistical measurements from the case study. *Source:* Compiled from [2, 4, 10, 3].

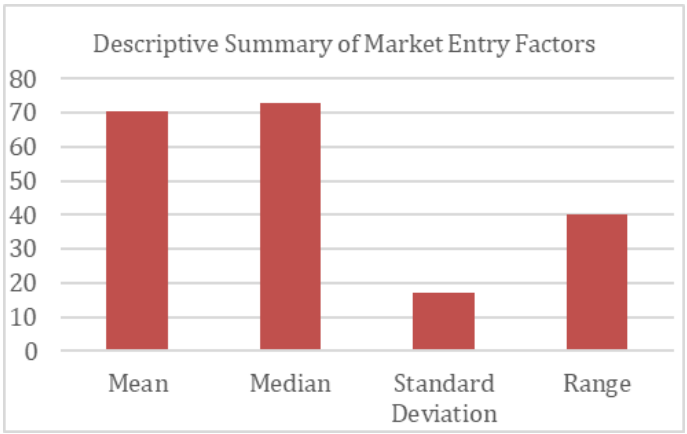

Figure 2: Descriptive summary of indicative market entry outcome benchmarks

To identify factors that influence entry-mode success, descriptive data were compiled on utilization and typical success rates across 11 key factors. The patterns in Table 2 and Figure 3 indicate that certain strategic and operational factors are consistently associated with improved market entry outcomes across industrial B2B contexts. Regulatory compliance exhibits the strongest indicative association with successful entry, reflecting its critical role in approval processes, operational continuity, and institutional legitimacy. Product localization and cultural alignment also appear prominently, reinforcing the importance of adapting technical specifications, communication practices, and organizational processes to local market conditions. Other factors, such as pricing strategy, distribution expansion, and digital initiatives, demonstrate more moderate utilization, suggesting that Indian B2B firms prioritize compliance and technical fit over aggressive market penetration strategies during initial entry stages. These observations serve as contextual indicators supporting qualitative insights from the case analysis rather than as statistically validated relationships.

Table 2: Indicative Success Factors Influencing Market Entry Outcomes

Factor	**Utilization (%)**	**Typical Success Rate (%)**
Product Localization	72	72.5
Marketing Customization	60	67.5
Supply Chain Optimization	48	62.5
Talent Acquisition	40	60
Pricing Strategy	32	55
Distribution Expansion	24	50
Regulatory Compliance	80	87.5
Cultural Alignment	72	70
JV/Local Partnership	63	67.5
E-commerce Testing	45	50
Digital-First Approach	35	57.5

Note: Utilization and success-rate values are secondary descriptive indicators used to contextualize qualitative insights and are not derived from primary empirical measurement. *Source:* Adapted from [6, 10, 11, 3].

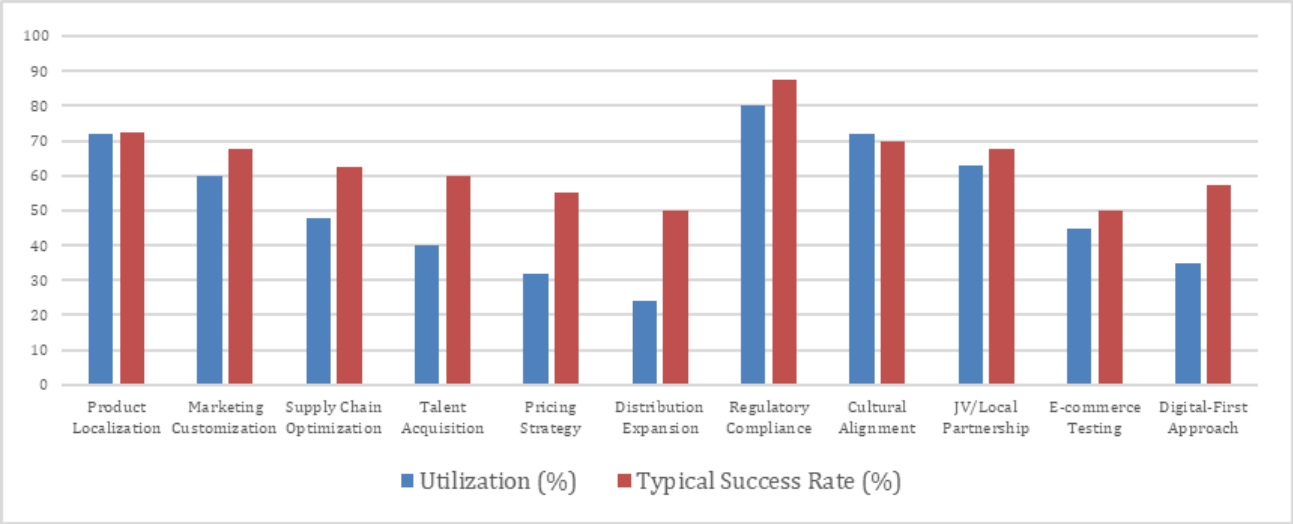

Figure 3: Utilization rates and typical success rates across key market entry factors

The analysis further examines common challenges faced by Indian B2B firms during international expansion. Regulatory non-compliance emerges as the most frequently cited obstacle, emphasizing the complexity of host-country legal and certification frameworks. Cultural differences represent another significant challenge, particularly in relation to negotiation styles, communication norms, and relationship-building practices. Competitive intensity and infrastructure-related constraints further contribute to entry difficulties, especially in emerging markets with uneven institutional development. Firms that engaged local partners or adopted phased entry approaches demonstrated greater adaptive capacity in addressing these challenges.

Table 3: Indicative Challenges Associated with Market Entry Difficulties

Challenge Factor	Success (%)	Failure (%)
Regulatory Compliance	20	80
Cultural Differences	28	72
Competition	40	60
Infrastructure Gaps	52	48

Note: Success and failure percentages represent aggregated secondary observations intended for explanatory illustration only. *Source:* Synthesized from Meyer et al. [10]; Surana [3]; industry regulatory benchmarking reports.

3.2. Synthesis and Key Findings

Integrating both descriptive and contextual findings, the analysis reveals that successful internationalization of Indian B2B firms is driven by three interdependent pillars: (1) Regulatory Mastery and Institutional Alignment, where firms with robust compliance frameworks consistently outperform competitors in approval rates and market longevity; (2) Localization and Cultural Responsiveness, where product, communication, and talent localization increase acceptance, especially in culturally diverse markets such as Southeast Asia and Africa; and (3) Collaborative Entry Structures, where joint ventures and alliances balance risk-sharing with local insight, achieving sustainable success over high-control modes. Indicative industry examples reported in prior literature complement the case illustrations, collectively showing that context-sensitive strategy selection significantly improves market performance.

The study finds that the success of Indian B2B industrial firms in international markets is determined by how effectively they align regulatory compliance, localization, and strategic collaboration with their internal capabilities and market environments. Regulatory compliance emerged as the most decisive factor, with secondary industry benchmarks suggesting that structured compliance systems are associated with success rates approaching approximately 85 to 88%, based on aggregated industry reports. Proper licensing, certification, and adherence to host-country laws significantly improved market sustainability. Localization and cultural responsiveness enhanced customer trust and market fit, with firms that localized products, marketing strategies, and talent acquisition recording good success rates. This pattern demonstrates that adaptation to local conditions drives competitiveness. Secondary industry benchmarks indicate success rates of approximately 60 to 75% for joint ventures and partnerships in regulated industrial contexts, as these approaches enabled firms to share risks, access local knowledge, and navigate institutional barriers more efficiently. Wholly owned subsidiaries provided greater control but carried higher investment and operational risks, requiring advanced managerial capabilities and long-term commitment. Cultural and institutional challenges were responsible for the highest share of failures, while infrastructure and competitive intensity accounted for approximately half. Firms that proactively invested in local networks, digital infrastructure, and differentiated offerings achieved better resilience. Successful internationalization was achieved through a balanced approach, integrating compliance assurance, localized adaptation, and strategic partnerships suited to specific market contexts. All percentage-based observations referenced above are derived from secondary benchmarking literature and are not primary statistical findings of the present case study.

4. Discussion

4.1. Theoretical Implications for Indian B2B Entry Strategy

The findings of this study can be interpreted through established entry-mode theories, while also revealing important contextual nuances specific to Indian business-to-business (B2B) industrial firms. Drawing on Transaction Cost Economics, the Resource-Based View, and Institutional Theory, the discussion explains why certain market entry routes emerge as more viable under conditions of high product complexity, regulatory intensity, and market uncertainty.

From a Transaction Cost Economics perspective, the preference for joint ventures and strategic partnerships observed in the findings reflects firms' attempts to reduce uncertainty and safeguard against opportunism in foreign markets. For Indian B2B firms dealing in regulated and technically complex products, the costs associated with information asymmetry, compliance failure, and service delivery are significant. Collaborative entry modes allow firms to share these transaction costs with local partners while maintaining sufficient operational involvement to protect product quality and contractual obligations. The Resource-Based View further explains the reliance on collaborative structures during the early stages of internationalization. Many Indian industrial firms possess strong manufacturing capabilities and cost advantages but face constraints in terms of local market knowledge, regulatory expertise, and distribution infrastructure. Joint ventures and alliances enable firms to access complementary resources without the immediate need for full ownership, thereby aligning internal capabilities with external market requirements.

This finding extends existing RBV-based explanations by highlighting how capability gaps, rather than only capability strengths, shape entry-mode selection in emerging-market firms. Institutional Theory provides additional insight into the prominence of regulatory compliance and cultural alignment as decisive factors influencing entry success. Host-country institutional frameworks, particularly in healthcare-linked and industrial sectors, impose stringent approval processes, documentation standards, and relationship norms. Indian firms that align their entry strategies with local institutional expectations through partnerships or phased entry approaches are better positioned to gain legitimacy and sustain long-term operations. This reinforces the view that entry-mode decisions in emerging markets are influenced as much by institutional conformity as by efficiency considerations.

Collectively, these findings suggest that entry-mode selection for Indian B2B industrial firms is not a linear cost-control trade-off but a dynamic process shaped by regulatory exposure, resource complementarities, and institutional embeddedness. By integrating these theoretical lenses, the study refines existing entry-mode frameworks to better reflect the strategic realities faced by emerging-market industrial exporters operating in complex and regulated global environments.

4.2. Contribution to Knowledge

This study contributes to the literature on international market entry strategies by providing context-specific insights into entry-mode decision-making among Indian business-to-business (B2B) industrial firms operating in regulated and technologically intensive sectors.

First, the study extends traditional entry-mode perspectives by examining specialized industrial goods characterized by high product complexity, technical validation requirements, and regulatory scrutiny. Existing research has largely emphasized consumer markets, multinational enterprises from developed economies, or generalized manufacturing contexts. By focusing on Indian firms operating in sectors such as industrial machinery, medical devices, and nutraceutical ingredients, the study broadens the empirical scope of entry-mode analysis within emerging-market industrial settings.

Second, the findings position regulatory intensity as a central strategic determinant rather than a peripheral contextual constraint. While prior research acknowledges the role of institutional environments, this study illustrates how regulatory requirements actively shape entry-mode selection by influencing control preferences, partnership formation, sequencing of internationalization, and risk-sharing behavior among emerging-market exporters.

Third, the proposed framework integrates internal capability considerations with external institutional pressures, offering a context-sensitive lens for understanding entry-mode selection among specialized Indian B2B exporters. This perspective complements recent Indian studies that primarily examine inward foreign investment or broad manufacturing internationalization by emphasizing outward expansion decisions within highly regulated and technology-driven industrial domains. The framework, therefore, refines existing conceptual models by highlighting the interaction between compliance readiness, complementary resources, and market uncertainty.

Finally, the study contributes managerial relevance by translating theoretical insights into strategic considerations for firms navigating complex international environments. The findings provide interpretive guidance on how regulatory preparedness, localization, and collaborative entry structures may influence sustainable internationalization pathways for Indian industrial firms.

The proposed framework should be interpreted as exploratory and context-sensitive rather than universally prescriptive. Its primary contribution lies in refining conceptual understanding and offering an interpretive lens for analyzing entry-mode decisions among specialized B2B firms operating under regulatory and institutional complexity.

4.3. Limitations and Future Research

While this study provides valuable insights into Indian B2B entry-mode selection, several limitations should be acknowledged. The qualitative, multi-case design prioritizes analytical generalization over statistical generalization, and findings are exploratory rather than predictive. The single primary case, while treated as a critical and revelatory case, limits the breadth of firm-level evidence. Secondary benchmarks, while contextually illustrative, do not represent primary statistical findings. Future research should expand the number of primary cases across additional B2B sectors and employ mixed-methods designs to test the generalizability of the proposed framework. Longitudinal studies tracking firms through complete internationalization cycles would further validate the dynamic nature of entry-mode alignment.

4.4. Practical Implications and Recommendations

Based on the findings, the following recommendations are offered to enhance internationalization success among Indian B2B firms:

- Engage early with compliance consultants, trade associations, and government export facilitation programs to ensure seamless regulatory navigation in target markets.
- Customize products, marketing, and communication to local preferences and regulatory expectations rather than pursuing standardized global approaches.
- In complex or uncertain markets, use joint ventures or strategic alliances as preferred entry routes to reduce exposure, share risks, and accelerate localization and adaptation.
- Develop organizational capacity in cultural understanding and recruit local management talent to ensure smoother negotiation, stakeholder engagement, and operational alignment.
- Use e-commerce platforms, digital logistics, and data analytics for market testing, supply chain optimization, and evidence-driven decision-making.
- Advocate for streamlined export procedures, bilateral partnership frameworks, and sector-specific B2B facilitation programs at government and institutional levels.

5. Conclusions

The findings emphasize that regulatory mastery, localization, and collaborative partnerships are the core pillars of successful internationalization for Indian B2B industrial firms. Firms that combine these dimensions with internal capability development and contextual awareness achieve greater strategic control, sustainability, and global competitiveness. This study contributes a practical decision-making framework for managers and policymakers seeking to guide the outward expansion of India's industrial and healthcare-linked B2B sectors. The findings provide indicative strategic guidance and theoretical refinement, while further multi-case and quantitative research is required to test the broader generalizability of the proposed relationships.

Author Contributions

P. Lavanya: Conceptualization, Supervision, Writing: review and editing; **T. Vara Lakshmi**: Conceptualization, Methodology, Formal analysis, Writing: original draft, Supervision; **T. Sanjay Kumar**: Conceptualization, Data curation, Investigation, Writing: original draft.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Raw interview data are confidential per organizational agreements and cannot be disclosed. Methodological procedures are fully described in the Methods and Results sections, enabling reproducibility of the analytical framework. Secondary benchmarking data are from publicly available sources cited in references. Further information may be obtained from the corresponding author.

Use of AI Tools

AI tools were used solely for language refinement and grammar. No AI was used for data collection, analysis, interpretation, or content generation.

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Ethics Approval and Consent

Informed consent was obtained from interview participants. The study adheres to the Declaration of Helsinki principles and involves minimal risk. The case firm and participants are anonymized. Ethical review exemption applies due to the low-risk qualitative design.

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Evaluation of Mechanical Properties of Graphene-Reinforced PETG Filaments Fabricated by FDM: Influence of Reinforcement and Process Parameters

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Abstract

In this study, graphene-reinforced polyethylene terephthalate glycol (PETG) composites are fabricated using the Fused Deposition Modeling (FDM) technique. The influence of process parameters, namely layer thickness, print speed, and nozzle temperature, on tensile and flexural strength is investigated. A Taguchi design of experiments is employed to optimize the process parameters, and regression models are developed to predict tensile strength and flexural strength. The optimum combination for tensile strength is identified as a layer thickness of 0.1 mm, print speed of 20 mm/s, and nozzle temperature of 230 °C, while the optimum combination for flexural strength is found at a layer thickness of 0.1 mm, print speed of 20 mm/s, and nozzle temperature of 235 °C. Microstructural characterization performed using Scanning Electron Microscopy (SEM) revealed uniform dispersion of graphene within the PETG matrix and strong interlayer bonding at optimized conditions. Fractography analysis conducted using Field Emission Scanning Electron Microscopy (FE-SEM) confirmed ductile fracture behavior with limited void formation. The developed regression models exhibited strong predictive accuracy, demonstrating their suitability for process optimization and the prediction of mechanical properties.

Keywords: FDM Process; Flexural Strength; Tensile Strength; Graphene Reinforcement

1. Introduction

Additive Manufacturing (AM) enables the direct fabrication of complex products from digital CAD models, facilitating customer-specific demand. Among AM techniques, Fused Deposition Modeling (FDM) has been widely used due to its low cost and material flexibility. FDM-manufactured components exhibit low mechanical properties due to weak interlayer bonding, process parameter variations, and different material compositions [1]. Improving the mechanical properties of FDM-printed components requires process optimization and material reinforcement. Polyethylene Terephthalate Glycol-modified (PETG) has proven to be a reliable FDM material, offering good transparency, ductility, balanced stiffness, and chemical resistance in comparison to ABS and PLA [2]. Dimensional stability and toughness are also comparatively better for PETG than ABS and PLA [3].

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PETG is suitable for making functional components but is restricted for structural applications due to its moderate strength and limited stiffness. Reinforcement strategies enhance the mechanical performance of FDM-printed parts. Recent work has incorporated micro- and nanoparticle reinforcements, such as glass fibers, carbon fibers, carbon nanotubes (CNTs), and graphene nanoplatelets (GNPs), into the PETG matrix [4]. Incorporation of carbon fibers increases stiffness while reducing ductility, and incorporation of CNTs improves multifunctional characteristics, although their dispersion remains challenging [5]. Exceptional strength and surface area provided by graphene at low concentrations demonstrate significant potential to improve PETG composites. It was found that adding as little as 0.04 wt.% graphene enhances compressive strength, flexural strength, and tensile strength, indicating effective load transfer between the polymer matrix and graphene [6].

The mechanical properties of graphene-PETG (G-PETG) composite FDM-printed parts are found to be highly sensitive to process parameters, including printing speed, layer thickness, and nozzle temperature. Parameter variations influence porosity, crystallinity, and interlayer bonding [7]. Optimization has been conducted to support a comprehensive analysis of graphene-reinforced PETG and neat thermoplastics. Interactions between process conditions and reinforcement dispersion, such as the effect of temperature on graphene composition, are not well understood.

There is limited correlation among printing parameters, reinforcement dispersion, and filament compounding [7]. Few studies have examined interlayer toughness, fatigue, and fracture in G-PETG composites. Only a limited number of studies have investigated the effects of process parameters (e.g., layer height and nozzle temperature). There is a lack of understanding of optimal graphene loading (0.01–1.0 wt.%) due to inconsistent processing. Limited effort has been made toward integrating microstructural characterization (XRD, SEM, and micro-CT) with mechanical analysis [8].

The novelty of the present research lies in the combined influence of material extrusion process parameters on the tensile and flexural behavior of graphene-reinforced PETG filament. Unlike most existing studies that primarily focus on varying graphene content or reporting standalone mechanical improvements, this work emphasizes how critical printing parameters such as layer thickness, print speed, and nozzle temperature govern interlayer bonding and stress transfer at a fixed, practically viable graphene loading. The study provides new insights into the interaction between graphene's thermal and reinforcing characteristics and the thermal–mechanical history imposed during printing, thereby clarifying how process control can be leveraged to maximize mechanical performance.

2. Materials and Methods

2.1. Materials

In this research study, the research material, a graphene-reinforced PETG (polyethylene terephthalate glycol) filament, was procured from a commercial supplier (Graphenera Carbon Private Limited). The filament had a nominal diameter of 1.75 mm ± 0.05 mm. According to the supplier specifications, the graphene reinforcement consists of graphene nanoplatelets dispersed within the PETG matrix. The average lateral size of the platelets is in the micrometer range (5–10 µm), with an average thickness of 2–10 nm, corresponding to multilayer graphene. The graphene was used without additional surface functionalization and was incorporated into the filament during extrusion by the manufacturer. Graphene was incorporated into the PETG matrix by the manufacturer to improve the filament's strength, thermal conductivity, and interlayer adhesion, making it suitable for FDM printing applications.

Environmental control during printing was carefully maintained to account for PETG's moisture sensitivity. Before printing, the graphene-reinforced PETG filament was dried at 60 °C for 4 h in a convection dryer and subsequently stored in a sealed, desiccant-assisted container. Printing was performed under controlled laboratory conditions with a relative humidity of 40 ± 5% and an ambient temperature of 25 ± 2 °C. The filament was exposed to ambient air for less than 2 h during printing to minimize moisture uptake. These measures were adopted to ensure consistent extrusion quality, reduce porosity, and maintain interlayer bonding integrity. The selection of 1.0 wt.% graphene as a fixed reinforcement level was guided by the broader literature on graphene–polymer nanocomposites, which demonstrates that significant mechanical improvements can be achieved with low graphene loadings up to 1 wt.% due to graphene's high aspect ratio and interfacial reinforcement effect without severe agglomeration [9].

2.2. 3D Printing of Test Specimens

An FDM printer (Anycubic Kobra 3 Combo) was used to print all specimens. The printer's build volume was 250 × 250 × 260 mm. A Taguchi L9 orthogonal array was used for optimizing printing parameters and to study the influence of process parameters on mechanical properties. The Taguchi L9 experimental design is a statistical method used to minimize the number of experimental trials and optimize printing process parameters.

In the present study, the Taguchi optimization design employed three controllable printing parameters, namely print speed, layer thickness, and nozzle temperature, studied at three levels. In a full factorial design, 27 experimental runs would be required; the Taguchi L9 array reduces this to only 9. The Taguchi L9 array provides a balanced distribution of factor levels, allowing identification of the most significant parameters and their optimal settings with maximum reliability. The Taguchi method enhances design robustness by calculating the signal-to-noise (S/N) ratio, emphasizing parameter combinations that yield consistent performance and minimize external variations.

In this investigation, the L9 orthogonal array was used to systematically evaluate the effects of print speed, layer thickness, and nozzle temperature on the mechanical properties of graphene-reinforced PETG specimens printed via FDM, ensuring efficient experimentation and statistically meaningful conclusions. However, the L9 orthogonal array has inherent limitations, particularly in capturing higher-order interaction effects and in providing full predictive capability beyond the selected factor levels. The L9 design was chosen to efficiently screen the dominant process parameters with a minimal number of experiments while maintaining experimental feasibility. The results are interpreted primarily in terms of main effects.

The selected process parameters and their levels are listed in Table 1. The printing bed temperature was maintained at 80 °C. All specimens were fabricated using a rectilinear infill pattern with a nominal infill density of 100%, as defined by the slicing software. It is noted that in FDM processes, this setting corresponds to the maximum material deposition for the selected extrusion width and flow parameters and does not necessarily imply a completely void-free structure. An orientation of 0°/90°was used for all specimens, with the loading direction parallel to the deposited layers. A 0.4 mm nozzle was used with an extrusion width of 0.45 mm to ensure sufficient bead overlap and interlayer fusion. Each specimen was printed with 3 perimeters. The cooling fan speed was limited to 20% to avoid premature solidification and to promote polymer chain diffusion between layers, as recommended for PETG-based composites. Printing was carried out under ambient laboratory conditions (25 ± 2 °C) without an actively heated enclosure.

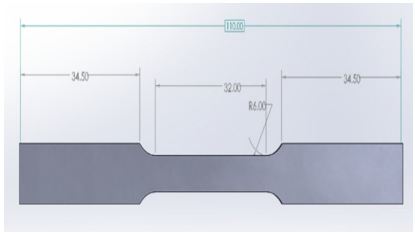
Specimens were prepared in accordance with ASTM D638 Type I (tensile) and ASTM D790 (flexural) standards [9]. After printing, all samples were conditioned at room temperature (23 ± 2 °C) for 24 h before testing. Table 2 shows the Taguchi orthogonal array L9. Figure 1 shows the 3D CAD models and 3D-printed test specimens for tensile and flexural testing. Three samples were printed for each experimental run, and their average value was used for data analysis.

Table 1: Process parameters and their levels

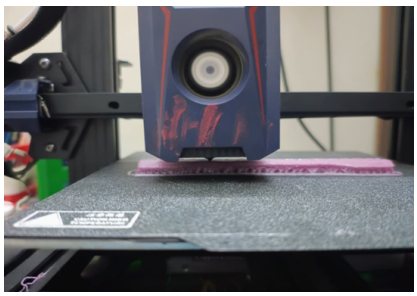
Process Parameters	**Level 1**	**Level 2**	**Level 3**
Layer Thickness (mm)	0.1	0.15	0.2
Print Speed (mm/s)	20	40	60
Nozzle Temperature (°C)	230	235	240

Table 2: Experimental plan (Taguchi L9 orthogonal array)

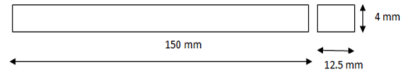
Run	**Layer Thickness**	**Print Speed**	**Nozzle Temp**
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2



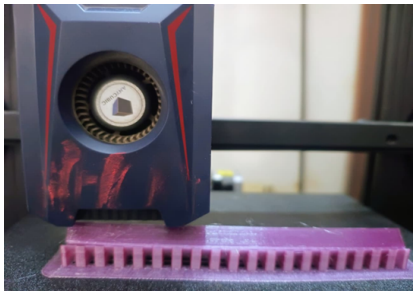
(a) 3D CAD model of the tensile test specimen



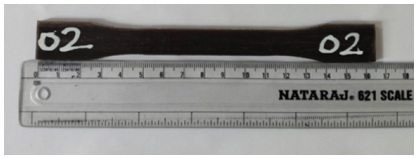
(b) 3D-printed tensile test specimen



(c) Dimensions of flexural test specimen



(d) 3D-printed bending test specimen



(e) Printed tensile test specimen showing scale

(f) Printed bending test specimen showing scale

Figure 1: Test specimens used in the study

2.3. Evaluation of Tensile Strength

Dog-bone specimens of graphene-reinforced PETG were 3D-printed to ASTM D638 Type I dimensions, conditioned at 25 ± 2 °C and 50 ± 5% RH for 24 h, and tested on an Instron universal testing machine (System ID 3382AB1533) calibrated on 18-03-2024 [10]. The frame was fitted with a 100 kN load cell. Tests were performed at a crosshead speed of 0.5 mm min^{-1} (rigid plastics per ASTM D638) and a gauge length of 32 mm; an extensometer was used to measure deformation. Force–displacement data were converted to engineering stress–strain using the initial cross-sectional area (A_0) of the fabricated test specimen and original gauge length (L_0). Ultimate tensile strength (σ_{UTS}) was computed as:

$$\sigma_{\text{UTS}} = \frac{F_{\text{max}}}{A_0} \tag{1}$$

The dimensions of the fabricated and CAD specimens, including length, width, and thickness, are reported in Table 3. For each experimental run, 3 replicates were tested; results are reported as mean ± SD. Figure 2 shows the fabricated tensile test specimens, tensile testing of 3D-printed specimens, and fractured tensile test specimens.

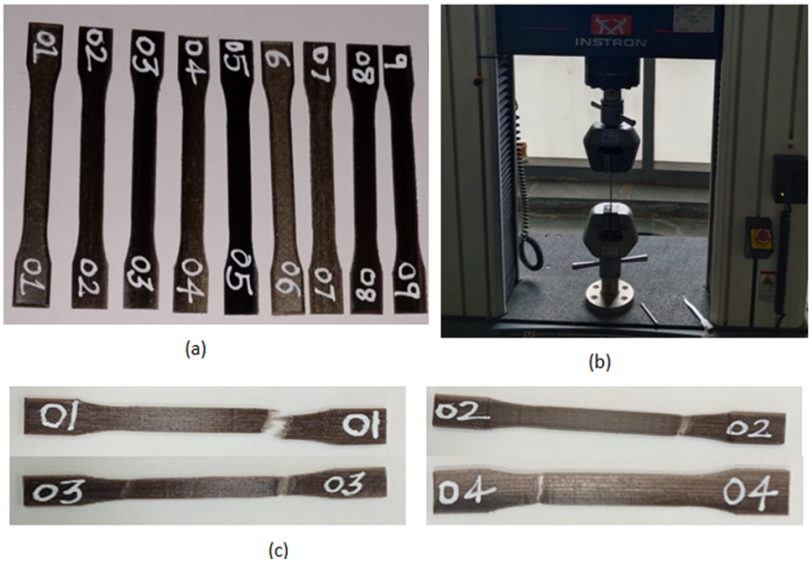


Figure 2: (a) Fabricated tensile test specimens, (b) Tensile testing of 3D-printed specimens, (c) Fractured tensile test specimen.

2.4. Evaluation of Flexural Strength

The flexural strength of the 3D-printed PETG/graphene composite specimens was evaluated using the same universal testing machine (UTM) (System ID 3382AB1533) calibrated on 18-03-2024. The test environment for the flexural test was the same as the tensile test: 25 ± 2 °C and 50 ± 5% RH. The test was conducted following the ASTM D790 standard for polymeric materials [11, 12]. A three-point bending fixture was mounted on the UTM, consisting of two support rollers and a centrally applied loading nose. The specimens were printed and surface-finished to remove burrs formed during printing. The dimensions of the test specimen were 150 mm × 12.7 mm × 4 mm. The span length between supports was maintained at 64 mm, corresponding to a span-to-depth ratio of 16:1. The crosshead speed was set to 2 mm/min, ensuring quasi-static loading conditions.

During testing, the load and deflection were continuously recorded using the machine's integrated data acquisition system. The flexural strength was determined from the load-deflection curves. All tests were conducted at ambient laboratory conditions (temperature 25 ± 2 °C and relative humidity 50 ± 5%). Three specimens were tested for each set of process parameters to ensure repeatability and to minimize experimental uncertainty [13, 14]. Table 3 shows the average values of measured tensile strength and flexural strength of printed samples. Figure 3 shows the flexural test setup.

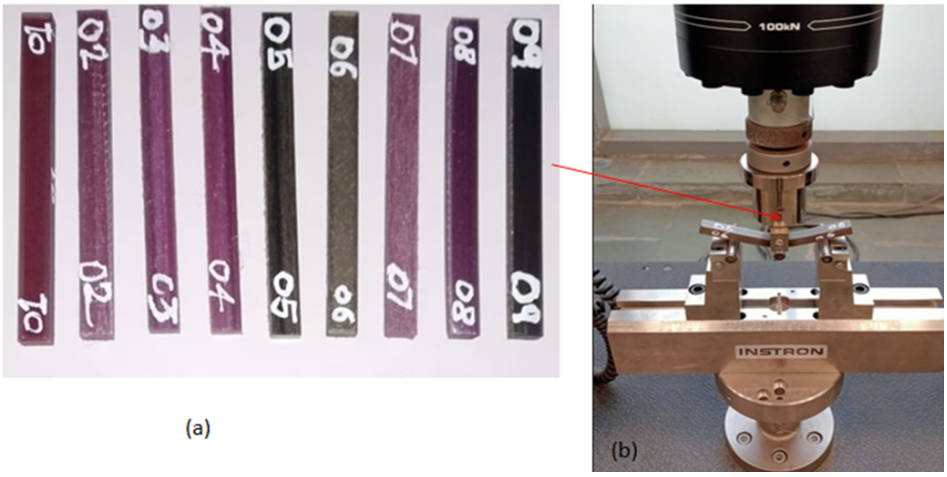


Figure 3: (a) Flexural test specimen, (b) Flexural strength testing on Instron machine.

Table 3: Average tensile strength and flexural strength of printed samples

Run	Layer (mm)	Speed (mm/s)	Temp (°C)	Actual Thick. (mm)	Tensile Strength (MPa)	Flexural Strength (MPa)
1	0.1	20	230	4.192	55.12 ± 1.4	80.91 ± 3.8
2	0.1	40	235	4.056	52.23 ± 1.2	78.13 ± 2.9
3	0.1	60	240	4.064	50.34 ± 0.98	75.89 ± 3.9
4	0.15	20	235	4.004	53.56 ± 1.1	77.21 ± 1.8
5	0.15	40	240	4.02	51.25 ± 1.3	74.35 ± 2.4
6	0.15	60	230	4.232	50.87 ± 0.99	73.46 ± 1.8
7	0.2	20	240	4.1	48.92 ± 1.8	72.78 ± 1.9
8	0.2	40	230	4.168	47.14 ± 1.5	70.32 ± 2.2
9	0.2	60	235	4.084	46.23 ± 1.5	69.37 ± 2.6

3. Results and Discussion

3.1. Development of Regression Models for Tensile Strength and Flexural Strength

To establish the relationship between the FDM process parameters and the mechanical performance of graphene-reinforced PETG composites, linear regression models were developed for tensile and flexural strengths as functions of the coded values of layer thickness, print speed, and nozzle temperature.

The statistical adequacy of the developed models was evaluated based on the coefficient of determination (R^2), adjusted R^2, predicted R^2, and standard deviation (S) values, as obtained from the model summary and ANOVA results [15].

The tensile strength model exhibited an R^2 value of 0.873; adjusted R^2 (0.7968) and predicted R^2 (0.623) values suggest a reasonably good fit with moderate predictive capability. The standard deviation ($S = 1.29771$) indicates an acceptable level of residual error between experimental and predicted values. However, this regression analysis was primarily presented as a trend-based tool to identify the relative influence of process parameters and to support comparative optimization within the studied design space, rather than as a strong predictive model.

The ANOVA results presented in Table 4 indicate that the overall regression model is statistically significant ($F = 11.46$, $p = 0.011$), confirming that process parameters influence tensile strength significantly. Nozzle temperature ($F = 0.68$, $p = 0.44$) had an insignificant effect, while layer thickness ($F = 23.47$, $p = 0.005$) was found to be the most significant factor, followed by print speed ($F = 10.22$, $p = 0.024$). The negative influence of print speed and higher layer thickness is attributed to increased interlayer voids and reduced interfacial bonding, which deteriorate load transfer efficiency within the printing system. Equation 2 shows the developed model for tensile strength.

In the case of the flexural strength model, significantly higher goodness of fit was observed, with $R^2 = 0.9793$, adjusted $R^2 = 0.9669$, and predicted $R^2 = 0.928$, reflecting good agreement between predicted responses and experimental responses. The relatively low standard deviation ($S = 0.6667$) indicates minimal deviation between model-predicted values and measured values. ANOVA analysis (Table 5) confirms that the models are statistically significant ($F = 79.00$, $p = 0.000$).

Similar to tensile strength, layer thickness ($F = 181.50$, $p = 0.000$) emerged as the most dominant factor affecting flexural strength, followed by print speed ($F = 54.00$, $p = 0.001$), while nozzle temperature ($F = 1.50$, $p = 0.275$) remained statistically insignificant. The high sensitivity of flexural strength to layer thickness is attributed to its direct influence on interlayer adhesion and on structural continuity across the neutral axis during bending. Thinner layers promote better fusion between successive filaments, thereby enhancing load-carrying capacity under bending conditions. Equation 3 shows the developed model for flexural strength. The S/N ratio can be calculated from Equation 4.

$$\text{Tensile Strength (MPa)} = 60.02 - 2.567 \times \text{Layer Thickness} - 1.693 \times \text{Print Speed} - 0.437 \times \text{Nozzle Temp} \quad (2)$$

$$\text{Flexural Strength (MPa)} = 86.222 - 3.667 \times \text{Layer Thickness} - 2.000 \times \text{Print Speed} - 0.333 \times \text{Nozzle Temp} \quad (3)$$

For the Taguchi Signal-to-Noise (S/N) ratio with the "Larger-is-Better" quality characteristic, the calculation uses:

$$\text{S/N} = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right) \quad (4)$$

where y_i is the observed response value in the ith trial and n is the number of observations (replications).

Table 4: Analysis of variance for tensile strength

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	57.875	19.292	11.46	0.011
Layer Thickness (mm)	1	39.527	39.527	23.47	0.005
Print Speed (mm/s)	1	17.204	17.204	10.22	0.024
Nozzle Temp (°C)	1	1.144	1.144	0.68	0.447
Error	5	8.420	1.684		
Total	8	66.295			

Table 5: Analysis of variance for flexural strength

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	105.333	35.1111	79.00	0.000
Layer Thickness (mm)	1	80.667	80.6667	181.50	0.000
Print Speed (mm/s)	1	24.000	24.0000	54.00	0.001
Nozzle Temp (°C)	1	0.667	0.6667	1.50	0.275
Error	5	2.222	0.4444		
Total	8	107.556			

3.2. Effect of Process Variables on Tensile Strength

Main effects plots, surface plots, a Pareto chart, and residual analysis were used to examine the impact of the main process parameters on the tensile strength of the 3D-printed samples, namely layer thickness, print speed, and nozzle temperature. Table 6 presents tensile strength S/N ratios.

Figure 4(a) indicates that the main effects plot reveals that layer thickness has a significant impact on tensile strength. The results revealed that specimens printed with a smaller layer thickness exhibited superior tensile strength than those printed with a larger layer thickness. This improvement is primarily due to enhanced heat transfer and interlayer bonding during the material extrusion process. A reduced layer thickness increases the number of deposited layers for a given part height, resulting in repeated thermal exposure of previously deposited layers. This promotes improved thermal diffusion and interdiffusion of polymer chains across adjacent layers, leading to stronger interfacial bonding.

From a porosity perspective, thinner layers allow more uniform material flow and better filling of inter-raster gaps, thereby reducing void formation and interlayer defects. In contrast, a larger layer thickness limits adequate heat penetration into the underlying layer, resulting in insufficient fusion and higher porosity, which act as stress concentration sites and reduce tensile strength. The presence of graphene further influences this behavior. Due to its high thermal conductivity, graphene facilitates localized heat dissipation and improves thermal homogeneity within the deposited filament. At a smaller layer thickness, this effect becomes more pronounced, as the enhanced heat distribution supports improved melting and wetting between layers, strengthening the graphene–PETG interface. Additionally, well-dispersed graphene restricts polymer chain mobility and contributes to effective load transfer, thereby delaying crack initiation and propagation under tensile loading.

Tensile strength is also highly influenced by print speed. Tensile strength decreases as printing speed increases. Increased speed reduces the time available for adequate heat transfer between the extruded filament and the existing layer, thereby decreasing interfacial adhesion. Conversely, low print speeds enhance layer melting and diffusion, leading to improved bonding and tensile strength. When nozzle temperature is increased moderately, tensile strength initially increases; however, excessive temperatures may cause material degradation or over-melting, thereby weakening structural integrity. Therefore, an optimal temperature interval is key to achieving the best mechanical performance.

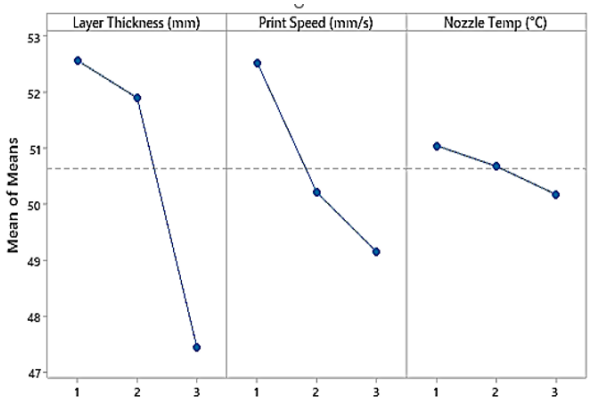
Figure 4(b) indicates that surface plots show that a combination of low layer thickness and medium print speed achieves optimum tensile strength. The interaction effects appear insignificant, indicating that tensile strength is largely controlled by the main effects of the process parameters rather than their interactions. The Pareto Chart of Standardized Effects (Figure 4(c)) also confirms that layer thickness (A) was the most influential variable on tensile strength, followed by print speed (B). The effect of nozzle temperature (C) is comparatively smaller but falls under the significance level ($\alpha = 0.05$).

As demonstrated in Figure 4(d), results of the Residual Plots (Normal Probability, Histogram, and Versus Fits) confirm the suitability of the regression model. Normal distribution is confirmed because the normal probability plot shows that the residuals are nearly distributed along a straight line. The residuals show no systematic trend, and the order plots show no systematic pattern, indicating that the model is reliable and free of bias.

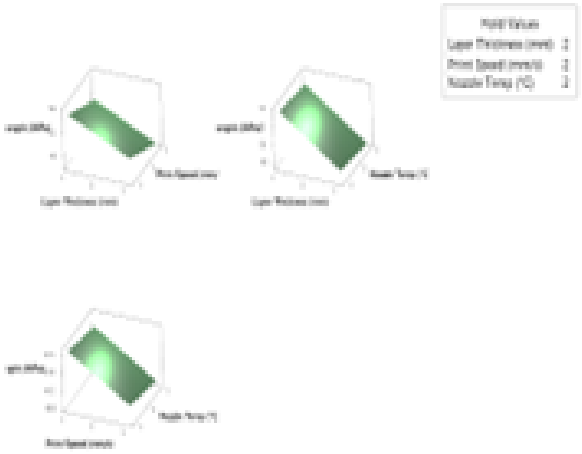
Figure 4(e) shows the interaction plot for tensile strength, revealing notable interaction effects among layer thickness, print speed, and nozzle temperature. The interaction between layer thickness and print speed shows non-parallel trends, indicating that the influence of print speed on tensile strength depends on the selected layer thickness. At lower layer thickness, tensile strength decreases more sharply with increasing print speed, whereas at higher layer thickness, the variation is comparatively moderate, suggesting improved process stability. A similar interaction is observed between layer thickness and nozzle temperature: tensile strength decreases with increasing nozzle temperature at lower layer thicknesses but exhibits a less pronounced change at higher thicknesses, indicating reduced thermal sensitivity. The interaction between print speed and nozzle temperature is stronger, as evidenced by the intersecting lines, suggesting that the combined effect of these parameters significantly governs interlayer bonding and material consolidation.

Table 6: Signal-to-noise ratios for tensile strength

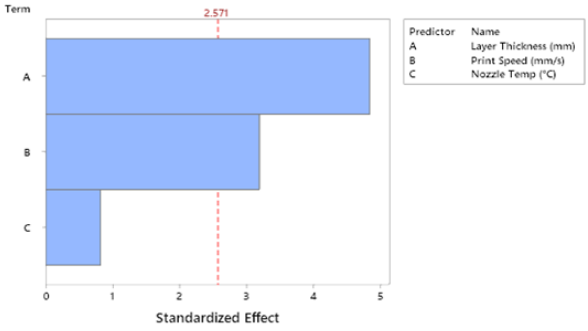
Level	**Layer Thickness (mm)**	**Print Speed (mm/s)**	**Nozzle Temp (°C)**
1	34.41	34.40	34.14
2	34.30	34.01	34.08
3	33.52	33.82	34.01
Delta	0.89	0.58	0.13
Rank	1	2	3



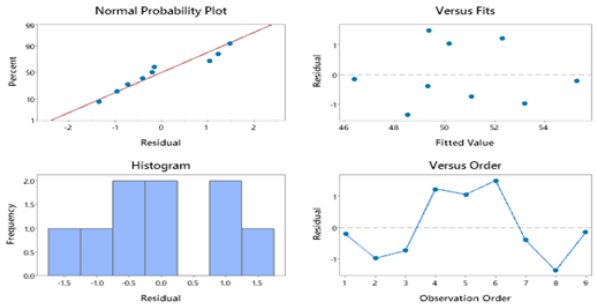
(a) Main effect plot for tensile strength



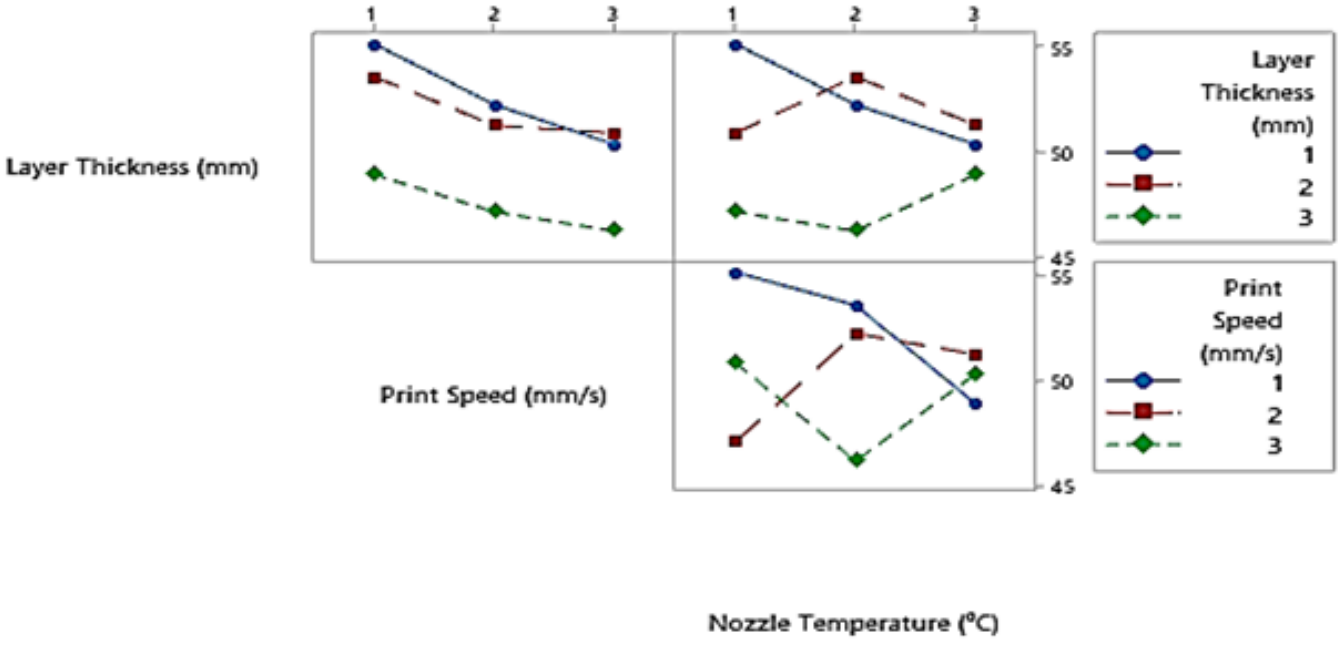
(b) Surface plot of process variables



(c) Pareto chart



(d) Residual plot for tensile strength



(e) Interaction plot

Figure 4: Tensile strength analysis plots

The stress–strain curves of samples are illustrated in Figure 5. Analysis of the stress–strain curves shows that the maximum strain at break lies in the range of approximately 4–12%, depending on the processing condition. These elongation-at-break values, together with the presence of dimples and plastic deformation features observed in the FE-SEM fractographs, substantiate the ductile fracture behavior.

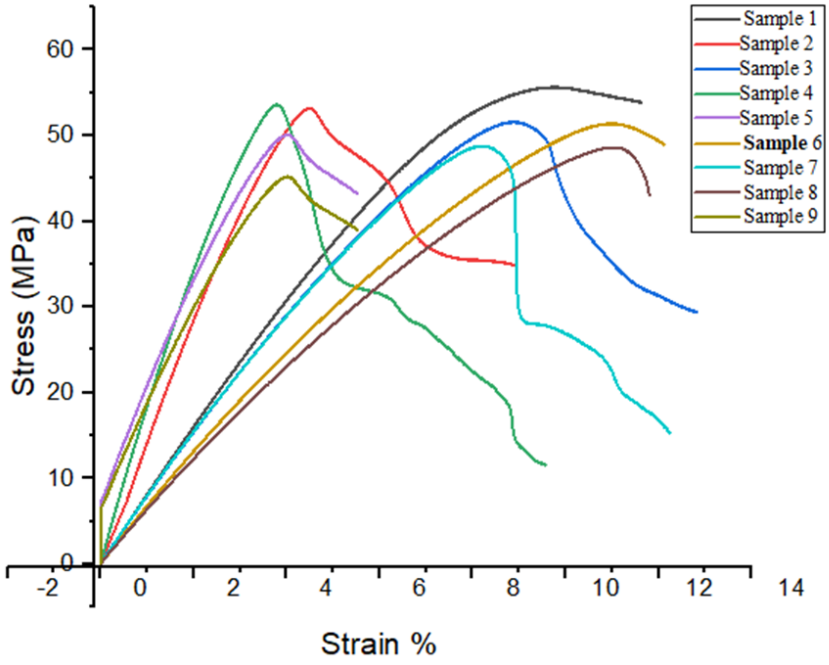
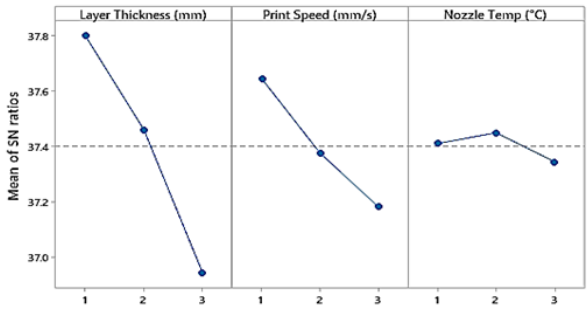


Figure 5: Stress versus strain curves of fabricated samples.

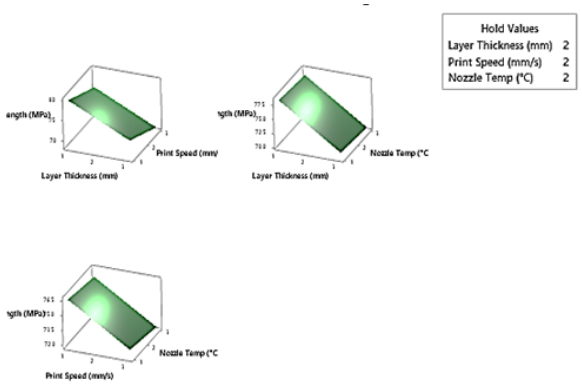
3.3. Effect of Process Parameters on Flexural Strength

The main effects plot of S/N ratios and the Pareto chart of standardized effects were used to examine the effect of FDM process parameters, namely layer thickness, print speed, and nozzle temperature, on the flexural strength of graphene-reinforced PETG composite. The Main Effects Plot in Figure 6(a) represents the S/N ratios where the "larger is better" criterion is used. Results showed that flexural strength is most affected by layer thickness. The S/N ratio (Table 7) reduces significantly with an increase in layer thickness, which implies that smaller layer thickness results in greater flexural strength. This is because thinner layer thicknesses lead to stronger interlayer bonding and lower void content, enabling more effective load transfer between layers. Thicker layers, conversely, exacerbate poor interfacial bonding and an uneven distribution of graphene particles, which act as stress concentrators and reduce bending resistance. Print speed also plays a significant role in flexural performance. Higher print speed yields a lower S/N ratio, indicating that slower print speed results in higher flexural strength. This is attributed to adequate residence time for heat transfer and diffusion among deposited filaments, which facilitates high interlayer adhesion. At higher speeds, degraded bonding between adjacent layers and irregularities in graphene dispersion degrade mechanical properties. The nozzle temperature has a comparatively minor impact on flexural strength in comparison to layer thickness and print speed. As nozzle temperature is moderately increased, the rate of material flow and the dispersion of graphene in the PETG composite improve, thereby increasing bonding strength. Nevertheless, large increments can degrade the polymer matrix or induce thermal stress, thereby decreasing the overall flexural strength by a small margin.

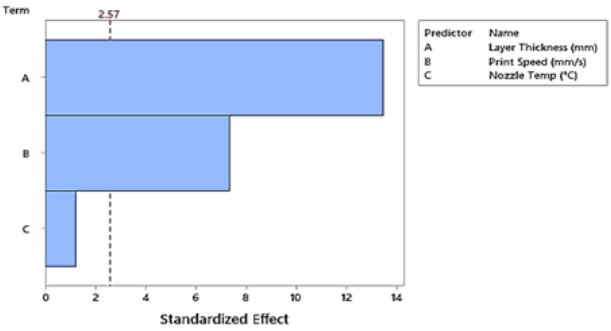
The Pareto Chart of Figure 6(b) in Standardized Effects confirms that the most dominant parameter affecting flexural strength is layer thickness (A), followed by print speed (B), and lastly nozzle temperature (C), which is below the significance level ($\alpha = 0.05$). Figure 6(c) represents the surface plot for flexural strength, and Figure 6(d) represents the residual plot for flexural strength. Figure 6(e) shows the interaction plot for flexural strength, indicating pronounced interaction effects among layer thickness, print speed, and nozzle temperature. The interaction between layer thickness and print speed shows nearly parallel downward-sloping trends, suggesting that flexural strength consistently decreases with increasing print speed across all layer thicknesses, while thinner layers yield higher strength due to improved interlayer bonding. The interaction between layer thickness and nozzle temperature shows mild non-parallel behavior, indicating that nozzle temperature has a stronger influence at lower layer thickness, where an optimal temperature enhances material fusion and flexural performance. In contrast, the interaction between print speed and nozzle temperature is strong, as evidenced by intersecting lines, revealing that the effect of nozzle temperature on flexural strength is highly dependent on print speed. Moderate nozzle temperatures combined with intermediate print speeds yield the highest flexural strength, whereas higher speeds or temperatures reduce bonding efficiency. These findings are important because interlayer bonding, heat transfer, and uniformity of graphene distribution are crucial elements that determine the flexural performance of printed composites. The best flexural strength is achieved by combining a minimum layer thickness, a low print speed, and an optimal nozzle temperature that enhances polymer chain diffusion and evenly distributes the graphene reinforcement. Table 8 shows a comparative study with the present work.



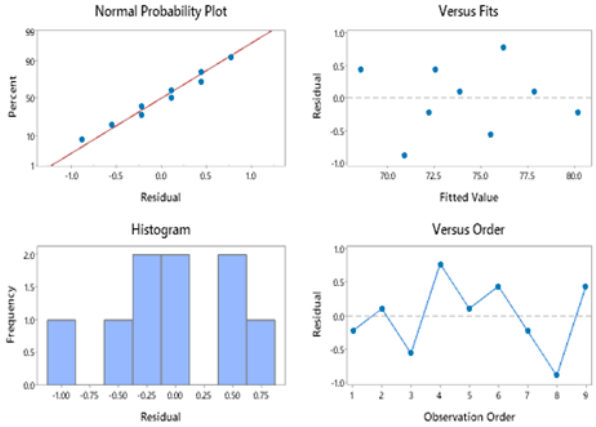
(a) Main effect plot for flexural strength



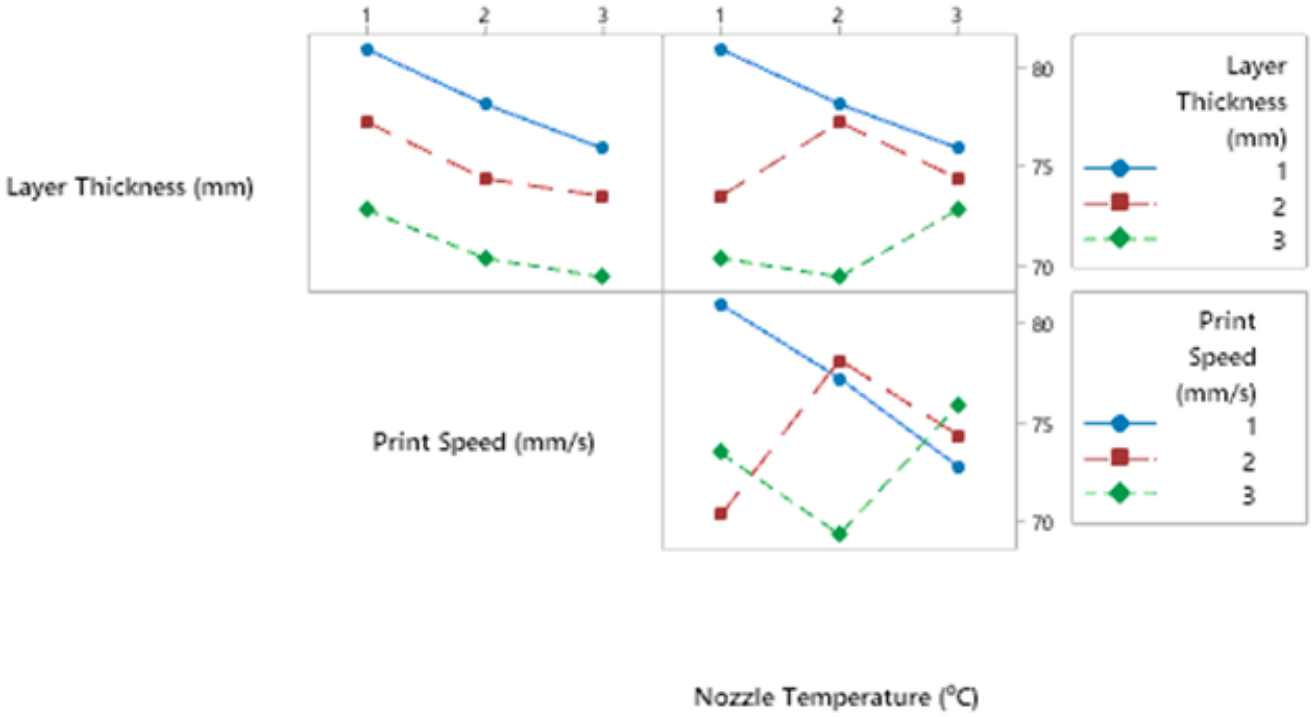
(b) Surface plot of process variables



(c) Pareto chart



(d) Residual plot for flexural strength



(e) Interaction plot

Figure 6: Flexural strength analysis plots

Table 7: Signal-to-noise ratios for flexural strength

Level	**Layer Thickness (mm)**	**Print Speed (mm/s)**	**Nozzle Temp (°C)**
1	37.80	37.65	37.41
2	37.46	37.38	37.45
3	36.94	37.18	37.34
Delta	0.86	0.46	0.11
Rank	1	2	3

Table 8: Comparative study with present work

Material	**Process Parameters**	**Mechanical Properties**	**Optimum Parameters**	**Ref.**
Gr 1 wt.% PETG	Layer thickness, Nozzle temp, Printing speed	UTS 55.32 MPa, Flexural 79.89 MPa	Layer 0.1 mm, speed 20 mm/s, temp 230 °C	Present
G-PETG (AHP)	Layer height, print speed, raster angle	UTS 49.1 MPa, E 735.6 MPa	Layer 0.20 mm, 40 mm/s, 0°raster	[16]
G-PETG (FAHP-TOPSIS)	Infill density, layer height, print speed, temp	UTS 56.16 MPa	65% infill, 0.20 mm, 50 mm/s, 240 °C	[17]
PETG with Graphene	Not specified	Tensile 50 MPa, Flexural 95 MPa	—	[18]
PETG	Layer height, raster angle, build orientation	Tensile 48 MPa, Flexural 68 MPa	Layer 0.20 mm, raster 0°, flat	[19]

3.4. Microstructural Analysis

The SEM micrograph of the graphene-reinforced PETG specimen fabricated using the FDM process (Figure 7) reveals the surface morphology and interfacial features at different magnifications (100×, 150×, 500×, and 997×). The surface appears smooth, with minor undulations, indicating good layer adhesion and consistent material deposition during printing. Some discrete particle agglomerates are observed; they are attributed to localized clustering of graphene nanoparticles within the PETG matrix. These agglomerates suggest partial dispersion of graphene, a common phenomenon due to strong van der Waals interactions between graphene sheets.

The absence of major voids at the layer interfaces indicates satisfactory fusion between successive printed layers, demonstrating the effectiveness of the selected process parameters. Regions in which graphene is richly embedded within the polymer matrix appear as bright contrast areas, where load transfer capability is enhanced, improving both flexural and tensile strength. Minor thermal inconsistencies during extrusion are indicated in the tilted traces. The SEM analysis shows a uniform and well-consolidated printed structure along with a moderately homogeneous graphene distribution, which validates the suitability of FDM technology for fabricating graphene-reinforced composites.

3.5. Fractographic Analysis

A SEM micrograph of a fractured graphene-reinforced PETG composite sample (Figure 8) was obtained after tensile testing, providing valuable insights into the interlayer bonding characteristics and fracture behavior of FDM-printed structures. Layer-by-layer morphology is observed at magnifications of 51×, 250×, and 497× of different layers of the FDM-printed specimen. Improper coalescence among extruded layers is evident from the semi-fused filament morphology, indicating that interlayer diffusion of molten polymer did not occur fully; this is attributed to thermal gradients and cooling rates during deposition.

Analysis shows that the fractured surface exhibits both brittle and ductile failure characteristics. Many regions display stretched, elongated filaments and fibrillated zones, suggesting localized plastic deformation prior to fracture, whereas other regions exhibit flat, smooth facets indicative of brittle fracture. The presence of inter-bead gaps and voids suggests that interlayer adhesion was the weakest link in the sample's failure. This feature is characteristic of FDM-printed composites, where anisotropy and insufficient fusion are the dominant failure mechanisms.

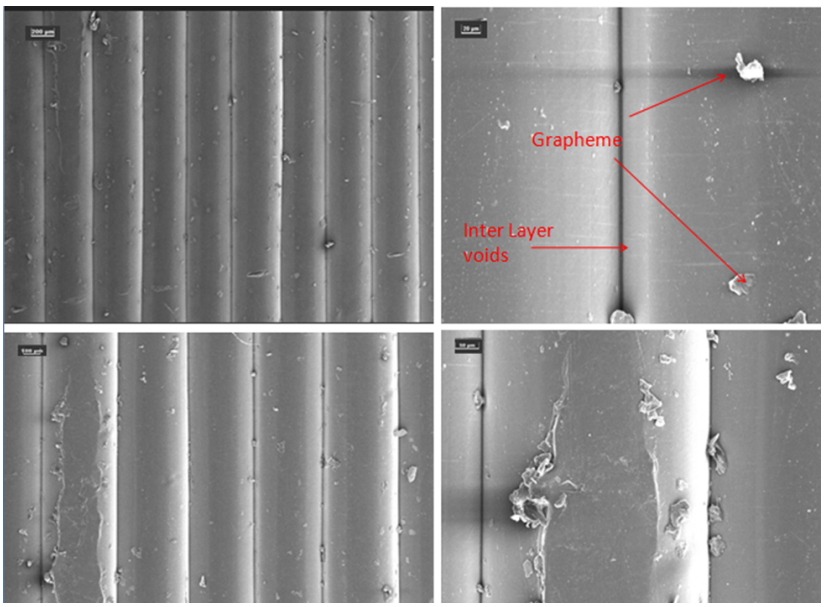


Figure 7: SEM micrograph of 3D-printed graphene/PETG composite exhibiting uniform deposition and minor graphene agglomeration.

Uniform graphene dispersion and filament fusion-dominated bonding are correlated with enhanced load transfer and higher strength. Furthermore, graphene agglomeration and brittle fracture features contribute to localized stiffness mismatch, crack propagation, and strength degradation. The reinforced graphene nanoparticles embedded in the PETG matrix likely enhance load transfer efficiency and restrict polymer chain mobility, thereby increasing strength and stiffness. The aggregation of graphene in particular areas may have acted as local stress concentration points, initiating microcracks under tensile loading. The overall morphology suggests that while graphene reinforcement improved interlayer cohesion and mechanical integrity, optimizing process parameters, such as nozzle temperature and print speed, is essential to enhance interlayer diffusion and minimize void formation.

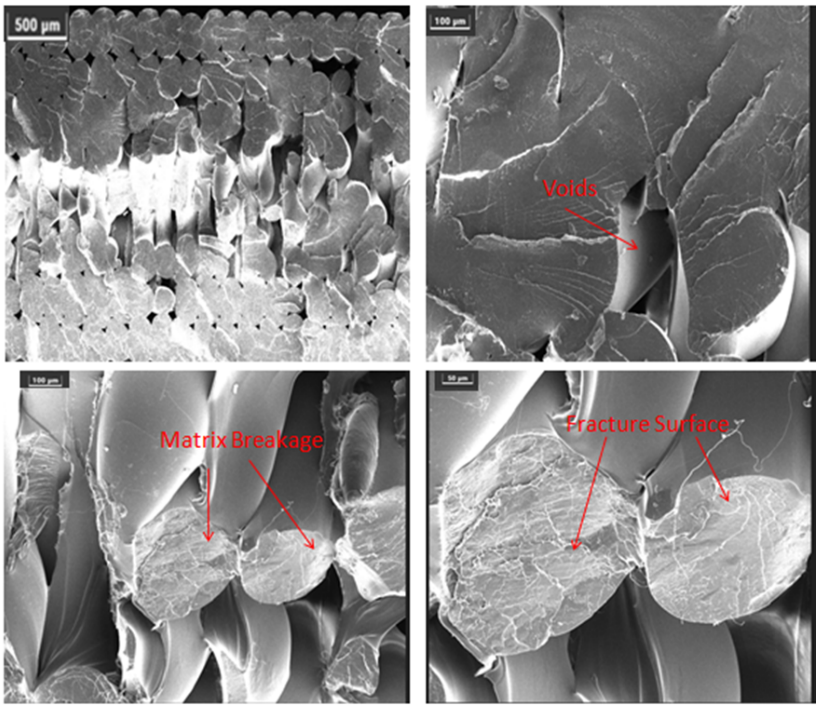


Figure 8: SEM micrograph of fracture surface at different magnifications.

4. Conclusions

The present research comprehensively investigated the effects of key FDM process parameters — layer thickness, print speed, and nozzle temperature — on the mechanical performance of graphene-reinforced PETG composites. Experimental results revealed that the optimum combination of process parameters for achieving maximum tensile strength (55.32 MPa) was a layer thickness of 0.1 mm, print speed of 20 mm/s, and nozzle temperature of 230 °C, whereas the optimum condition for flexural strength (79.89 MPa) was a layer thickness of 0.1 mm, print speed of 20 mm/s, and nozzle temperature of 235 °C. The developed regression models for both responses exhibited good predictive accuracy, confirming their reliability for process optimization. Graphene exhibits a generally homogeneous distribution with localized agglomeration, which is consistent with the SEM observations. Fractography analysis (FE-SEM) shows intact fracture surfaces with minimal voids, indicating enhanced interfacial adhesion and efficient stress transfer between the polymer matrix and the graphene reinforcement.

Author Contributions

Ram Kishore Shakya: Conceptualization, Methodology, Investigation, Data curation, Writing: original draft; **Dharamvir Mangal**: Supervision, Writing: review and editing; **Nagendra Kumar Maurya**: Supervision, Validation, Writing: review and editing.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Use of Generative AI

AI-assisted tools were used solely for language and grammar improvement. The authors retain full responsibility for the scientific content and conclusions.

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Funding Declaration

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Ethics Approval and Consent

This study does not involve human participants, animals, or sensitive personal data. No ethics approval was required.

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Humidity-Aware Hybrid Transformer-LSTM Framework for IoT-Enabled Photovoltaic Power Prediction

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Abstract

Accurate short-term photovoltaic (PV) power forecasting is essential for Internet of Things (IoT)-enabled monitoring, control, and performance assessment of small-scale solar installations. While electrical variables and temperature are widely used in data-driven PV forecasting models, the contribution of ambient humidity remains insufficiently characterized, particularly in persistently humid environments. This study investigates the role of ambient humidity as a contextual environmental feature and evaluates a humidity-aware Hybrid Transformer-LSTM framework for short-term PV power prediction using real-world IoT data collected from multiple photovoltaic panels over a 34-day monitoring period. The proposed hybrid architecture integrates a Transformer-based self-attention mechanism for cross-feature interaction modeling with LSTM-based recurrent learning to capture temporal persistence. Model performance is evaluated against LSTM-only, Transformer-only, Random Forest, and Linear Regression baselines using a strictly time-ordered train-test split, complemented by architectural and feature ablation studies, rolling time-based validation, cross-panel testing, and robustness analysis under input perturbation. Experimental results show that LSTM-based models achieve the highest predictive accuracy on the short-duration dataset, while ambient humidity provides only marginal and context-dependent benefit as a supplementary environmental feature. Transformer-only models perform poorly under data-limited conditions, while the Hybrid Transformer-LSTM achieves competitive accuracy and demonstrates stable behavior under temporal validation, spatial generalization, and sensor noise. These findings highlight that the primary contribution of this study lies in rigorous evaluation and deployment-aware validation rather than absolute accuracy gains, positioning hybrid attention-recurrent architectures as robustness-oriented solutions for IoT-enabled solar PV monitoring systems.

Keywords: Photovoltaic Power Prediction; IoT-Based PV Monitoring; Humidity-Aware Modeling; Hybrid Transformer-LSTM; Smart Energy Systems

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1. Introduction

The rapid deployment of photovoltaic (PV) systems in distributed and residential environments has increased the need for accurate short-term power forecasting and reliable monitoring infrastructures [1]. Unlike utility-scale solar plants, small-scale PV installations operate under localized microclimatic conditions and limited instrumentation, making data-driven forecasting approaches essential for operational optimization, energy management, and fault detection [2].

PV power output is primarily governed by solar irradiance and cell temperature [3, 4]. Elevated panel temperatures reduce conversion efficiency, while irradiance variability drives short-term power fluctuations. Ambient humidity has traditionally been regarded as a secondary environmental factor and is therefore often excluded from short-term PV forecasting models. Nonetheless, several studies suggest that humidity can indirectly influence PV performance. These effects are commonly attributed to reduced convective cooling, surface moisture accumulation, and coupled thermal dynamics, particularly in tropical and subtropical climates [5–7]. Despite these physical insights, the explicit contribution of humidity to data-driven PV power prediction remains insufficiently validated using real-world operational data.

Recent advances in Internet of Things technologies have enabled continuous, high-resolution acquisition of electrical and environmental measurements from PV installations using low-cost sensors, embedded devices, and lightweight communication protocols [8, 9]. However, many PV forecasting studies still rely on randomized data splitting or isolated evaluation windows [10], which can introduce temporal leakage and optimistic performance estimates, limiting their applicability in real deployments.

To address these gaps, this study investigates humidity-aware PV power forecasting using a Hybrid Transformer-LSTM framework trained on real-world IoT-collected data. Unlike many existing studies, this work adopts strictly time-ordered data splitting, rolling (walk-forward) validation, cross-panel testing, and robustness analysis to avoid temporal leakage and optimistic bias. This evaluation-first design prioritizes deployment realism and generalization reliability over headline accuracy metrics. In addition, the study presents a deployment-realistic IoT data pipeline incorporating edge-level persistence and an application-layer MQTT acknowledgment mechanism, ensuring reliable end-to-end data delivery under intermittent connectivity.

The main contributions of this work are summarized as follows:

- Empirical characterization of humidity-power relationships using real-world IoT PV data, clarifying the contextual and regime-dependent role of ambient humidity in short-term solar PV power prediction.
- Systematic architectural and feature ablation comparing LSTM-only, Transformer-only, and Hybrid Transformer-LSTM models under identical training and validation conditions.
- A rigorously validated IoT-oriented forecasting framework emphasizing leakage-free preprocessing, time-ordered and rolling validation, cross-panel generalization analysis, and robustness testing, thereby prioritizing reliability and methodological rigor over headline accuracy metrics.

The remainder of this paper is organized as follows. Section 2 reviews related work on PV power forecasting, environmental effects, and IoT-based monitoring systems. Section 3 presents the system architecture, dataset, preprocessing, and the proposed Hybrid Transformer-LSTM model. Section 4 reports the experimental results, including ablation studies and validation outcomes. Section 5 discusses the findings and their practical implications. Section 6 concludes the study and outlines limitations and future research directions.

2. Related Work

Photovoltaic performance modeling has traditionally relied on physical and semi-empirical formulations derived from equivalent circuit representations, thermodynamic principles, and empirical loss models [4, 11]. While these approaches offer physical interpretability, they require detailed system parameters that are often unavailable in small-scale deployments.

To address these limitations, data-driven machine learning methods have been widely adopted. Techniques such as support vector regression, random forests, and artificial neural networks have demonstrated strong predictive capability by learning nonlinear relationships directly from historical measurements [12, 13]. However, many classical machine learning models operate on fixed input vectors and lack explicit mechanisms to model temporal dependencies, limiting their effectiveness for PV power forecasting, where sequential dynamics are prominent. Recurrent neural networks, particularly Long Short-Term Memory (LSTM) architectures, address this limitation and have demonstrated strong performance in PV power forecasting [14]. More recent studies have explored hybrid architectures combining attention

mechanisms or convolutional layers with recurrent models [15, 16]. While such hybrids may improve robustness, the benefits are often evaluated under limited validation settings.

Ambient humidity has received comparatively little attention as an explicit input feature in short-term PV forecasting. Despite some literature discussing indirect physical effects, data-driven prediction models rarely include humidity, even in humid climates [6, 7]. Consequently, the empirical value of humidity as a predictive variable remains poorly characterized.

Developments in IoT-based PV monitoring emphasize the importance of reliable data pipelines and edge resilience for reliable data analytics [17–19]. These insights motivate forecasting studies that prioritize validation rigor and deployment realism alongside predictive performance.

3. Methodology

To ensure a leakage-free, deployment-realistic evaluation, all preprocessing and model assessments in this study strictly adhere to temporal ordering. A strictly time-ordered train-test split is employed, where earlier observations are used exclusively for training and later observations for testing, without random shuffling. Data imputation, normalization, and sequence construction are performed after time-ordered splitting, with all learned statistics derived exclusively from the training subset. Model performance is evaluated using this fixed split, complemented by rolling (walk-forward) validation to assess temporal generalization under conditions representative of real IoT deployments.

3.1. IoT-Based Photovoltaic Monitoring Architecture

An end-to-end IoT-based monitoring architecture was deployed to enable reliable acquisition, fault-tolerant transmission, and analytics-driven utilization of electrical and environmental data from small-scale photovoltaic (PV) panels under realistic network conditions. All sensors were sampled synchronously at fixed 60-second intervals to ensure temporal alignment across electrical and environmental measurements. The architecture, illustrated in Figure 1, is organized into six functional layers: sensing, edge processing, local persistence, communication, backend analytics and machine learning, and visualization.

At the sensing layer, each rooftop PV panel is instrumented with multiple sensors to capture synchronized electrical and environmental parameters. An INA226 sensor measures panel voltage and current, from which instantaneous electrical power is computed. Panel surface temperature is measured using a DS18B20 sensor, while ambient temperature and relative humidity are recorded using an SHT45 sensor. Together, these measurements provide the necessary inputs to analyze thermal behavior, humidity–temperature interactions, and their combined influence on PV power output.

The edge processing layer is implemented on a Raspberry Pi Zero W, which performs periodic data acquisition at 60-second intervals, timestamps all measurements, and executes lightweight preprocessing tasks, such as data formatting and integrity checks. To ensure robustness under intermittent network connectivity, each acquired data record is first written to a local publisher database residing on the edge device. This local persistence mechanism enables fault tolerance by preventing data loss during temporary communication outages.

The communication layer employs the Message Queuing Telemetry Transport (MQTT) protocol over Wi-Fi to support lightweight and efficient data transmission. The Raspberry Pi operates as an MQTT publisher, transmitting sensor data to a remote broker. An acknowledgment (ACK) mechanism is implemented so that, once data are successfully received and stored in the server-side subscriber database, an ACK is returned to the edge node. Upon receipt of the ACK, the corresponding local record is marked as synchronized, ensuring eventual consistency between edge and server storage while avoiding redundant retransmissions.

At the backend analytics and machine learning layer, the MQTT subscriber service stores incoming data in a centralized database that serves as the authoritative repository for long-term storage, statistical analysis, and model development. This database is used to train, validate, and evaluate machine learning models for short-term PV power prediction. In the present study, the collected time-series data are used to train recurrent, attention-based, and hybrid deep learning models, enabling systematic architectural and feature ablation, temporal validation, and robustness analysis.

Finally, the visualization layer provides a monitoring dashboard for real-time visualization of PV power output, environmental conditions, and historical trends. Model outputs can be integrated into the dashboard to support predictive insights, performance assessment, and decision-making. The proposed architecture enables reliable, high-resolution data acquisition and analytics, forming a practical foundation for IoT-enabled PV forecasting and monitoring applications.

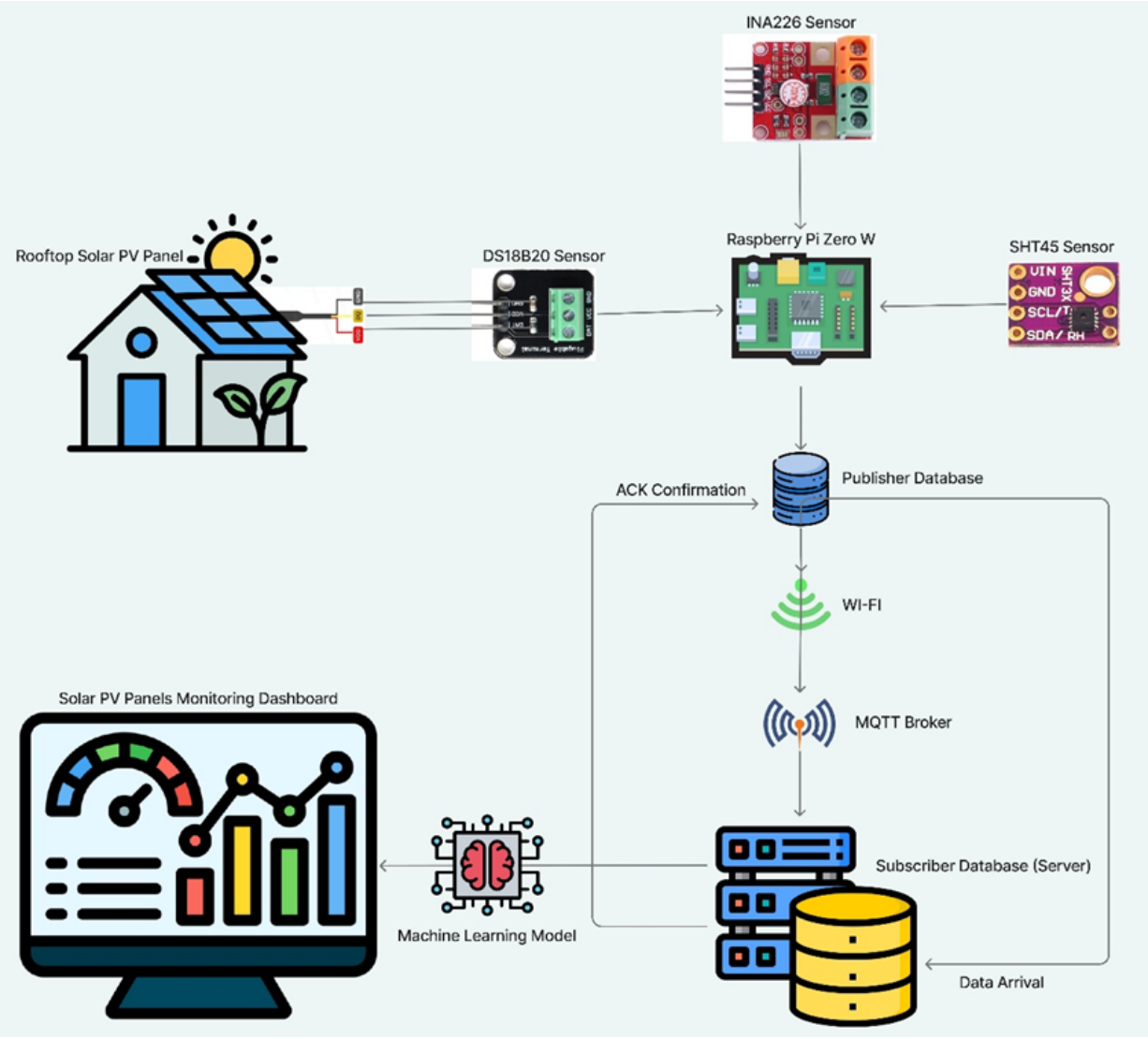

Figure 1: End-to-end IoT-based photovoltaic monitoring and data transmission architecture.

3.2. Dataset Description

3.2.1 Data Collection System

The dataset comprises 66,982 observations collected from three PV panels (PV000, PV001, PV002) over a 34-day period (17 November–21 December 2025), sampled at 60-second intervals.

Solar irradiance measurements were not available in the deployed system due to hardware and cost constraints typical of small-scale and residential IoT installations. Instead, the dataset reflects a minimal-sensor configuration commonly encountered in real-world deployments, where electrical and basic environmental measurements are prioritized over specialized radiometric instrumentation. While the absence of irradiance limits physical interpretability, it enables evaluation of forecasting performance under realistic sensing constraints and motivates the emphasis on temporal learning and validation rigor. The database schema for data storage is given in Table 1.

Table 1: Database schema for IoT-based PV monitoring dataset

Column Name	Data Type	Description
id	BIGINT (PK)	Unique auto-increment identifier for each sensor record
panel_id	VARCHAR	Logical identifier of the PV panel (e.g., PV000, PV001, PV002)
device_id	VARCHAR	Unique hardware identifier of the IoT edge device
voltage	FLOAT	Measured panel output voltage (V)
current	FLOAT	Measured panel output current (A)
power	FLOAT	Instantaneous electrical power output (W)
energy	FLOAT	Accumulated energy produced by the panel (Wh)
panel_temperature	FLOAT	Surface temperature of the solar PV panel (°C)
ambient_temperature	FLOAT	Surrounding environmental temperature (°C)
ambient_humidity	FLOAT	Ambient relative humidity (%)
sent_data_count	INTEGER	Counter for data packets transmitted
sent_at	BIGINT	Timestamp (UNIX epoch in ms) when sent
received_at	BIGINT	Timestamp when received by server
created_at	DATETIME	Server-side record creation timestamp
is_synced	TINYINT	Synchronization flag (0 = not synced, 1 = synced)

3.3. Data Preprocessing

3.3.1 Missing Value Handling

An initial data quality assessment revealed a small proportion of missing values across several attributes. Specifically, voltage, current, and power measurements contained 13 missing records (0.019%), ambient temperature and humidity contained 454 missing records (0.678%), and panel temperature contained a single missing record (0.001%).

To prevent temporal information leakage, missing values were handled after time-ordered data splitting. Panel-wise median imputation and time-based interpolation were applied separately to the training and test subsets, ensuring that future information did not influence model training. This approach preserves panel-specific temporal continuity while maintaining strict separation between training and evaluation data.

Given the low proportion of missing values and strong temporal smoothness of the signals, this preprocessing step minimizes distortion while ensuring leakage-free model evaluation:

$$x_{i,t}^{\text{imputed}} = \text{median}\left(\{x_{i,s} : s \in T_i, x_{i,s} \neq \text{null}\}\right) \tag{1}$$

where $x_{i,t}$ represents the value of attribute i at time t, and T_i denotes all timestamps for the same panel where attribute i is non-null.

3.3.2 Feature Scaling

Feature normalization was performed using Min-Max scaling. Scaling parameters were learned exclusively from the training data and subsequently applied to the test data. Although models were trained using normalized inputs for numerical stability, all predictions were inverse transformed prior to evaluation, and all reported metrics and figures are presented in physical units (watts).

3.4. Correlation Analysis

To quantify relationships between environmental variables and PV power output, Pearson correlation coefficients were computed for all numerical features. The Pearson correlation coefficient between variables X and Y is defined as:

$$r_{XY} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{2}$$

To empirically assess the relevance of environmental variables prior to model training, Pearson correlation coefficients were computed between PV power output and key electrical and environmental parameters, as illustrated in Figure 2. As expected, PV power shows strong positive correlations with current ($r = 0.96$) and voltage ($r = 0.71$), reflecting their direct electrical relationship. Panel temperature shows a moderate positive correlation with power ($r = 0.41$), consistent with thermal effects observed in small-scale PV systems.

Ambient humidity demonstrates a weak but consistent positive correlation with PV power output ($r = 0.15$). Although the magnitude of this relationship is modest, its stability across the dataset supports including humidity as a contextual feature rather than a primary driver. Notably, ambient humidity is strongly negatively correlated with ambient temperature ($r = -0.85$), indicating coupled environmental dynamics that may indirectly influence PV performance. These observations motivate the inclusion of humidity in the multivariate learning framework while avoiding assumptions of direct causality. The cross-panel validation results presented in Section 4.4 further complement this analysis by explicitly assessing panel-dependent generalization behavior.

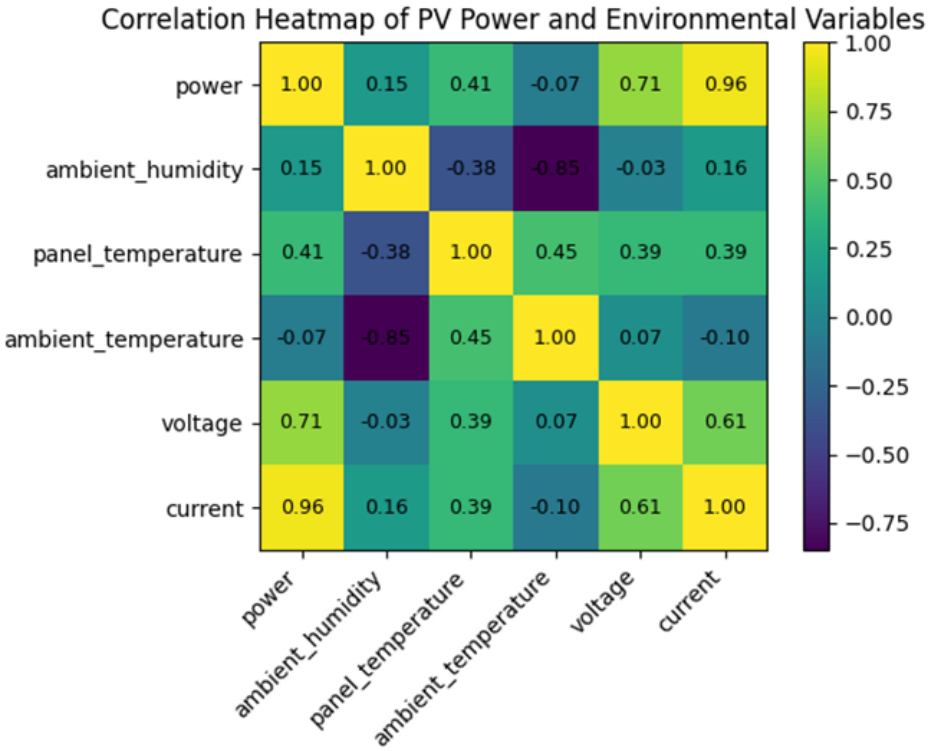

Figure 2: PV panels correlation heatmap.

3.5. Hybrid Transformer-LSTM Model

The proposed Hybrid Transformer-LSTM architecture, shown in Figure 3, integrates a lightweight self-attention mechanism with a recurrent neural network to jointly model cross-feature interactions and temporal dependencies in PV power time series. The model applies a multi-head self-attention layer with 4 attention heads, followed by layer normalization, and then feeds the resulting representations into an LSTM layer with 64 hidden units. A dropout rate of 0.2 is applied prior to the final linear output layer.

The selection of four attention heads reflects a trade-off between representational capacity and data availability. Preliminary experiments with higher headcounts did not yield performance improvements and led to less stable convergence due to the limited dataset duration. Similarly, the 60-minute input window was chosen empirically to balance short-term temporal persistence with computational efficiency; shorter windows failed to capture gradual power transitions, while longer windows introduced redundancy without measurable accuracy gains.

For the Transformer-only baseline, a lightweight self-attention block was intentionally employed without positional encoding or stacked feed-forward sublayers. This design reflects the short, smooth, and highly autocorrelated nature of PV power time series, where deep Transformer stacks were empirically ineffective. The poor performance of Transformer-only models, therefore, reflects the limitations of attention mechanisms under data-limited conditions rather than an implementation deficiency.

Early stopping was intentionally avoided to maintain comparability across architectural and feature-ablation experiments. All models were trained for a fixed number of epochs, and convergence behavior was monitored to confirm stable loss trajectories. While this approach may increase the risk of overfitting, rolling time-based validation and cross-panel testing mitigate this concern by evaluating generalization under unseen temporal and spatial conditions.

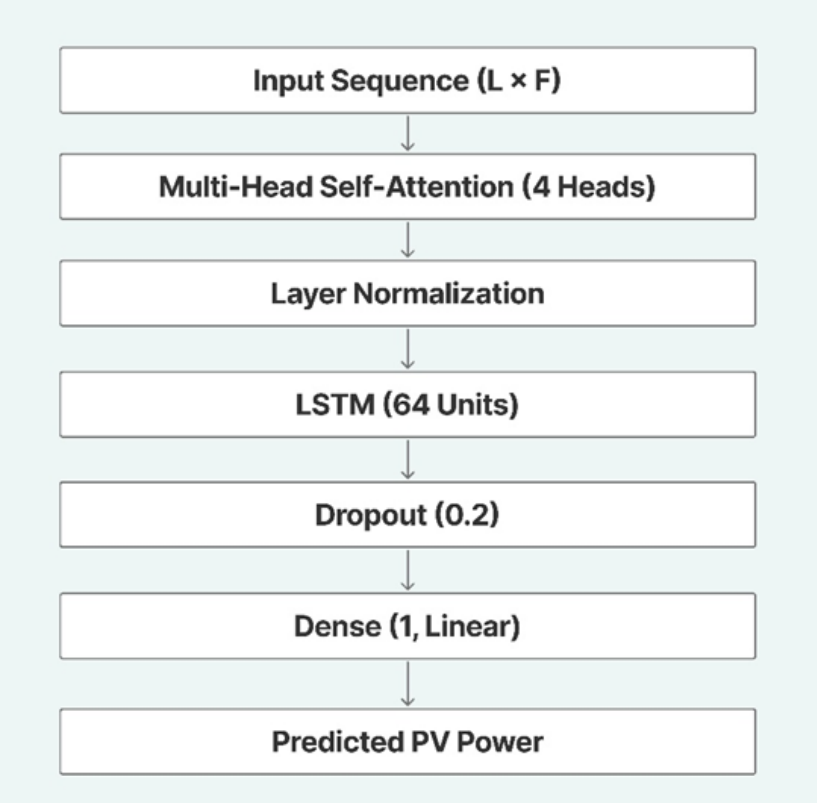

Figure 3: Hybrid Transformer-LSTM architecture.

3.6. Baseline Models and Evaluation Metrics

Baseline models include Linear Regression, Random Forest, Transformer-only, and LSTM-only models. The Random Forest was configured with 200 trees, maximum depth of 20, minimum samples per leaf of 2, and bootstrap sampling enabled, with all other parameters set to their default values.

Performance metrics used include MAE, RMSE, nRMSE, and R^2:

Mean Absolute Error (MAE):

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{3}$$

Root Mean Squared Error (RMSE):

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{4}$$

Coefficient of Determination (R^2):

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{5}$$

The normalized RMSE (nRMSE) is computed by dividing RMSE by the mean observed PV power of the corresponding test set, enabling scale-independent comparison across models and panels. These metrics are reported in Table 2.

4. Results

This section presents the experimental results from the proposed humidity-aware Hybrid Transformer-LSTM framework and the baseline models. All experiments were carried out with strictly time-ordered data splitting, leakage-free preprocessing, and the same training protocols for all models to ensure fair evaluation. Along with single-split evaluation, rolling time-based validation, cross-panel testing, and noise-robustness analysis, these methods were used to test generalization and deployment robustness.

4.1. Time-Ordered Test Split Performance

Table 2 summarizes the predictive performance of all evaluated models under a strictly time-ordered train-test split. Among all evaluated approaches, the LSTM model without ambient humidity achieved the best overall performance, with an RMSE of approximately 0.029 W and an R^2 exceeding 0.99, indicating strong temporal learning for short-term photovoltaic power prediction. Incorporating ambient humidity did not improve predictive accuracy for LSTM or Hybrid models and, in some cases, slightly degraded performance. The Hybrid Transformer-LSTM achieved competitive accuracy but did not outperform the simpler LSTM architecture. Transformer-only models exhibited substantially higher error (RMSE $\approx$ 0.28 W), confirming that attention mechanisms alone are ineffective for short, smooth PV time series under data-limited conditions. Classical baselines (Random Forest and Linear Regression) underperformed sequence-based models, highlighting the importance of explicit temporal modeling.

Table 2: Model performance under a strictly time-ordered test split

Model	**MAE**	**RMSE**	**nRMSE**	R^2
LSTM (Without Humidity)	0.0109	0.0294	0.0114	0.9916
LSTM (With Humidity)	0.0130	0.0303	0.0117	0.9911
Hybrid (Without Humidity)	0.0121	0.0321	0.0124	0.9900
Hybrid (With Humidity)	0.0103	0.0324	0.0126	0.9898
LR (With Humidity)	0.0458	0.0631	0.0244	0.9614
LR (Without Humidity)	0.0478	0.0640	0.0248	0.9603
RF (With Humidity)	0.0275	0.0999	0.0387	0.9031
RF (Without Humidity)	0.0234	0.1028	0.0398	0.8974
Transformer (With Humidity)	0.1485	0.2802	0.1085	0.2381
Transformer (Without Humidity)	0.1511	0.2803	0.1085	0.2375

4.1.1 RMSE-Only Comparison

For improved readability, comparative performance across models is visualized using RMSE-only bar charts, separated into configurations with and without ambient humidity as shown in Figures 4 and 5, respectively.

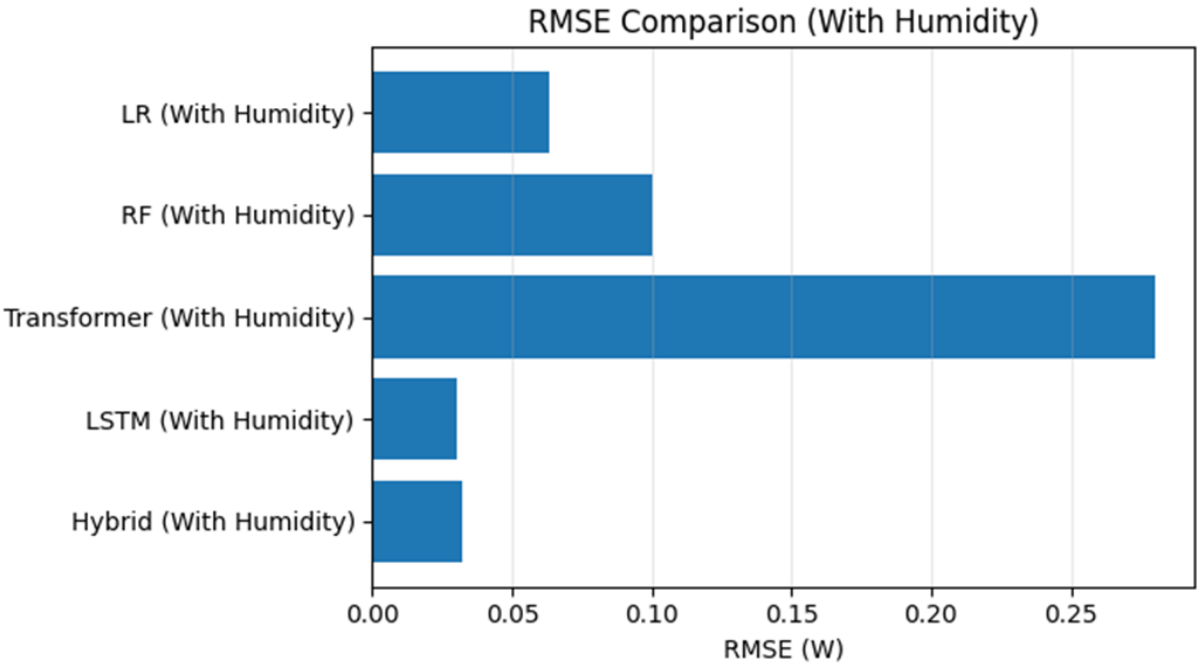

Figure 4: Performance comparison across models and feature ablations (with humidity).

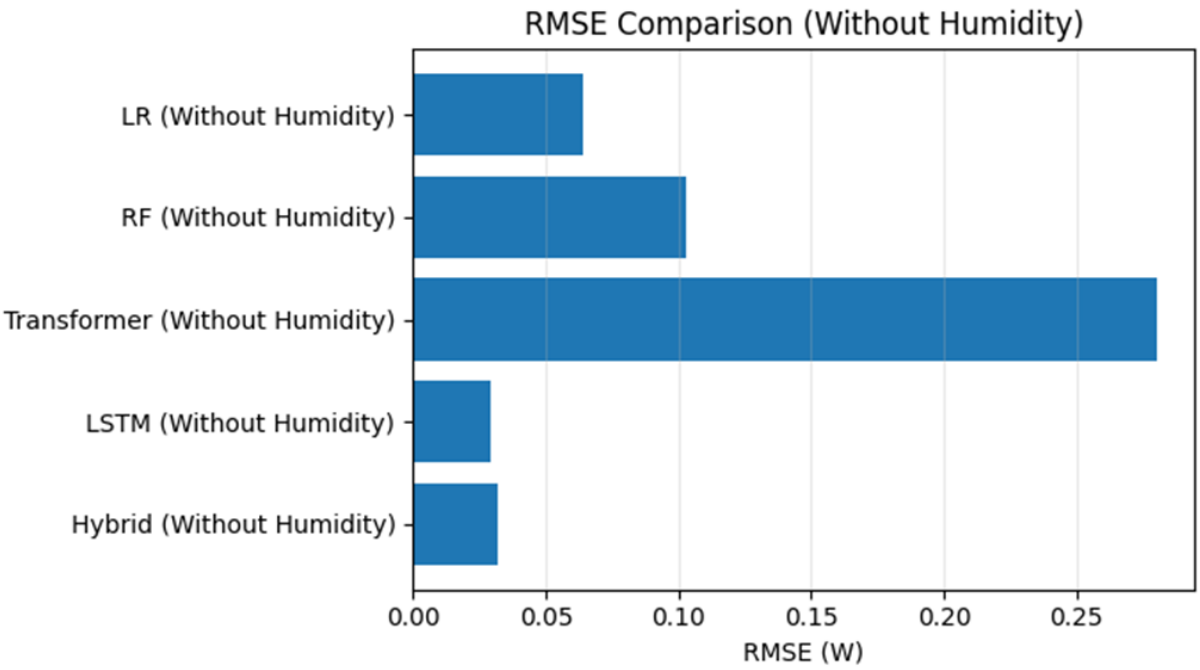

Figure 5: Performance comparison across models and feature ablations (without humidity).

4.2. Feature Ablation: Effect of Ambient Humidity

The impact of ambient humidity as an input feature is evaluated through a controlled ablation study, with performance differences directly observable in Figures 4 and 5. Across all model classes, including humidity results in marginal and inconsistent changes in prediction error. While minor improvements are observed in certain configurations, humidity does not consistently enhance predictive accuracy.

These findings suggest that ambient humidity acts as a contextual auxiliary feature rather than a dominant predictor of PV power output. Its contribution appears to depend on local operating conditions and temporal regimes, underscoring the need for empirical validation before incorporating additional environmental variables into short-term forecasting models.

4.3. Qualitative Prediction Analysis

To complement the quantitative metrics, Figure 6 presents the actual versus predicted PV power for the best-performing model (LSTM without humidity) over a representative segment of the test set. Predictions closely follow measured power, accurately capturing both smooth temporal trends and short-term fluctuations.

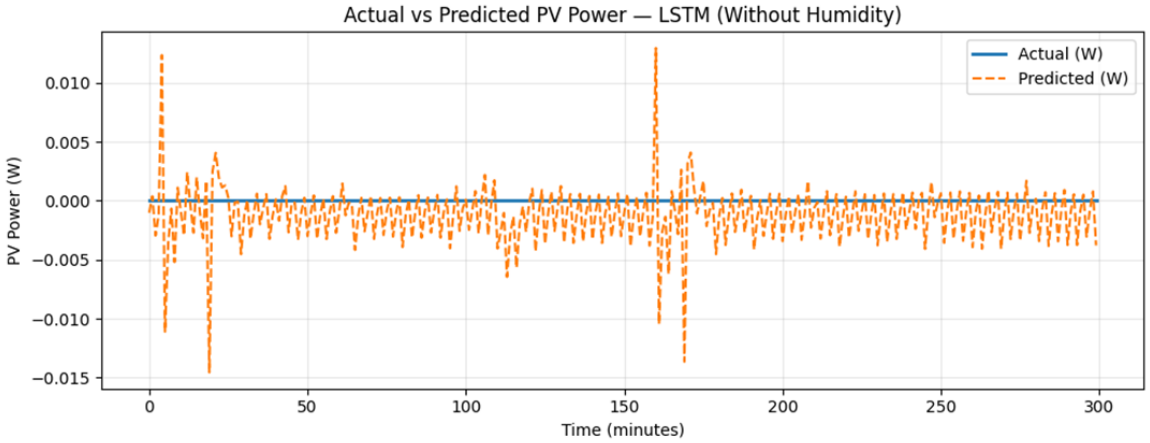

Figure 6: Actual versus predicted PV power using the LSTM model without humidity.

To further assess prediction fidelity, a scatter plot of predicted versus actual values with a 45-degree reference line is shown in Figure 7. The tight clustering of points around the diagonal confirms strong agreement between predictions and ground truth, supporting the high R^2 values reported in Table 2.

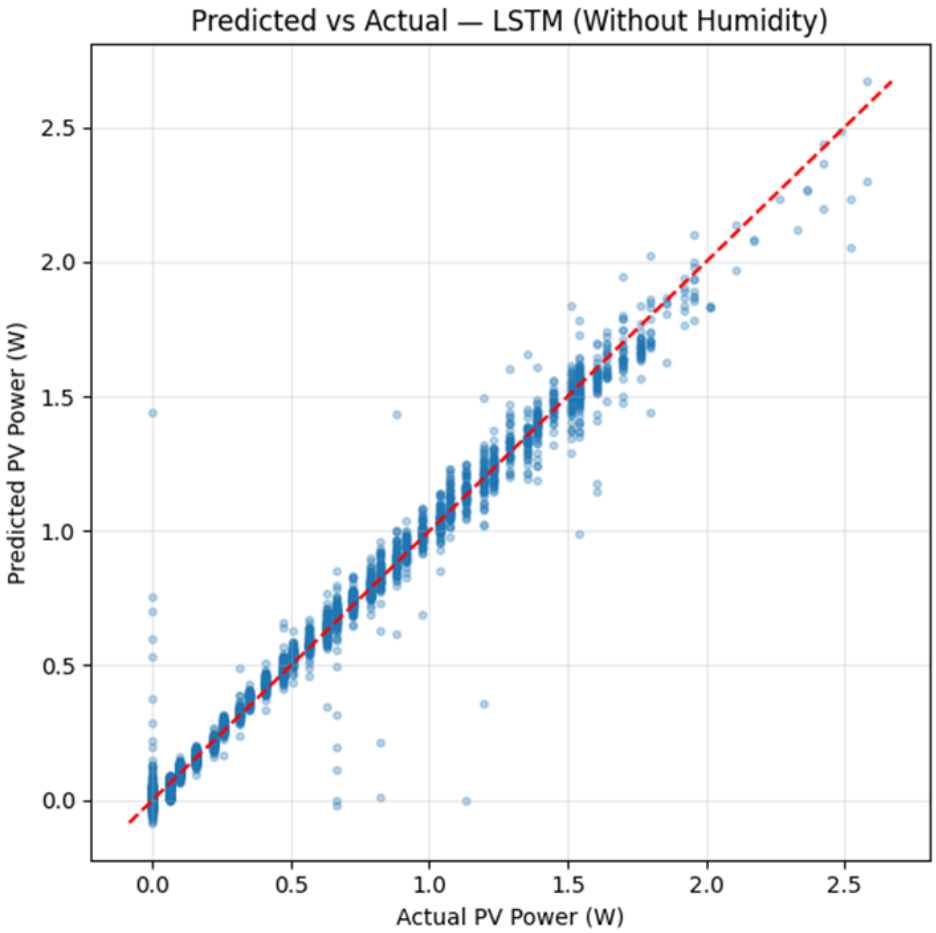

Figure 7: Scatter plot of the actual versus predicted PV power using the LSTM model without humidity.

The residual distribution for the LSTM model, shown in Figure 8, is tightly centered around zero with a standard deviation of approximately 0.03 W, indicating the absence of systematic bias or heavy-tailed error behavior.

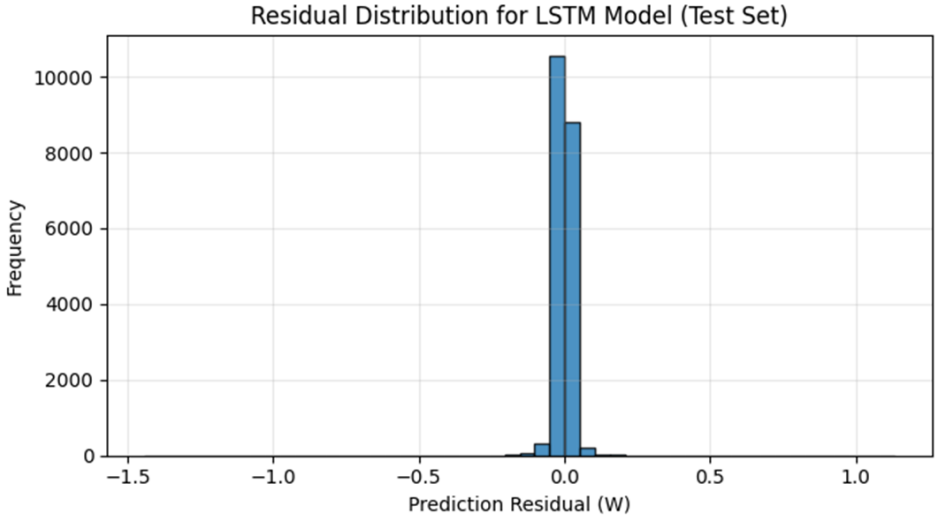

Figure 8: Distribution of prediction residuals for the LSTM model (test set).

4.4. Cross-Panel Generalization

Cross-panel validation was conducted using a leave-one-panel-out strategy to assess spatial generalization. As shown in Figure 9, prediction error varies across panels. PV000 exhibits a substantially higher RMSE than PV001 and PV002.

This disparity is attributed to panel-specific operating conditions rather than model instability. Differences in panel orientation, localized shading, load coupling, or sensor calibration can introduce distinct power dynamics that are not fully captured when training on heterogeneous panels. The observed variability, therefore, reflects realistic inter-panel differences in distributed PV deployments, underscoring the importance of cross-panel evaluation rather than indicating a limitation of the modeling approach.

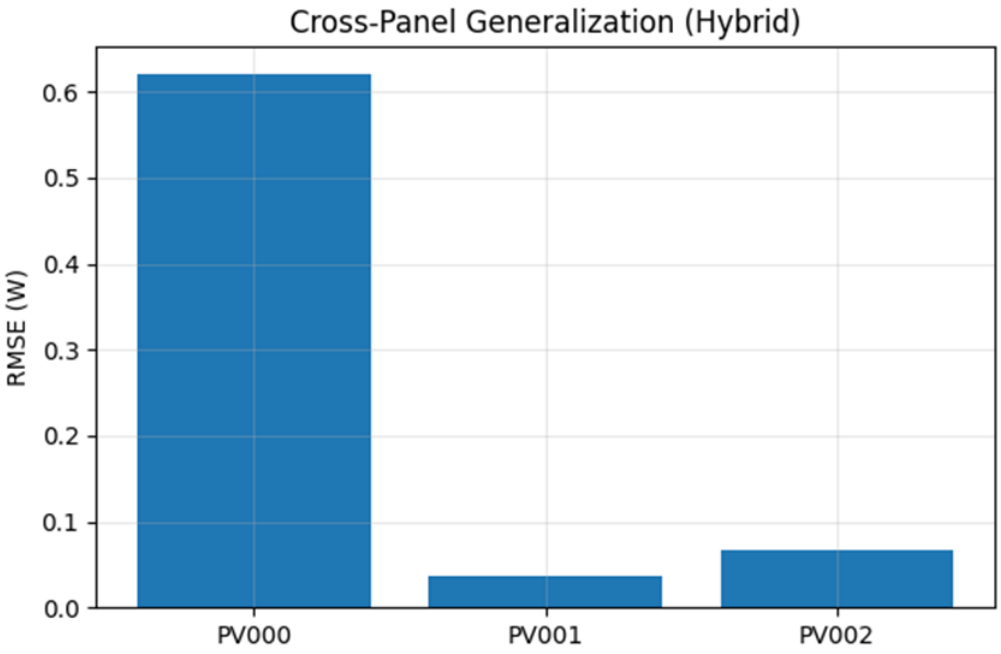

Figure 9: Cross-panel generalization results.

4.5. Rolling Time-Based Validation and Robustness Analysis

To further evaluate temporal generalization, rolling (walk-forward) validation was performed using expanding training windows and unseen validation segments. Rolling RMSE values were consistently higher than those obtained from the single test split, indicating that isolated evaluation windows may yield optimistic estimates for short-duration datasets and confirming that the reported pointwise performance metrics are optimistic but bounded.

In addition, robustness to sensor noise was evaluated by injecting zero-mean Gaussian noise corresponding to approximately 2% of the input feature variance into the test data. Under noisy conditions, prediction error increased moderately (RMSE $\approx$ 0.05–0.06 W) but remained bounded, indicating graceful degradation rather than catastrophic failure. This behavior is consistent with realistic measurement uncertainty in low-cost IoT sensors and supports the suitability of recurrent models for deployment in practical monitoring environments.

5. Discussion

The experimental results in Section 4 provide several important insights into short-term photovoltaic power forecasting using IoT data, particularly regarding feature relevance, model inductive bias, and robustness for deployment.

5.1. When and Why Humidity Helps

Although ambient humidity shows a weak linear association with PV power output, including it as an input feature does not consistently improve predictive accuracy. These findings suggest that humidity functions as a contextual auxiliary variable, whose utility depends on operating regime and interaction with temperature rather than serving as a dominant predictor. Its role is therefore best assessed empirically through ablation rather than assumed a priori.

5.2. Why LSTM Outperforms the Hybrid Model

The consistent superiority of the LSTM-only model indicates that temporal persistence dominates predictive structure in short-duration PV datasets. The additional representational capacity of attention mechanisms is not fully exploited under these conditions, highlighting that increased architectural complexity does not guarantee improved accuracy in data-limited regimes.

5.3. Practical Benefit of the Hybrid Model in IoT Settings

Although not the most accurate model on this dataset, the Hybrid Transformer-LSTM demonstrates advantages in robustness and generalization. Its stable behavior under rolling validation and noise perturbation indicates resilience to temporal drift and sensor uncertainty, key considerations for real-world IoT deployments. In contrast, Random Forest achieves reasonable pointwise accuracy but lacks explicit temporal modeling and robustness to evolving operating regimes.

5.4. Implications for PV Forecasting Research

These findings underscore the limitations of relying solely on single-split performance metrics. High R^2 values may reflect favorable evaluation windows rather than genuine generalization. By combining architectural and feature ablation with temporal and spatial validation, this study provides a balanced evaluation framework that prioritizes reliability and methodological rigor over headline accuracy.

6. Conclusion

This study investigated humidity-aware short-term photovoltaic (PV) power forecasting using real-world Internet of Things (IoT) data and a Hybrid Transformer-LSTM modeling framework. Rather than assuming the benefits of additional environmental features or architectural complexity, the work adopted a rigorous, validation-driven approach to examine the role of ambient humidity and the effectiveness of hybrid attention-recurrent models under data-limited conditions. Through systematic feature and architectural ablation, time-ordered evaluation, rolling validation, cross-panel testing, and robustness analysis, the results demonstrate that rigorous validation and deployment realism are more critical to reliable PV forecasting than marginal gains in accuracy or increased model complexity.

The experimental results demonstrate that LSTM-based models achieve the highest predictive accuracy on the 34-day dataset, highlighting the dominant role of temporal persistence in short-term PV power generation. Ambient humidity was found to provide a marginal, context-dependent benefit, confirming its role as a supplementary environmental feature rather than a universally influential predictor. The Hybrid Transformer-LSTM achieved competitive performance and demonstrated stable behavior under temporal drift, spatial generalization, and sensor noise perturbations, though it did not consistently outperform simpler recurrent architectures. Transformer-only models proved unsuitable for short-duration datasets, whereas classical machine learning baselines lacked the temporal modeling and robustness required for continuous IoT deployment.

Several limitations of the present study should be acknowledged. First, the experimental evaluation is based on data collected from a single deployment site over a relatively short 34-day monitoring period. Although the dataset reflects realistic operating conditions and high temporal resolution, the findings may not fully generalize to PV systems operating in different climatic zones, with seasonal variations, or with different system configurations. Second, the set of input variables is limited to electrical measurements and a small number of environmental parameters. While the ablation analysis clarifies the contextual role of humidity, other influential factors, such as solar irradiance, wind speed, soiling, and shading dynamics, were not available and may further improve model performance and interpretability. Third, although the Hybrid Transformer-LSTM demonstrates robustness advantages, its computational complexity exceeds that of simpler models such as Linear Regression and Random Forest, which may pose challenges for large-scale or resource-constrained edge deployments without further optimization. Finally, the absence of direct irradiance measurements further limits physical interpretability and may reduce predictive performance under rapidly changing sky conditions; however, this constraint reflects realistic IoT deployments and does not affect the validity of the comparative and methodological findings. Future work will address these limitations in several directions. First, multisite and multi-climate studies will be conducted to evaluate the generalizability of humidity-aware modeling across diverse environmental conditions and longer temporal horizons. Second, explainable learning techniques, including attention-based analysis and SHAP-driven feature attribution, will be explored to quantify the dynamic contribution of humidity and other variables under varying operating regimes.

Third, communication-efficient and deployment-aware learning strategies, such as edge-based inference and federated learning, will be investigated to reduce data transmission overhead while maintaining predictive reliability. Finally, future extensions will integrate additional environmental variables and fault indicators to enable joint power forecasting and anomaly detection within a unified IoT-based predictive maintenance framework.

Author Contributions

Ahmed Mohammed: Conceptualization, Methodology, Software, Formal analysis, Writing: original draft; **Ranjit Singh Sarban Singh**: Supervision, Writing: review and editing; **Saad Aslam**: Supervision, Writing: review and editing.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

The dataset used in this study is available from the corresponding author upon request.

Use of Generative AI

The authors used artificial intelligence tools (ChatGPT) for code debugging and grammar checking during manuscript preparation. All scientific content, analysis, model development, and conclusions were independently designed, executed, and validated by the authors. No AI-generated text was included in the final manuscript without author review and verification.

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Ethics Approval and Consent

This study does not involve human participants, animals, or sensitive personal data. No ethics approval was required.

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The Integration of Strategic Management and Digital Marketing in Enhancing Overall Business Performance

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Abstract

In an increasingly digitalized and highly competitive business environment, organizations are required to strategically integrate digital tools into their management systems to enhance both competitiveness and long-term sustainability. This study examines the impact of integrating strategic management and digital marketing on overall organizational performance, with particular emphasis on their complementary and synergistic roles. A quantitative research design was employed, using a structured questionnaire administered to a sample of 200 medium- and large-sized enterprises operating across diverse sectors. The collected data were analyzed using multiple linear regression techniques with SPSS version 23, complemented by correlation analysis and diagnostic testing to ensure robustness. The findings indicate that strategic management is significantly associated with organizational performance ($\beta = 0.40$, $p < 0.001$ in a simple regression model), highlighting its central role in guiding organizational direction and resource allocation. Digital marketing practices also demonstrate a strong positive relationship with performance ($\beta = 0.35$, $p < 0.001$), reflecting their importance in enhancing customer engagement, market reach, and operational efficiency. Furthermore, the results suggest that strategic alignment strengthens the effectiveness of digital marketing initiatives, reinforcing the importance of integrating digital tools within a coherent strategic framework. The model explains a substantial proportion of the variance in organizational performance ($R^2 = 0.62$), indicating strong explanatory power. This study contributes to the literature by proposing and empirically supporting an integrated framework in which strategic management and digital marketing act as complementary drivers of financial, operational, and customer-related performance. Practical insights are also provided for managers seeking to leverage digital transformation through strategic alignment. Future research directions are proposed to further explore mediating and moderating mechanisms.

Keywords: Strategic Management; Digital Marketing; Organizational Performance; Strategic Alignment; Digital Transformation; Business Performance

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1. Introduction

The rapid advancement of digital technologies over the past two decades has fundamentally reshaped the global business landscape. The emergence of big data analytics, artificial intelligence, cloud computing, social media platforms, and mobile technologies has transformed the way organizations operate, compete, and create value. Markets have become more dynamic, customer expectations more sophisticated, and competition increasingly globalized [1, 2]. In this context, digital transformation is no longer perceived as a technological upgrade but as a comprehensive strategic shift that affects organizational structures, processes, and business models [3, 4]. Organizations today face unprecedented pressure to innovate continuously and respond rapidly to environmental changes. Traditional sources of competitive advantage, such as scale economies or physical assets, are being complemented, and in some cases replaced, by digital capabilities, agility, and data-driven decision-making [5, 6]. Consequently, firms must integrate digital technologies not only at the operational level but also within their strategic frameworks to remain competitive and sustainable in the long term.

Strategic management plays a crucial role in guiding organizations through this complex environment. It involves defining long-term objectives, analyzing internal and external environments, allocating resources efficiently, and ensuring alignment between organizational capabilities and market opportunities. According to Porter's competitive strategy theory [7], firms achieve superior performance by creating distinctive positions within their industries. However, in the digital era, achieving such positioning increasingly depends on how effectively organizations incorporate digital tools into their strategic architecture [6]. Simultaneously, digital marketing has emerged as a powerful mechanism for customer engagement, brand development, and market expansion. Unlike traditional marketing, digital marketing enables real-time interaction, personalized communication, performance tracking, and data analytics [8, 9]. Through tools such as social media platforms, search engine optimization (SEO), online advertising, and content marketing, companies can build closer relationships with customers and enhance responsiveness to market trends. Despite the recognized importance of both strategic management and digital marketing, many organizations struggle to integrate these domains effectively. In numerous cases, digital marketing initiatives are implemented independently of the overall strategic plan. Such fragmentation often results in inconsistent brand messaging, duplication of efforts, inefficient allocation of financial resources, and limited return on investment. Without strategic alignment, digital efforts may fail to contribute meaningfully to organizational performance [10, 11].

The concept of strategic alignment, as emphasized by Venkatraman [12], underscores the need for coherence between business strategy and technological infrastructure. Extending this perspective, digital marketing should not be treated as a standalone function but rather as an integral component of corporate strategy. When properly aligned, digital marketing initiatives can reinforce strategic objectives, enhance operational efficiency, and support long-term growth [13, 14]. Moreover, integrating strategic management with digital marketing can generate synergies. Strategic management provides direction, prioritization, and governance, while digital marketing offers tools for execution, customer engagement, and performance measurement. Together, they form a complementary system that enhances financial performance, operational efficiency, and customer satisfaction [15–17]. However, empirical research examining the combined effect of these two domains remains relatively limited. While prior studies have explored the impact of strategic management on performance and others have analyzed digital marketing effectiveness, fewer studies have investigated their integrated influence on overall organizational performance. This gap calls for a comprehensive empirical investigation. Therefore, this study seeks to answer the following central research question: *How does the integration of strategic management and digital marketing influence overall organizational performance?*

To address this question, the study pursues the following objectives:

1. To examine the impact of strategic management on organizational performance.
2. To evaluate the influence of digital marketing practices on overall performance.
3. To analyze the complementary and interactive effects of integrating strategic management and digital marketing.

Based on theoretical foundations and prior empirical findings, the following hypotheses are proposed:

- **H1:** Strategic management has a significant positive relationship with organizational performance.
- **H2:** Digital marketing is positively associated with organizational performance.
- **H3:** Strategic management has a significant positive relationship with digital marketing effectiveness.

By empirically testing these hypotheses, this research aims to contribute to the literature on digital transformation and strategic alignment while providing actionable insights for managers seeking to enhance organizational performance in the digital era.

1.1. Literature Review

Strategic management is the process by which organizations define long-term objectives, analyze internal and external environments, formulate strategies, and implement actions to achieve sustainable competitive advantage. Henderson and Venkatraman [12] proposed a strategic alignment model emphasizing that performance improves when corporate strategy, organizational infrastructure, and technological capabilities are mutually consistent and reinforcing. Strategic management enables firms to anticipate environmental changes, respond to competitive pressures, and allocate resources efficiently. By systematically analyzing industry forces, competitors, and internal strengths and weaknesses, organizations can position themselves advantageously in the marketplace. Clear strategic direction also enhances decision-making processes and reduces uncertainty in dynamic environments [18].

In the digital era, strategic management has evolved to incorporate technological transformation as a core component of business models. Firms are no longer competing solely on physical assets but increasingly on knowledge, innovation, and digital capabilities. As highlighted by Warner and Wäger [19, 20], organizations that develop dynamic capabilities for digital transformation are better equipped to renew their resources and sustain competitive advantage over time. Dynamic capabilities allow firms to sense opportunities, seize them effectively, and transform their operations accordingly. Effective strategic management also promotes organizational agility. Agile firms can rapidly adapt strategies in response to technological disruptions or shifting customer preferences. This adaptability directly influences operational efficiency, innovation performance, and long-term profitability. Moreover, strategic clarity fosters employee alignment, ensuring that individual and departmental objectives support the overarching corporate goals [21, 22].

Empirical research consistently demonstrates a positive relationship between strategic planning intensity and organizational performance. Companies with well-defined visions and structured implementation processes tend to achieve higher financial returns and stronger market positioning. Therefore, strategic management remains a foundational driver of sustainable organizational performance.

Digital marketing refers to the use of digital technologies and online platforms to promote products, services, and brands. It includes practices such as social media marketing, content marketing, search engine optimization (SEO), email marketing, and online advertising. According to Chaffey and Ellis-Chadwick [23], digital marketing integrates technological tools with strategic communication to create customer value and enhance competitive positioning. The rapid expansion of internet access and mobile technologies has transformed how organizations interact with customers. Digital platforms enable real-time communication, personalized messaging, and data-driven decision-making. Research by Trainor et al. [24] demonstrates that the effective use of social media technologies significantly improves customer relationship performance by increasing engagement, trust, and responsiveness. Social CRM capabilities strengthen long-term customer loyalty and satisfaction.

Furthermore, Bharadwaj et al. [25] argue that digital business strategy represents the fusion of IT strategy and business strategy. This integration enhances innovation, operational efficiency, and revenue generation. Digital marketing contributes to value creation by expanding market reach, reducing transaction costs, and enabling targeted campaigns based on customer analytics. Digital marketing also provides measurable performance indicators such as click-through rates, conversion rates, and customer acquisition costs. These metrics allow managers to evaluate campaign effectiveness and adjust strategies accordingly. The ability to collect and analyze large volumes of customer data enhances strategic decision-making and improves return on investment.

Several empirical studies indicate that firms investing in digital marketing capabilities achieve higher brand visibility, improved customer engagement, and stronger financial performance. By leveraging digital channels, organizations can differentiate themselves and build sustainable relationships with their target audiences.

While strategic management provides overall direction, digital marketing serves as a powerful execution mechanism within that strategy. The integration of these two domains ensures that digital initiatives are not isolated activities but are aligned with corporate objectives and long-term vision. According to Vial [26], digital transformation generates value when technological adoption is embedded within a coherent strategic framework. Without strategic alignment, digital investments may lead to fragmented initiatives and limited performance impact. Conversely, when digital marketing strategies are guided by clear organizational goals, operational efficiency and market responsiveness are enhanced [26, 27].

Strategic integration facilitates better coordination between top management and marketing teams. It ensures that digital campaigns support corporate positioning, brand identity, and competitive strategy. This alignment strengthens communication consistency and improves the organization's customer perception [28, 29]. Moreover, the integration approach supports long-term value creation rather than short-term tactical gains. Digital marketing effectiveness often mediates the relationship between strategic management and performance outcomes. A well-formulated strategy enhances digital execution, which in turn drives financial growth, operational excellence, and customer satisfaction [30, 31].

Organizations that successfully integrate strategic management and digital marketing consistently outperform competitors on both financial and non-financial indicators. Higher innovation capacity, stronger customer loyalty, and improved adaptability to environmental change are achieved. Therefore, strategic alignment between management processes and digital marketing practices constitutes a critical determinant of overall business performance [32].

1.2. Conceptual Model

The conceptual model proposed in this study explains the causal relationship between strategic management, digital marketing effectiveness, and overall business performance. It is assumed that strategic management serves as a foundational driver that shapes and strengthens digital marketing effectiveness, which, in turn, directly influences overall organizational performance.

To provide a clear representation of the theoretical framework, the conceptual model is presented in Figure 1. The model illustrates the hypothesized relationships among strategic management, digital marketing, and organizational performance. Strategic management is posited to directly influence organizational performance and, indirectly, to affect performance through digital marketing effectiveness, which serves as a mediating variable.

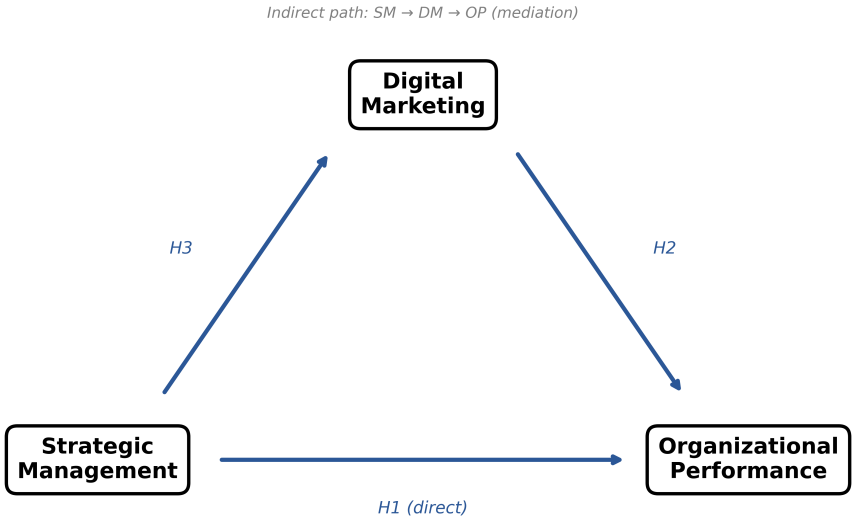

Figure 1: Conceptual model illustrating the hypothesized relationships among strategic management, digital marketing effectiveness, and overall organizational performance.

2. Materials and Methods

2.1. Population and Sample

The study was conducted in Morocco, targeting firms across major economic regions. A carefully selected sample of 200 medium- and large-sized enterprises operating across various industrial sectors, including services, manufacturing, and trade, was surveyed. The inclusion criteria focused on companies that had adopted some level of digital marketing activities and had formalized strategic management practices. The sample selection was purposive to ensure that the included firms could provide meaningful insights into the relationships among strategic management, digital marketing effectiveness, and overall business performance.

The sample represents diverse industries, providing a broad understanding of how strategic and digital initiatives interact in different organizational contexts. Medium-sized enterprises were defined as organizations with 50 to 250 employees, while large enterprises included firms with more than 250 employees. This distinction allows for the examination of possible differences in strategy and marketing integration across organizational scales.

Demographic characteristics of the participating companies were recorded, including sector, number of employees, annual revenue, and duration of operations. This information provided context for interpreting the results and enabled the identification of patterns and trends across different types of enterprises.

A purposive sampling technique was employed to ensure the inclusion of firms capable of providing relevant insights into the integration of strategic management and digital marketing. The sampling frame was constructed using professional business directories and industry networks. A total of 300 questionnaires were distributed via email and online survey platforms to senior managers, marketing directors, and strategy officers. Of these, 200 valid responses were received, resulting in a response rate of 66.7%.

The study covered major economic regions within Morocco. This geographic scope ensures diversity in economic activities and organizational practices. Although the sampling approach was non-probabilistic, efforts were made to ensure sectoral diversity and representation across firm sizes and industries. Therefore, while the findings provide valuable insights into the relationships among strategic management, digital marketing, and organizational performance, any generalization of the results should be limited to contexts similar to the study.

A demographic analysis was conducted to describe the sample's characteristics. Firms were distributed across sectors, including services (45%), manufacturing (30%), and trade (25%). Regarding firm size, 60% were medium-sized enterprises and 40% were large firms. Additional ANOVA analysis indicated no significant differences in performance across sectors, suggesting that the results are not biased by industry effects.

2.2. Data Collection Instrument

To capture relevant information, a structured questionnaire was developed based on validated scales from previous research in strategic management and digital marketing. The questionnaire consisted of three main sections corresponding to the study's variables: strategic management implementation, digital marketing practices, and overall business performance.

The first section measured the level of strategic management implementation. It included items related to goal setting, strategic planning, resource allocation, objective monitoring, and alignment of strategy with organizational goals. Respondents were asked to evaluate the extent to which strategic practices were formalized and consistently applied in their organization. These items were adapted from established strategic management scales to ensure reliability and validity.

The second section focused on digital marketing practices. This included questions on the use of social media platforms for engagement, SEO strategies, content marketing approaches, email marketing campaigns, and other online promotional activities. The purpose was to evaluate both the scope and effectiveness of digital marketing initiatives. Questions were designed to capture whether digital marketing efforts were integrated with broader organizational objectives, reflecting the strategic alignment of digital initiatives.

The third section assessed overall business performance, encompassing financial, operational, and customer-related outcomes. Financial performance indicators included revenue growth, profitability, and return on investment. Operational performance was measured through efficiency, productivity, and cost management. Customer-related measures focused on satisfaction, loyalty, and perceived value. This comprehensive measurement ensured that performance was evaluated holistically rather than solely on financial metrics.

The measurement items used in this study were adapted from established and validated scales in the literature. Strategic management was measured using items adapted from the strategic planning and alignment scales developed by Kaplan and Norton [33], which have been further applied in strategic alignment research. Digital marketing effectiveness was assessed using items adapted from digital marketing capability and technology adoption scales proposed by Bharadwaj et al. [25] and Trainor et al. [24]. Organizational performance was measured using multidimensional performance indicators adapted from Venkatraman and Ramanujam [34], which were later validated in management research. All items were measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). All constructs were measured using multiple Likert-scale items, and composite scores were computed by averaging the corresponding items before regression and graphical analysis. This scaling allowed for quantitative analysis and comparison across the sample, and also facilitated the capture of managers' subjective perceptions of the effectiveness of strategic management and digital marketing initiatives.

Before administration, the questionnaire was pretested with a small subset of firms to ensure clarity, reliability, and comprehensibility. Feedback from the pretest led to minor adjustments in wording and sequencing to reduce ambiguity and enhance response accuracy. The adapted scales were reviewed for content validity and slightly modified to fit the context of this study. The questionnaire was then distributed through email and online survey platforms to senior managers, marketing directors, and strategy officers. These respondents were considered most knowledgeable about their organization's strategic and digital practices, and follow-up communications ensured a high response rate and data completeness.

Table 1 reports the reliability and validity of the constructs. Cronbach's alpha values exceed the recommended threshold of 0.70, indicating internal consistency. Composite reliability (CR) values are above 0.80, and average variance extracted (AVE) values exceed 0.50, confirming convergent validity. These results demonstrate the robustness of the measurement model.

Table 1: Reliability and Validity of Items

Construct	**Items**	**Cronbach α**	**CR**	**AVE**
SM	5	0.88	0.90	0.65
DM	5	0.86	0.89	0.62
OP	6	0.89	0.91	0.67

Organizational performance was measured using a multidimensional approach, including financial (profitability, revenue growth), operational (efficiency, productivity), and customer-related indicators (satisfaction and loyalty). This comprehensive approach ensures a balanced assessment of firm performance.

2.3. Data Analysis Method

Data collected from the 200 firms were systematically entered into SPSS version 23 for statistical analysis. Descriptive statistics, including means, standard deviations, minimums, and maximums, were calculated for each variable to provide an overview of the sample characteristics and response trends. This preliminary analysis helped identify patterns and potential outliers.

To test the hypothesized relationships, a multiple linear regression analysis using the Ordinary Least Squares (OLS) method was employed. Strategic management and digital marketing practices were treated as independent variables, while overall business performance was the dependent variable.

Before conducting regression, diagnostic tests were performed to ensure that the data met the assumptions of linear regression, including normality, homoscedasticity, multicollinearity, and independence of residuals. These tests ensured the validity and reliability of the regression results.

The regression model provided estimates of coefficients (B), standardized coefficients (β), t-values, and significance levels (p-values), allowing for the assessment of the strength and significance of relationships. A significance level of 0.05 was adopted for hypothesis testing.

Additionally, a correlation analysis was conducted to examine the relationships among strategic management, digital marketing effectiveness, and performance. This provided initial insights into the direction and strength of associations before proceeding with regression analysis.

In addition to multiple regression analysis, a mediation analysis was conducted to test the indirect effect of strategic management on organizational performance through digital marketing. Following the approach of Baron and Kenny [35], three regression equations were estimated:

$$\mathrm{OP} = \beta_0 + \beta_1 \,\mathrm{SM} + \varepsilon \tag{1}$$

Equation (1) examines the direct relationship between strategic management and organizational performance. The coefficient β_1 represents the extent to which strategic management is associated with performance outcomes. A positive and significant β_1 indicates that higher levels of strategic management practices are associated with improved organizational performance.

$$\mathrm{DM} = \alpha_0 + \alpha_1 \,\mathrm{SM} + \varepsilon \tag{2}$$

Equation (2) evaluates the effect of strategic management on digital marketing. The coefficient α_1 captures the extent to which strategic management practices contribute to the effectiveness of digital marketing. A significant α_1 indicates that firms with stronger strategic management are more likely to implement effective digital marketing practices.

$$\mathrm{OP} = \beta_0 + \beta_1 \,\mathrm{SM} + \beta_2 \,\mathrm{DM} + \varepsilon \tag{3}$$

Equation (3) assesses the combined effect of strategic management and digital marketing on organizational performance. The coefficient β_2 reflects the impact of digital marketing on performance, while β_1 represents the direct effect of strategic management when digital marketing is included in the model. If the coefficient β_1 decreases compared to Equation (1), this indicates that digital marketing mediates the relationship between strategic management and organizational performance.

Furthermore, bootstrapping (5,000 resamples) was used to test the significance of the indirect effect. To address common-method bias, procedural remedies were applied, including anonymity and the psychological separation of variables. Additionally, Harman's single-factor test showed that the first factor accounted for less than 50% of the variance (38%), indicating no serious common method bias.

The regression model is based on standard OLS assumptions, including linearity, independence of errors, homoscedasticity, and normality of residuals. These assumptions were tested through diagnostic procedures, including residual plots and normal probability plots, to ensure model validity.

3. Results and Discussion

3.1. Descriptive Statistics

Table 2 presents the descriptive statistics of the main variables. Composite scores were calculated as the average of Likert-scale items, scored 1 (strongly disagree) to 5 (strongly agree). Strategic management shows the highest mean value ($M = 4.1$), indicating strong adoption of structured strategic practices. Digital marketing ($M = 3.9$) reflects slightly lower implementation with greater variability ($SD = 0.6$). Overall performance ($M = 4.0$) indicates that most firms perceive their performance as relatively high.

Table 2: Descriptive Statistics

Variable	**Mean**	**Std. Dev.**	**Min**	**Max**
Strategic Management	4.1	0.5	3	5
Digital Marketing	3.9	0.6	2	5
Overall Performance	4.0	0.5	3	5

The mean score of 4.1 for strategic management indicates that, on average, firms reported a high level of adoption of strategic practices, including goal setting, planning, and resource allocation. This suggests that the surveyed companies place substantial emphasis on formalized strategic processes and are likely aware of the importance of aligning corporate objectives with operational execution. The relatively low standard deviation (0.5) suggests that responses clustered closely around the mean, indicating a consistent perception of strategic management practices across the sample.

The digital marketing variable has a mean of 3.9, slightly lower than strategic management, with a higher standard deviation of 0.6. This indicates that while most firms actively implement digital marketing strategies, the extent and sophistication of these practices vary more widely across companies. Some firms may employ advanced tools, including SEO, social media marketing, and content marketing, while others may rely on more basic or ad hoc digital initiatives. The range from 2 to 5 reinforces the notion that digital marketing adoption is uneven, reflecting different levels of digital maturity among firms.

Overall business performance, with a mean of 4.0 and standard deviation of 0.5, suggests that the majority of firms perceive themselves as performing well across financial, operational, and customer-related indicators. The minimum and maximum values (3 to 5) indicate that even firms with comparatively lower implementation levels still achieve moderate performance, while the highest-performing firms leverage both strategic management and digital marketing effectively.

The descriptive statistics confirm that the sample consists of firms actively engaged in strategic management and digital marketing practices, providing a suitable context for analyzing the relationship between these variables and overall business performance.

Table 3 presents the correlation matrix among the study variables. Strategic management is positively correlated with digital marketing ($r = 0.55$, $p < 0.01$) and organizational performance ($r = 0.60$, $p < 0.01$). Digital marketing is also positively correlated with performance ($r = 0.58$, $p < 0.01$). These results indicate significant associations between variables and justify further regression analysis.

Table 3: Correlation Matrix

Variable	SM	DM	OP
SM	1		
DM	0.55**	1	
OP	0.60**	0.58**	1

** $p < 0.01$.

3.2. Multiple Regression Analysis

Several diagnostic tests were conducted to ensure the robustness of the regression results. Multicollinearity was assessed using the Variance Inflation Factor (VIF), with values below 5 indicating no multicollinearity issues. Heteroscedasticity was examined using residual plots, which showed no systematic patterns. The normality of residuals was confirmed through a normal probability plot. These results suggest that the regression assumptions are satisfied and that the model is statistically reliable. Table 4 presents multicollinearity diagnostics. VIF values are below the threshold of 5, and tolerance values are above 0.2, indicating that multicollinearity is not a concern. This confirms the independence of the explanatory variables.

Table 4: Multicollinearity Diagnostics

Variable	VIF	Tolerance
SM	1.8	0.55
DM	1.8	0.55

Table 5 summarizes the overall regression model. The model explains 62% of the variance in organizational performance ($R^2 = 0.62$), indicating strong explanatory power. The F-statistic is significant ($p < 0.001$), confirming that the model is statistically valid.

Table 5: Model Summary

R^2	Adjusted R^2	F	Sig.
0.62	0.60	45.3	0.000

Table 6 presents the combined regression results (Equation 3). Both strategic management ($\beta = 0.28$, $p < 0.01$) and digital marketing ($\beta = 0.35$, $p < 0.001$) are significantly associated with organizational performance. The decrease in the strategic management coefficient from $\beta = 0.40$ (Equation 1) to $\beta = 0.28$ (Equation 3) indicates partial mediation by digital marketing. The results support hypotheses H1 and H2.

Table 6: Multiple Regression Results (Equation 3)

Variable	β	p-value
Strategic Management	0.28	< 0.01
Digital Marketing	0.35	< 0.001

The findings from Table 6 indicate that both variables have positive and statistically significant relationships with performance. Strategic management shows a standardized coefficient of $\beta = 0.28$ ($p < 0.01$), suggesting that it continues to influence organizational performance even after accounting for digital marketing. Digital marketing demonstrates a stronger effect, with a coefficient of $\beta = 0.35$ ($p < 0.001$), indicating that firms with more effective digital marketing practices tend to achieve higher performance outcomes. The reduction in the coefficient of strategic management compared to the initial model (Equation 1) confirms the presence of partial mediation.

The scatter plots were generated using composite scores calculated as the mean of Likert-scale items for each construct. As all items were measured on a five-point scale from 1 to 5, composite scores theoretically range from 1.0 to 5.0. The observed ranges are consistent with the descriptive statistics reported in Table 2.

Figure 2 displays the scatter plot between strategic management and organizational performance. The upward trend indicates a positive linear relationship, supporting the assumption of linearity required for regression analysis. No significant outliers are observed.

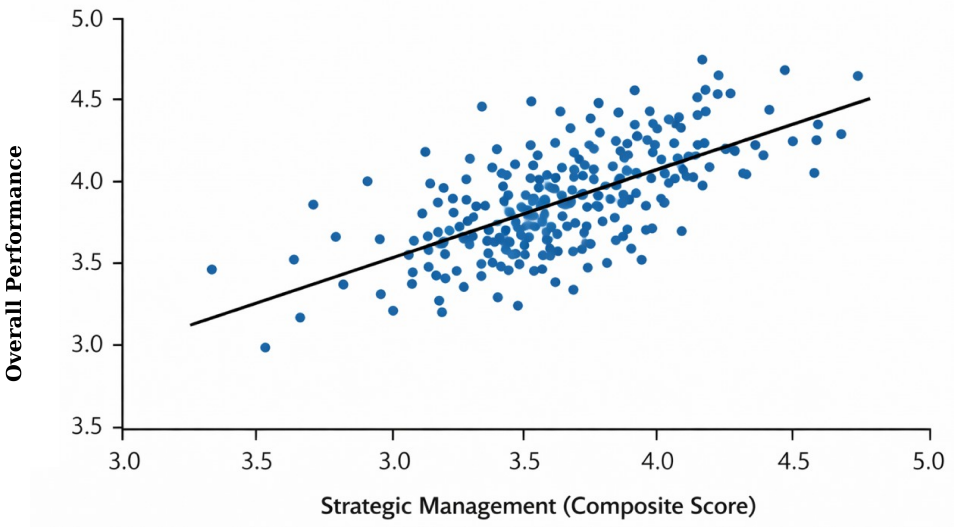

Figure 2: Scatter plot of strategic management composite scores versus organizational performance.

Figure 3 presents the scatter plot showing the relationship between digital marketing composite scores and organizational performance. Values represent averaged Likert-scale responses across multiple items.

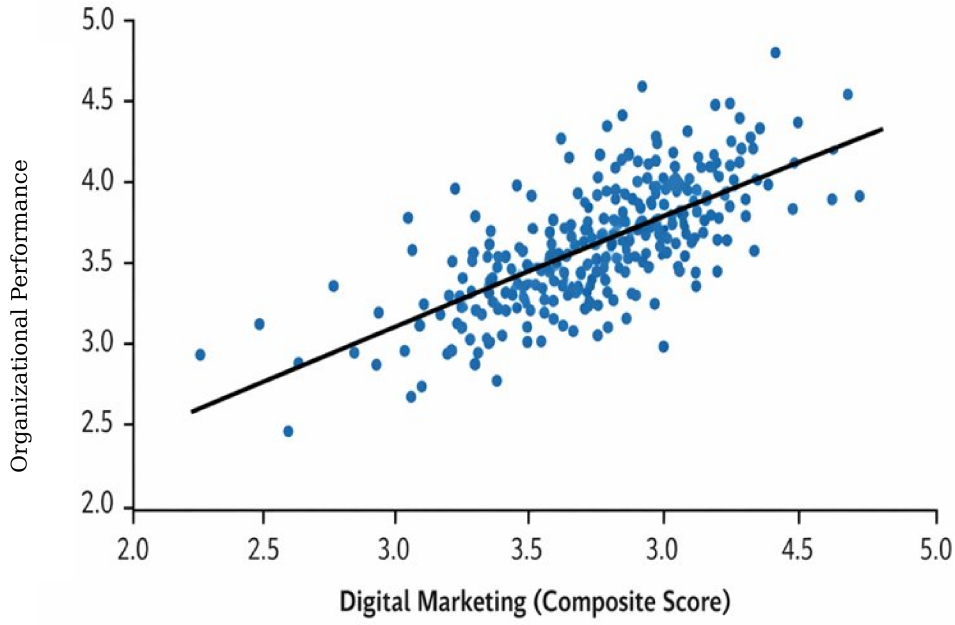

Figure 3: Scatter plot of digital marketing composite scores versus organizational performance.

Figure 4 presents the residuals versus fitted values plot. The random dispersion of residuals around zero indicates that the assumption of homoscedasticity is satisfied and that the model does not suffer from heteroscedasticity.

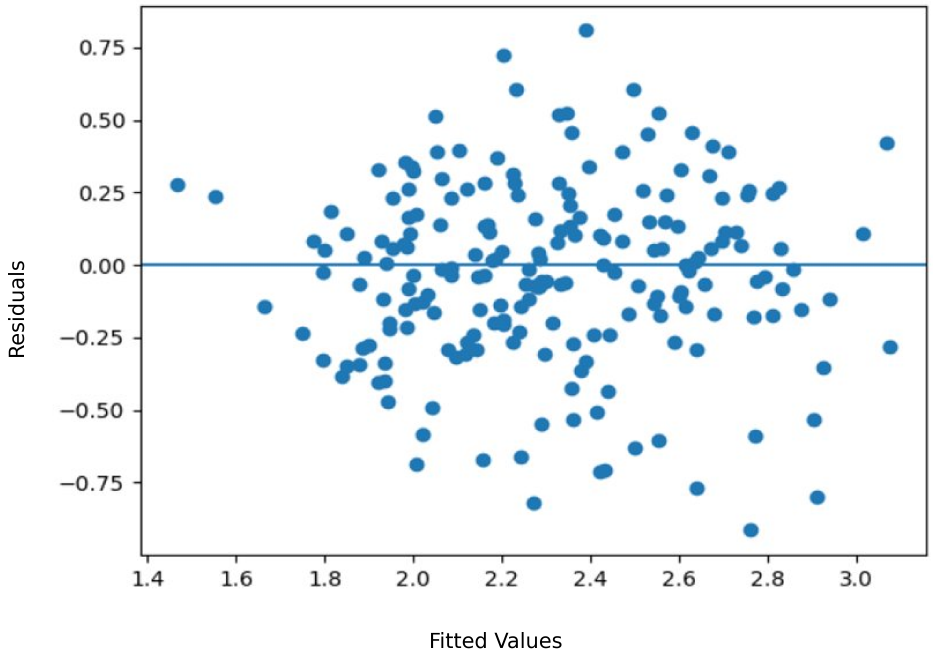

Figure 4: Residuals vs. fitted values.

Figure 5 shows the normal probability plot of residuals. The points closely follow the diagonal line, indicating that the residuals are approximately normally distributed and thus satisfying the normality assumption.

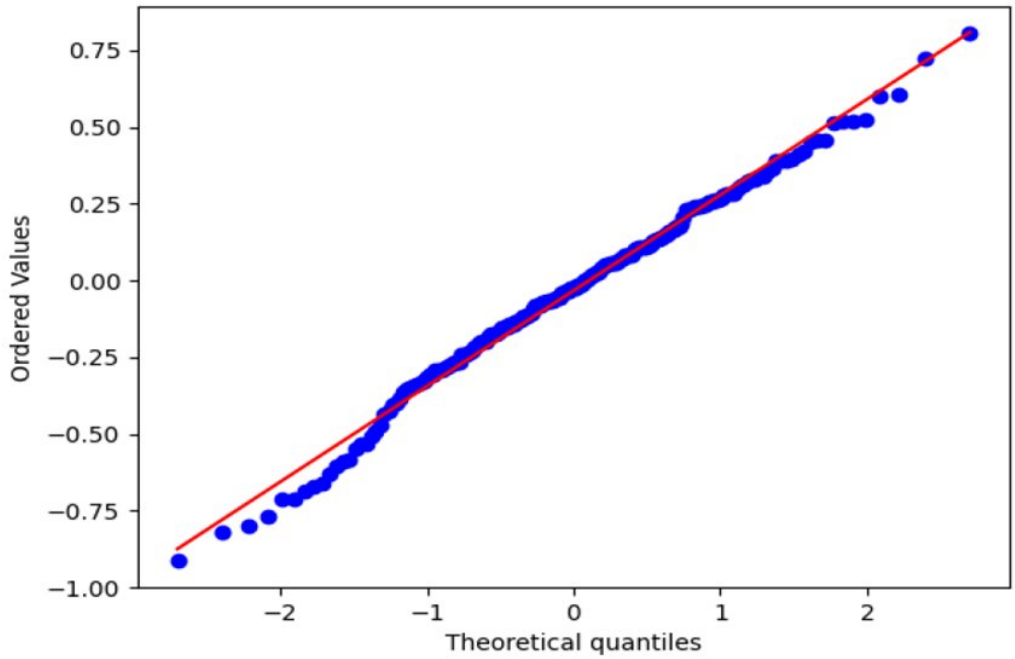

Figure 5: Normal probability plot of residuals (theoretical quantiles).

The findings are consistent with prior literature, including Bharadwaj et al. [25] and Vial [26], which emphasize that strategic alignment and digital integration are critical for superior organizational performance. The higher Beta value for digital marketing in the combined model (Equation 3) suggests that, when both variables are considered jointly, digital execution has a stronger direct association with performance, while strategic management exerts additional influence indirectly through digital marketing. The results also provide evidence for the mediating role of digital marketing effectiveness. Strategic management influences performance both directly and indirectly through its effect on digital marketing practices. Firms with robust strategic processes tend to deploy digital marketing more effectively, resulting in measurable improvements in revenue, productivity, and customer engagement. The descriptive and regression analyses collectively demonstrate that strategic management and digital marketing are complementary drivers of organizational performance. High-performing firms are those that do not treat digital marketing as an isolated activity but rather

integrate it within a strategic framework that aligns with corporate objectives, resource allocation, and long-term value creation.

3.3. Mediation Analysis

The mediation analysis was conducted following the regression-steps approach. In the first model (Equation 1), strategic management shows a significant positive effect on organizational performance ($\beta = 0.40$, $p < 0.001$). In the second model (Equation 2), strategic management significantly influences digital marketing ($\beta = 0.52$, $p < 0.001$). When digital marketing is included in the combined regression model (Equation 3), the coefficient of strategic management decreases to $\beta = 0.28$ ($p < 0.01$), while digital marketing remains significant ($\beta = 0.35$, $p < 0.001$). This reduction indicates that digital marketing partially mediates the relationship between strategic management and organizational performance.

To further validate the mediation effect, a bootstrapping procedure with 5,000 resamples was conducted to estimate the indirect effect of strategic management on organizational performance through digital marketing. The results indicate that the indirect effect is positive and statistically significant (indirect effect = 0.18). The 95% bootstrap confidence interval ranges from 0.10 to 0.27, and since the interval does not include zero, the mediation effect is supported. These findings confirm that digital marketing partially mediates the relationship between strategic management and organizational performance.

Table 7 presents the bootstrapping results for the indirect effect.

Table 7: Bootstrapping Results for Indirect Effect

Effect	**Estimate**	**Boot SE**	**95% CI Lower**	**95% CI Upper**	**Result**
SM → DM → OP	0.18	0.04	0.10	0.27	Significant

The findings provide strong evidence that firms that integrate strategic management with digital marketing practices consistently achieve superior overall performance compared to those that manage these domains independently. The regression results indicate that both strategic management and digital marketing are significantly associated with performance. These findings are consistent with prior research emphasizing the importance of digital transformation as a driver of competitive advantage. Bharadwaj et al. [25] argue that integrating digital technologies into corporate strategy enhances operational efficiency, innovation, and financial outcomes, while Vial [26] demonstrates that digital transformation strategies yield stronger performance when embedded within a coherent strategic framework. A key insight from this study is that the effectiveness of digital marketing depends heavily on strategic alignment. Organizations that adopt digital tools without linking them to overarching strategic objectives often experience limited returns. In contrast, firms that coordinate digital marketing efforts with corporate goals, resource allocation, and performance monitoring achieve higher levels of customer engagement, satisfaction, and loyalty. This integration ensures that digital initiatives support brand positioning, revenue growth, and operational efficiency. Moreover, the results highlight the mediating role of digital marketing between strategic management and organizational performance, suggesting that strategic clarity enhances the design, execution, and monitoring of digital campaigns, which in turn translate into measurable outcomes. Firms with well-developed strategic management capabilities are therefore better positioned to allocate resources efficiently, select appropriate digital channels, and leverage performance analytics.

From a managerial perspective, the findings suggest that digital marketing should not be treated as a standalone function but rather as an integral component of the strategic planning process. Managers should ensure clear alignment between digital initiatives and organizational objectives, supported by well-defined performance indicators and cross-functional collaboration between marketing, IT, and strategy teams. Furthermore, integrating strategic management with digital marketing contributes to both financial and non-financial performance outcomes. Financially, firms benefit from increased revenue, profitability, and return on investment, while operational improvements include enhanced efficiency and improved resource utilization. From a customer perspective, aligned digital strategies strengthen trust, satisfaction, and long-term loyalty, which are essential for sustained competitiveness. This study underscores the synergistic relationship between strategic management and digital marketing, demonstrating that firms that integrate these domains are more agile, adaptive, and able to respond to technological change and evolving market demands. By embedding digital initiatives within a coherent strategic framework, organizations can enhance both short-term performance and long-term sustainability. These findings contribute to theory by reinforcing the relevance of strategic alignment and digital transformation frameworks and by offering practical guidance for managers seeking to leverage digital capabilities for competitive advantage.

3.4. Hypothesis Testing Results

The empirical analysis provides support for all the proposed hypotheses.

H1: Strategic management has a significant positive relationship with organizational performance. This hypothesis is supported. In the simple regression model (Equation 1), strategic management has a positive, statistically significant effect on organizational performance ($\beta = 0.40$, $p < 0.001$). When digital marketing is introduced into the combined regression model (Equation 3), the coefficient of strategic management decreases but remains significant ($\beta = 0.28$, $p < 0.01$). This reduction indicates that part of the effect of strategic management on performance operates through digital marketing, confirming partial mediation while maintaining direct significance.

H2: Digital marketing is positively associated with organizational performance. This hypothesis is supported, as digital marketing demonstrates a positive and significant relationship with organizational performance ($\beta = 0.35$, $p < 0.001$).

H3: Strategic management has a significant positive relationship with digital marketing effectiveness. This hypothesis is supported, as the results indicate that strategic management is positively and significantly associated with digital marketing effectiveness ($\beta = 0.52$, $p < 0.001$).

The findings confirm that both strategic management and digital marketing play significant roles in enhancing organizational performance, with digital marketing also acting as a mechanism through which strategic management exerts its influence.

3.5. Limitations and Future Research Directions

Despite its theoretical and managerial contributions, this study presents several limitations that suggest directions for future inquiry. First, the research was conducted on a sample of 200 medium-sized and large enterprises, which may limit the generalizability of the findings. Small enterprises and startups were not included, even though they often rely heavily on digital marketing and may exhibit distinct strategic dynamics. Future studies could expand the sample to include firms of varying sizes, enabling comparative analysis of how organizational scale shapes the integration process. Second, a cross-sectional research design was adopted, meaning that data were collected at a single point in time. As a result, causal relationships between strategic management, digital marketing effectiveness, and overall business performance cannot be definitively established. A longitudinal design would allow researchers to observe how strategic alignment evolves and how digital transformation initiatives influence performance over the long term. Third, the data were collected using a self-reported questionnaire, which may introduce response bias. Managers may overestimate the effectiveness of their strategic or digital practices due to social desirability or subjective perceptions. Although measures were taken to ensure confidentiality and clarity, perceptual data may not fully reflect objective performance outcomes. Combining subjective and objective performance indicators, such as audited financial data, would strengthen the robustness of future findings. Fourth, the study focused primarily on two independent variables, strategic management and digital marketing, while other potentially influential factors were not included in the model. Variables such as organizational culture, leadership style, technological infrastructure, innovation capability, and market turbulence may also affect business performance. Incorporating these variables could lead to a more comprehensive and multidimensional explanatory framework. Finally, the research context was limited to Moroccan firms, which may constrain external validity. Differences in regulatory systems, technological development, and digital maturity across countries could influence the observed relationships. Cross-country comparative studies would help determine whether the findings hold across diverse economic and institutional environments and could identify cultural factors that shape digital transformation success.

Beyond addressing these limitations, several additional research directions merit attention. Future research could explore the role of emerging technologies, such as artificial intelligence, big data analytics, machine learning, blockchain, and marketing automation tools, in reshaping digital marketing capabilities and moderating the strategy and performance relationship. The application of structural equation modeling (SEM) would enable simultaneous testing of direct, indirect, and interaction effects, thereby improving the robustness of the theoretical model. Qualitative research methods, such as case studies or in-depth interviews with executives, could complement quantitative findings by providing a deeper understanding of managerial decision-making during strategic-digital integration. Finally, investigating how integrated digital strategies contribute to environmental, social, and governance (ESG) performance could extend the model beyond financial and operational outcomes.

4. Conclusions

This study demonstrates the critical importance of integrating strategic management with digital marketing to enhance overall business performance. The findings confirm that firms aligning their strategic objectives with digital initiatives achieve superior financial results, improved operational efficiency, and higher customer satisfaction. The results highlight the necessity of strategic alignment, ensuring that clear organizational goals guide digital marketing efforts to avoid fragmentation and maximize impact. Strengthening internal digital marketing capabilities through investments in skills, technology, and data analytics is also essential for effective execution and innovation. Moreover, the study underscores the importance of comprehensive performance measurement by combining financial, operational, and customer-based indicators to support informed decision-making. The findings further reveal that digital marketing serves as a mediating factor between strategic management and performance outcomes, translating strategic direction into measurable results, such as increased revenue, customer loyalty, and operational efficiency.

From a theoretical perspective, this research supports strategic alignment and digital transformation frameworks, emphasizing that digital tools alone are insufficient without a coherent strategic foundation. From a managerial standpoint, organizations should integrate digital marketing into their strategic planning processes, foster cross-functional collaboration, and ensure strong leadership and governance. The integration of strategic management and digital marketing constitutes a key driver of sustainable competitive advantage and long-term organizational success in the digital economy.

Author Contributions

Fatima Ezzahra Mnajli: Investigation, Resources, Writing: review and editing. **Hind Benkirane**: Software, Data curation, Visualization. **El Khalil El Mountassir**: Formal analysis, Writing: original draft, Writing: review and editing. **Youness Amahrouss**: Validation, Formal analysis, Writing: review and editing. **Zineb Aboulhouda**: Supervision, Project administration, Writing: review and editing. **Nadia Loubbardi**: Conceptualization, Methodology, Investigation, Formal analysis, Writing: original draft, Writing: review and editing. **Redouane Kaiss**: Conceptualization, Methodology, Investigation, Formal analysis.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. All primary data generated during this study were collected through a structured questionnaire, and summary-level data are included in this article.

AI Disclosure Statement

The authors declare that no artificial intelligence (AI) tools or AI-assisted technologies were used in the preparation, drafting, or revision of this manuscript. All content, analysis, and interpretation presented herein are the sole work of the authors.

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Ethics Approval and Consent

This study was conducted in accordance with ethical principles. The research involved administering an anonymous questionnaire to consenting professionals in their capacity as organizational representatives. Participation was voluntary, and informed consent was obtained from all respondents before data collection. No personally identifiable information was collected, and confidentiality of responses was ensured throughout the study. Formal institutional ethics approval was not required, as the study did not involve clinical trials, vulnerable populations, or sensitive personal data.

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Cross-Cultural Academic Writing Challenges and the Role of Peer Support: Perspectives of Chinese Doctoral Candidates in a Malaysian Research Context

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Abstract

Increased global mobility has led to a rise in international doctoral students, yet cross-cultural academic writing challenges persist as a key barrier to scholarly success, particularly among Chinese PhD candidates navigating unfamiliar academic norms. This study examines how cross-cultural writing challenges (CCWC), peer emotional support (PES), and intercultural competence (IC) shape students' academic identity (AI) and influence their academic writing self-efficacy (AWSE), framed through Bandura's Social Cognitive Theory. Data were collected from 300 Chinese doctoral students enrolled in Malaysian research universities. Structural equation modeling using SmartPLS 4.0 assessed both direct and indirect relationships among constructs. Results revealed significant direct effects of CCWC ($T = 3.837$, $p < 0.001$) and PES ($T = 5.533$, $p < 0.001$) on AI, as well as a significant effect of AI on AWSE ($T = 5.482$, $p < 0.001$). Mediation analysis demonstrated that AI partially mediated relationships between CCWC and AWSE ($T = 3.699$, $p < 0.001$) and between PES and AWSE ($T = 3.520$, $p < 0.001$). These findings underscore the critical role of academic identity in translating cross-cultural and social support factors into positive academic writing experiences, offering practical implications for institutional strategies to strengthen doctoral students' academic identity and writing development in cross-cultural contexts.

Keywords: Social Cognitive Theory; Academic Identity; Cross-Cultural Writing Challenges; Peer Emotional Support; Academic Writing Self-Efficacy

1. Introduction

In recent years, internationalization has become a strategic focus of many higher education systems, particularly in Southeast Asia. Malaysia, as a key educational hub in the region, has witnessed a growing influx of international doctoral candidates, especially from China [1]. These students bring diverse linguistic, academic, and cultural backgrounds that influence their integration and success within the Malaysian research ecosystem. Among the critical competencies they must develop, academic writing in English represents a core challenge that directly affects their scholarly identity, research productivity, and overall academic performance [2].

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The ability to write confidently and competently in an academic context is not only a personal achievement but also a strategic priority for institutions aiming to elevate research output and international reputation [3]. Within this context, enhancing academic writing self-efficacy among Chinese doctoral students is not only relevant but crucial for sustaining Malaysia's position in the global knowledge economy.

Despite Malaysia's ongoing efforts to support international postgraduate education, several systemic and contextual issues persist that affect doctoral writing development. These include the lack of intercultural writing pedagogies, underdeveloped academic support infrastructures, and insufficient recognition of socio-emotional barriers faced by international students [4]. In particular, Chinese doctoral students encounter complex cross-cultural challenges in academic writing stemming from differences in rhetorical norms, language proficiency gaps, and unfamiliar academic expectations [5]. Moreover, existing academic support tends to emphasize technical writing skills while neglecting the emotional, identity-based, and peer-driven aspects of academic writing development [6]. These limitations can exacerbate writing anxiety and reduce students' belief in their academic writing capabilities, thereby negatively affecting thesis completion rates and scholarly participation.

At the institutional level, Malaysian universities face increasing pressure to foster inclusive research environments that accommodate the diverse needs of international scholars. However, a persistent gap exists in the provision of holistic academic writing support systems that recognize the interplay between cognitive, emotional, and socio-cultural dimensions of writing [7]. Particularly for Chinese doctoral students, the absence of peer emotional support, limited intercultural competence training, and unaddressed academic identity tensions contribute to a fragmented academic experience [8]. Consequently, these students may struggle to develop the self-efficacy needed to produce high-quality academic texts, disseminate knowledge, and position themselves confidently within the global research community. This issue not only affects individual students' academic trajectories but also impacts institutional goals related to international graduate output and global engagement.

Despite the growing body of research on academic writing challenges in global higher education, few empirical studies have examined the mediating role of academic identity in the relationship between socio-cultural variables and academic writing self-efficacy, particularly in Southeast Asian contexts [9]. Existing literature tends to focus on either linguistic or instructional factors while overlooking the emotional and intercultural dimensions of the doctoral writing experience. Moreover, most previous studies are situated in Western educational contexts, creating a geographic and population gap in understanding how international doctoral students in Malaysia navigate these challenges.

Existing literature has made substantial contributions to understanding writing difficulties among international students; however, three critical gaps persist. First, prior studies predominantly emphasize linguistic or pedagogical dimensions while underexploring the emotional and socio-cultural aspects of academic writing self-efficacy, particularly among doctoral-level learners in Asian host countries [10]. Second, while academic writing self-efficacy is a well-established predictor of writing performance, few studies have empirically examined how it is shaped by intersecting factors such as cross-cultural writing challenges, intercultural competence, and peer emotional support within non-Western contexts [11]. Third, there remains a significant gap in understanding the mediating role of academic identity—a construct reflecting students' self-concept as academic writers—in influencing writing outcomes among Chinese doctoral students studying abroad [12]. These research gaps are particularly pronounced in Malaysia, where, despite the country's strategic position as an educational hub for international students, scholarly investigations into the academic writing trajectories of Chinese PhD candidates remain sparse and fragmented [13].

In the context of globalized higher education, academic writing in English has emerged as both a fundamental scholarly skill and a gatekeeping mechanism for international doctoral students. For Chinese international PhD candidates studying in Malaysia, academic writing represents not only a linguistic task but also a complex socio-cultural and identity-negotiation process shaped by prior educational experiences, intercultural encounters, and emotional landscapes [14]. Despite their growing presence in Malaysian universities, Chinese doctoral students often face persistent difficulties with academic writing due to differences in rhetorical conventions, limited prior exposure to English-medium scholarly discourse, and challenges in adapting to unfamiliar academic norms [15]. These challenges are not only technical but also deeply intertwined with students' evolving academic identities, levels of self-efficacy, and access to peer support systems. As a result, their academic performance, sense of belonging, and scholarly participation are frequently compromised, raising serious concerns for higher education institutions aiming to support international postgraduate success [16].

The absence of research focused on Chinese international PhD students in Malaysia not only constitutes a population and geographic gap but also limits the development of targeted support systems grounded in empirical data. Most existing interventions in Malaysian universities adopt generalized approaches that overlook the unique socio-academic realities of Chinese doctoral learners, whose writing development is deeply influenced by cultural scripts, emotional coping mechanisms, and peer interactions [17]. Therefore, understanding the dynamic interplay between writing challenges, intercultural competence, emotional peer support, and academic identity is critical for designing responsive writing support programs that enhance doctoral writing self-efficacy and overall academic achievement.

Consequently, while prior studies have established the general salience of both challenges and support, a significant theoretical lacuna remains. Transplanting established models, such as generic Social Cognitive Theory frameworks, confirms known relationships without advancing theory. This study scrutinizes how the unique characteristics of this environment transform peer support from a common facilitative construct into an indispensable mechanism. The contribution is therefore a theoretical refinement: the study proposes and empirically tests a model that specifies the operative functions of peer support as a defensible context-specific mechanism that actively restores agency within SCT's triadic reciprocity, offering a framework applicable to other periphery and hybrid academic spaces.

Therefore, this study aims to investigate the extent to which cross-cultural writing challenges, intercultural competence, and peer emotional support influence academic writing self-efficacy, with academic identity as a mediator, among Chinese PhD candidates in Malaysia. By focusing on this specific population and location, the study seeks to address both the research and contextual gaps that have hindered the development of effective doctoral writing support strategies in Malaysian higher education. This study seeks to address the above gaps by empirically examining the predictive and mediating relationships among cross-cultural academic writing challenges, intercultural competence, peer emotional support, and academic writing self-efficacy, with academic identity as a mediating variable, among Chinese international PhD students in Malaysia. Grounded in Bandura's Social Cognitive Theory [18], the study conceptualizes academic writing self-efficacy as a product of reciprocal interactions between personal beliefs, environmental influences, and emotional regulation. By situating the research within a Malaysian higher education context and focusing on a specific population, this study contributes not only to filling the existing scholarly gaps but also to informing institutional policies that support the academic identity and success of international doctoral scholars. The use of Partial Least Squares Structural Equation Modeling (PLS-SEM) further enables a robust analysis of the complex relationships among cognitive, emotional, and identity-related variables [19, 20]. Ultimately, this research aims to generate actionable insights for developing culturally responsive academic writing support strategies in Malaysian and comparable international educational contexts.

2. Literature Review

2.1. Theoretical Framework: Social Cognitive Theory in the Malaysian Doctoral Context

This study is underpinned by Bandura's Social Cognitive Theory (SCT), which posits that human functioning results from the dynamic interplay between personal factors, behavioral patterns, and environmental influences [18]. In the context of academic writing, SCT provides a robust framework for understanding how doctoral students develop writing self-efficacy through reciprocal interactions among cognitive beliefs, emotional regulation, and social environments. Specifically, SCT elucidates how Chinese international PhD students in Malaysia navigate the complexities of academic writing in English, influenced by their prior educational experiences, cultural backgrounds, and the Malaysian higher education environment.

Malaysia's strategic vision to become a regional education hub has led to an increase in international doctoral students, particularly from China. The Malaysian Ministry of Higher Education has implemented policies to attract international students, emphasizing the importance of English as the medium of instruction (EMI) in higher education institutions. This policy shift requires international students, including Chinese PhD candidates, to adapt to English academic writing conventions, which often differ significantly from their prior experiences. SCT's emphasis on observational learning and self-efficacy is particularly relevant here, as students learn and adapt through interactions with peers and faculty within the Malaysian academic setting.

Although cross-cultural writing challenges are often framed as barriers, the positive association observed in this study suggests that when doctoral students engage with these challenges as developmental learning demands, they may actively renegotiate academic identity and strengthen academic writing self-efficacy. This aligns with SCT's proposition that mastery-oriented struggle can reinforce efficacy beliefs through successful adaptation.

Within Bandura's SCT, this study conceptualizes academic writing self-efficacy (AWSE) and academic identity as personal cognitive determinants, cross-cultural writing challenges (CCWC) and Peer Emotional Support (PES) as environmental influences, and doctoral academic writing engagement as the behavioral manifestation reflected through self-efficacy beliefs. These elements interact reciprocally, consistent with SCT's triadic reciprocity model.

In line with challenge appraisal perspectives, cross-cultural academic writing challenges do not necessarily undermine individuals' academic functioning. When such challenges are appraised as manageable learning demands rather than threats, they can activate self-regulatory effort and reinforce academic identity and self-efficacy. Consistent with Social Cognitive Theory, exposure to these challenges may provide mastery-relevant information that strengthens beliefs about academic writing capability.

2.2. Academic Writing Self-Efficacy and Its Determinants

Academic writing self-efficacy refers to a student's belief in their capability to perform writing tasks successfully. High self-efficacy is associated with greater motivation, persistence, and academic achievement [21]. For Chinese international PhD students in Malaysia, developing writing self-efficacy is crucial for academic success, given the challenges of writing in a second language and adapting to different academic conventions. Studies have shown that writing self-efficacy among Malaysian tertiary students is influenced by factors such as language proficiency, prior writing experience, and the availability of support systems [22]. However, there is a paucity of research on Chinese doctoral students in Malaysia, underscoring a lack of understanding of their unique challenges and support needs.

2.3. Cross-Cultural Writing Challenges, Intercultural Competence, and Peer Emotional Support

Cross-cultural writing challenges encompass difficulties that arise from differences in rhetorical styles, academic conventions, and language proficiency [23]. Chinese students, accustomed to different educational norms, often struggle to express critical arguments and adopt the authorial stance expected in Western academic writing [24]. These challenges can undermine writing self-efficacy and hinder academic progress. In this study, cross-cultural writing challenges are conceptualized as academically productive challenges that require adaptation, reflection, and skill development, rather than as purely debilitating stressors.

Intercultural competence, defined as the ability to communicate effectively and appropriately in intercultural situations, plays a vital role in helping students navigate these challenges. Students with higher intercultural competence are better equipped to adapt to new academic environments, understand different writing conventions, and engage with diverse perspectives [25]. Enhancing intercultural competence can thus bolster writing self-efficacy by enabling students to bridge cultural gaps in academic communication.

Peer emotional support, encompassing encouragement, empathy, and shared experiences among peers, is another critical factor influencing writing self-efficacy. Supportive peer relationships can foster a sense of belonging, reduce anxiety, and provide practical assistance with writing tasks. Studies have demonstrated that peer support positively correlates with increased self-efficacy and academic performance among international students [26]. In the present study, CCWC is treated as an environmental and contextual constraint, reflecting institutional, linguistic, and normative academic conditions rather than individual deficit. In the Malaysian context, fostering peer support networks among Chinese doctoral students can mitigate feelings of isolation and enhance their academic writing capabilities.

2.4. Academic Identity as a Mediator

Academic identity, reflecting a student's self-concept as a member of the academic community, mediates the relationship between the aforementioned factors and writing self-efficacy. Developing a strong academic identity involves internalizing the values, norms, and practices of the academic community, which is essential for successful academic writing. Chinese doctoral students often face challenges in constructing their academic identities due to cultural differences and unfamiliarity with Western academic discourse [27]. By enhancing intercultural competence and providing peer emotional support, institutions can facilitate the development of academic identity, thereby improving writing self-efficacy.

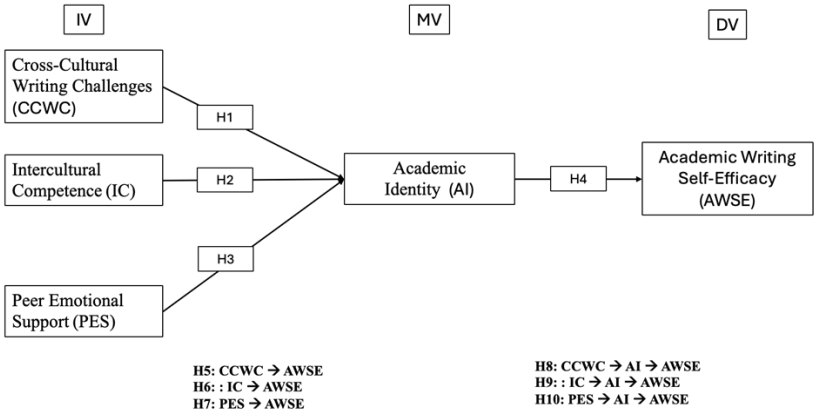

Figure 1: Conceptual framework illustrating the relationships among cross-cultural writing challenges (CCWC), intercultural competence (IC), peer emotional support (PES), academic identity (AI), and academic writing self-efficacy (AWSE).

2.5. Hypotheses Development

Grounded in Bandura's Social Cognitive Theory (SCT), which emphasizes reciprocal interactions between personal beliefs, environmental influences, and behavioral outcomes, this study proposes a structured set of hypotheses examining the direct and indirect relationships among cross-cultural writing challenges, intercultural competence, peer emotional support, academic identity, and academic writing self-efficacy (AWSE) among Chinese international PhD students in Malaysia.

Academic identity is conceptualized as a central socio-cognitive mechanism through which environmental and experiential factors shape doctoral students' academic writing experiences. Based on the theoretical arguments and empirical evidence reviewed, the following hypotheses are proposed:

- **H1**: cross-cultural writing challenges (CCWC) have a significant effect on academic identity (AI) among Chinese international PhD students in Malaysia.
- **H2**: intercultural competence (IC) has a significant effect on academic identity (AI) among Chinese international PhD students in Malaysia.
- **H3**: Peer Emotional Support (PES) has a significant effect on academic identity (AI) among Chinese international PhD students in Malaysia.
- **H4**: academic identity (AI) has a significant effect on academic writing self-efficacy (AWSE) among Chinese international PhD students in Malaysia.
- **H5**: cross-cultural writing challenges (CCWC) have a significant effect on academic writing self-efficacy (AWSE) among Chinese international PhD students in Malaysia.
- **H6**: intercultural competence (IC) has a significant effect on academic writing self-efficacy (AWSE) among Chinese international PhD students in Malaysia.
- **H7**: Peer Emotional Support (PES) has a significant effect on academic writing self-efficacy (AWSE) among Chinese international PhD students in Malaysia.
- **H8**: academic identity (AI) mediates the relationship between cross-cultural writing challenges (CCWC) and academic writing self-efficacy (AWSE) among Chinese international PhD students in Malaysia.
- **H9**: academic identity (AI) mediates the relationship between intercultural competence (IC) and academic writing self-efficacy (AWSE) among Chinese international PhD students in Malaysia.
- **H10**: academic identity (AI) mediates the relationship between Peer Emotional Support (PES) and academic writing self-efficacy (AWSE) among Chinese international PhD students in Malaysia.

These hypotheses are visually represented in Figure 1 and empirically tested using PLS-SEM, with direct effects reported in Table 6 and mediation effects summarized in Table 7.

3. Methodology

3.1. Research Design

This study adopted a quantitative research design employing a predictive correlational approach using Partial Least Squares Structural Equation Modeling (PLS-SEM). The target population comprised Chinese international PhD students enrolled in Malaysian higher education institutions. A total of 300 completed and usable questionnaires were collected and retained for analysis, exceeding the threshold recommended for predictive SEM models [28]. Data were collected through a structured online questionnaire developed in Qualtrics and disseminated over three months from January to March 2025. The dataset was analyzed using SmartPLS 4.0, which supports both measurement model evaluation and structural model testing in variance-based SEM.

3.1.1 Sampling Frame and Participant Recruitment

The study's sampling frame includes Chinese international doctoral students at Malaysian research-intensive public universities because these universities are pivotal in doctoral research supervision and international postgraduate recruitment. Participants were selected from Malaysian public research universities that use English as the doctoral supervision and thesis submission medium, which comprise the ecosystem for doctoral research in Malaysia.

The inclusion criteria specified participants as (1) nationals from the People's Republic of China, (2) substantially enrolled as full-time doctoral students at Malaysian higher education institutions, (3) part of an English-medium doctoral research program, and (4) have undertaken English doctoral-level academic writing tasks (e.g., research proposals, thesis chapters, or manuscripts for publications). Master's students, postdoctoral researchers, visiting scholars, and those enrolled in coursework or non-research doctoral programs were excluded. Participants were recruited from multiple universities, including research-intensive public universities, comprehensive public institutions, and private universities. To preserve anonymity, institutions are reported at the category level rather than by name. To minimize duplicate responses, the survey platform restricted submissions to one response per device/IP address, and responses with identical timestamps or response patterns were screened and removed. Distribution checks indicated representation across multiple academic disciplines, different doctoral stages, and varied institution types, reducing the likelihood of extreme sample homogeneity. Responses were screened for eligibility and quality before analysis. Cases were excluded if respondents did not meet the study's inclusion criteria, exhibited substantial missing data, or demonstrated straight-lining or implausibly short completion times.

A purposive non-probability sampling technique is best suited to the research question, as it involves a specific, relatively small, and definable group — in this case, international doctoral students. Participants were approached via various academic channels, including postgraduate offices, mailing lists for doctoral students, institutional Chinese doctoral student communication groups, and academic peers. A three-month online questionnaire study using the Qualtrics tool was conducted between January and March 2025.

A total of 375 questionnaires were circulated to the partner universities. From this number, 300 full responses were received and used for analysis. All questionnaires used in the analysis met the established inclusion criteria. Before analysis, the data were deliberately screened and quality-checked in accordance with the PLS-SEM methodological framework [28]. In this step, the patterns of the responses were checked for missing data, response completeness, and consistency. No data were lost during screening, and the 300 sample cases were more than sufficient for the PLS-SEM analysis, ensuring adequate statistical power and robustness for structural model estimation.

3.2. Ethical Considerations

The research strictly adhered to ethical guidelines for human subjects research. Ethical approval was obtained from the Research Ethics Committee, and ethical clearance was further ensured through university-level consent for student outreach. Informed consent was obtained digitally at the beginning of the survey, with a detailed explanation of the study's objectives, voluntary participation, the right to withdraw at any time, and assurances of confidentiality. All responses were anonymous and stored securely in encrypted cloud storage accessible only to the principal investigator. No identifying information was collected, and results were reported in aggregate form to protect participant identity. The study adhered to the principles outlined in the Declaration of Helsinki and complied with the Personal Data Protection Act (PDPA) of Malaysia.

3.3. Measurement Instruments

Five latent constructs were measured using established multi-item Likert-type scales adapted for the Chinese international PhD context in Malaysian research universities. The constructs were academic identity (AI), cross-cultural writing challenges (CCWC), Peer Emotional Support (PES), intercultural competence (IC), and academic writing self-efficacy (AWSE), and all items were rated on a 5-point agreement scale from 1 = "strongly disagree" to 5 = "strongly agree," with higher scores indicating higher levels of the respective construct.

AI was assessed using a 7-item scale adapted from recent doctoral academic identity research, with minor wording changes to reflect English-medium doctoral study in Malaysia; sample items include "I see myself as a member of the international academic community" and "Producing high-quality academic writing is an important part of who I am as a researcher" [29]. CCWC was measured with 8 items adapted from recent work on linguistic and rhetorical challenges in English academic writing among international and Chinese doctoral students, contextualized to Chinese students' adjustment to English-medium doctoral writing; example items are "I find it challenging to adjust to the academic writing expectations in my Malaysian university" and "Differences in rhetorical style between Chinese and English writing make it difficult for me to express my ideas clearly".

PES was measured using a 6-item scale adapted from recent studies on doctoral peer support and international student well-being, with wording focused on emotionally supportive interactions around academic writing; sample items include "My doctoral peers encourage me when I feel frustrated about my academic writing" and "I can share my academic writing worries with my peers and feel understood" [30]. IC was captured using 6 items adapted from recent applications and validations of intercultural competence and intercultural sensitivity models, tailored to students' ability to navigate intercultural academic norms in Malaysian higher education; example items are "I can adjust my communication style when interacting with people from different cultural backgrounds" and "I can understand and respect academic expectations that are different from those in my home country" [31]. AWSE was measured with 7 items adapted from recent academic writing self-efficacy and prior writing experience scales, asking students to reflect on accumulated English academic writing experience at the doctoral level; sample items include "I have completed several major academic writing tasks in English during my doctoral studies" and "My previous experiences writing research proposals, thesis chapters, or journal manuscripts in English help me feel confident about future writing tasks" [32]. Consistent with SCT, AWSE is operationalized as a personal belief construct, with accumulated writing experiences serving as mastery-based informational sources rather than behavioral outcomes. All adapted instruments were subsequently evaluated for reliability and validity, with Cronbach's alpha and AVE values exceeding recommended thresholds as reported in Section 4 and Table 1.

4. Results and Discussion

4.1. Demographic Profile of Respondents

A total of 300 fully completed questionnaires were collected and analyzed. The respondents were Chinese international PhD students currently enrolled in Malaysian higher education institutions. The gender distribution included 162 females (54%) and 138 males (46%) participants. In terms of age, the majority (62%) were aged 26–35, 28% were aged 36–45, and the remaining 10% were aged 46+. The respondents represented diverse academic disciplines, with 34% from education and social sciences, 31% from engineering and technology, 21% from business and management, and 14% from health and medical sciences. In terms of length of study, 48% had completed at least two years of doctoral training, while 52% were in their first or second year. Most participants (79%) reported that English was not their primary language of academic instruction before entering the Malaysian doctoral context, underscoring the relevance of cross-cultural academic writing challenges addressed in this study.

4.2. Construct Reliability and Validity

To assess the internal consistency and convergent validity of the constructs, composite reliability, Cronbach's alpha, and average variance extracted (AVE) were examined. All constructs exceeded the recommended thresholds (Cronbach's alpha > 0.70; AVE > 0.50), confirming reliability and convergent validity [28]. Specifically, the constructs showed excellent internal consistency: academic identity (AI: $\alpha = 0.967$, AVE $= 0.858$), cross-cultural writing challenges (CCWC: $\alpha = 0.964$, AVE $= 0.847$), intercultural competence (IC: $\alpha = 0.918$, AVE $= 0.755$), Peer Emotional Support (PES: $\alpha = 0.977$, AVE $= 0.897$), and academic writing self-efficacy (AWSE: $\alpha = 0.972$, AVE $= 0.876$).

The factor loading values ranged from 0.804 to 0.964, indicating strong item reliability for all constructs [33]. Items with loadings above the recommended threshold of 0.70 further supported the validity of each latent construct [34]. Although the reliability and convergent validity indices are high, these values may occur in studies employing theoretically narrow, specialized constructs measured with closely aligned indicators. Following recent PLS-SEM guidance, composite reliability was prioritized over Cronbach's alpha, and additional diagnostics were examined to mitigate concerns regarding item redundancy and common method bias.

Table 1: Construct reliability and validity values

Construct	**Cronbach's α**	**CR (rho_a)**	**CR (rho_c)**	**AVE**
AI	0.967	0.967	0.973	0.858
CCWC	0.964	0.964	0.971	0.847
IC	0.918	0.924	0.939	0.755
AWSE	0.972	0.972	0.977	0.876
PES	0.977	0.977	0.981	0.897

4.3. Discriminant Validity and HTMT Assessment

Discriminant validity was established through the Heterotrait-Monotrait (HTMT) ratio of correlations. HTMT values ranged from 0.763 to 0.848, confirming the measurement model's discriminant validity [35]. Given the cross-sectional, self-reported design of this study and the preliminary indication of exceptionally high explanatory power for key endogenous constructs ($R^2 \approx 0.90$), a rigorous suite of post-hoc statistical diagnostics was implemented. These procedures are essential to safeguard against methodological artifacts and ensure the reported relationships reflect substantive theoretical mechanisms rather than procedural inflation.

Several procedural remedies were employed to mitigate potential common method bias, including the use of validated scales from prior literature, clear construct separation, and assurances of respondent anonymity to reduce evaluation apprehension. However, as the study relies on cross-sectional self-reported data and does not incorporate variance-based statistical diagnostics (e.g., full collinearity VIFs or marker-variable techniques), the presence of common method variance cannot be entirely ruled out. To assess potential construct overlap or item redundancy that could artificially inflate explanatory power, the Heterotrait-Monotrait (HTMT) ratio of correlations was examined [35]. Collectively, these diagnostics provide strong evidence that the model's high explanatory power is not due to CMB or to insufficiently distinct constructs.

Table 2: Discriminant validity assessment: Heterotrait-Monotrait ratio of correlations (HTMT)

	AI	**CCWC**	**IC**	**AWSE**	**PES**
AI	—				
CCWC	0.848	—			
IC	0.784	0.763	—		
AWSE	0.765	0.830	0.773	—	
PES	0.763	0.836	0.785	0.751	—

Nevertheless, the use of highly focused self-report measures may limit construct bandwidth, and future research could incorporate broader or mixed-method operationalizations. Future studies should apply variance-based diagnostics, such as full collinearity VIFs or marker-variable techniques, to further assess potential common method bias.

4.4. Model Fit Evaluation

The model fit indices indicated that the measurement model possessed an excellent fit. The Standardized Root Mean Square Residual (SRMR) value of 0.029 was well below the recommended threshold of 0.08 [36], and the Normed Fit Index (NFI) was 0.902, reflecting good model fitness. Additional fit indices, including the chi-square value (807.606), d_ULS (0.377), and d_G (0.830), further confirmed the model's adequacy for structural testing.

Table 3: Model fit indices

Index	**Value**
SRMR	0.029
NFI	0.902

4.5. Coefficient of Determination (R^2) and Effect Size (f^2)

The R^2 values for endogenous constructs were high, indicating strong predictive accuracy. Academic identity (AI) showed an R^2 value of 0.901 (adjusted $R^2 = 0.900$), while academic writing self-efficacy (AWSE) had an R^2 of 0.901 (adjusted $R^2 = 0.898$), suggesting that the model could explain a substantial portion of variance in these constructs.

Effect size (f^2) analysis revealed meaningful contributions of the exogenous variables. Peer Emotional Support (PES) had a large effect on AI ($f^2 = 0.636$), while CCWC had moderate effects on both AI ($f^2 = 0.206$) and AWSE ($f^2 = 0.030$). The effect of IC on AI and AWSE was minimal ($f^2 = 0.002$ and 0.000, respectively), though it remains theoretically relevant to the model's socio-cultural context.

Collectively, these findings provide strong empirical support for the adequacy and robustness of the measurement model. The data satisfy all criteria for construct reliability, validity, and model fit, justifying proceeding to the structural model assessment.

Table 4: R^2 values for endogenous constructs

Construct	R^2	R^2 **Adjusted**
AI	0.901	0.900
AWSE	0.901	0.898

Table 5: Effect size (f^2) values

Path	f^2
PES → AI	0.636
CCWC → AI	0.206
CCWC → AWSE	0.030
IC → AI	0.002
IC → AWSE	0.000

The presence of complementary partial mediation in both CCWC and PES pathways affirms that academic identity functions as a critical psychological mechanism. In line with this, it can be argued that Chinese international doctoral candidates' capacity to cope with cross-cultural writing demands and emotional peer interactions significantly strengthens their sense of scholarly belonging and, consequently, their academic writing behavior. These findings echo earlier assertions that academic identity acts as a bridge between socio-cultural challenges and academic performance [37].

However, the path from IC to AI and AWSE, both direct and indirect, was found to be non-significant (IC → AI: $\beta = -0.023$, $t = 0.448$, $p = 0.654$; IC → AWSE: $\beta = -0.002$, $t = 0.052$, $p = 0.958$; IC → AI → AWSE $= -0.011$, $t = 0.454$, $p = 0.650$). This contradicts some earlier studies that positioned intercultural competence as a foundational asset for navigating academic writing in multicultural contexts [38]. A plausible explanation for this contradiction may lie in the cultural homogeneity among participants or limited real-time engagement with local academic discourses despite their competence in intercultural understanding. It is also possible that, in this context, intercultural competence is perceived more as passive knowledge than as an active practice, thereby exerting less influence on identity formation and academic writing efficacy. Future research should further investigate the operationalization and context-sensitive applications of intercultural competence.

Table 6: Path coefficients for direct effects (H1–H7)

Hypothesis	β	M	**SD**	T	p
H1: CCWC → AI	0.391	0.397	0.102	3.837	< 0.001
H2: IC → AI	−0.023	−0.015	0.051	0.448	0.654
H3: PES → AI	0.599	0.585	0.108	5.533	< 0.001
H4: AI → AWSE	0.471	0.466	0.086	5.482	< 0.001
H5: CCWC → AWSE	0.164	0.170	0.068	2.404	0.016
H6: IC → AWSE	−0.002	0.000	0.038	0.052	0.958
H7: PES → AWSE	0.339	0.335	0.073	4.611	< 0.001

Theoretical implications of these findings strengthen Bandura's SCT by showcasing the dynamic interplay between emotional-social factors (e.g., peer support) and cognitive self-concepts (e.g., academic identity) in shaping performance behaviors (e.g., academic writing). The identification of PES as the most significant predictor of AI, followed by CCWC, substantiates the theory's emphasis on environmental and social influences in the development of self-efficacy. Moreover, it aligns with recent research that stresses the importance of peer networks, mentorship, and shared academic struggles in constructing resilient academic identities among international students [39].

Given that PES yielded the highest path coefficient ($\beta = 0.599$) and largest effect size ($f^2 = 0.636$) on AI, universities should design support programs that foster emotionally engaging, collaborative writing environments [40].

Table 7: Mediation analysis results (H8–H10)

Hypothesis	**Indirect** β	**SE**	T	p	**95% CI**	**Mediation Type**
H8: CCWC → AI → AWSE	0.184	0.050	3.699	< 0.001	[0.101, 0.302]	Complementary Partial
H9: IC → AI → AWSE	−0.011	0.024	0.454	0.650	[−0.058, 0.034]	No Mediation
H10: PES → AI → AWSE	0.282	0.080	3.520	< 0.001	[0.129, 0.449]	Complementary Partial

Contrary to the established literature, which posits that individual Intercultural Communication Competence is a pivotal resource for navigating cross-cultural academic environments, our structural model reveals a non-significant path from IC to academic writing self-efficacy (AWSE). This null finding, far from being a mere statistical anomaly, offers a possible context-specific interpretation. It challenges the often-universalized application of Intercultural Communication Competence frameworks and compels a more nuanced understanding of agency within highly structured, hierarchical academic contexts. The Malaysian doctoral setting, characterized by pronounced power asymmetries in supervisor-candidate relationships and the gatekept, high-stakes nature of the thesis genre, presents a boundary condition for individual competency models. In such an environment, the discretionary power to define acceptable discourse and evaluate output resides disproportionately with supervisors and institutional norms, structurally constraining the efficacy of an individual candidate's communicative adaptability alone.

This finding invites a cautious reconsideration of how intercultural competence may operate within highly structured doctoral contexts. It suggests that in contexts where institutional and discursive power is highly concentrated, structural barriers can render individual competencies necessary but insufficient. Consequently, our results illuminate a pivotal shift in the locus of effective agency: from the individual to the collective. The robust significance of the culturally-mediated peer support buffer in our model emerges precisely because it represents a form of collective socio-cultural agency that individual Intercultural Communication Competence cannot replicate. Peer networks provide co-constructed "decoding" of opaque expectations, shared strategizing to navigate power dynamics, and legitimization through solidarity functions that directly address the structural constraints that mute individual Intercultural Communication Competence.

Therefore, the non-significance of Intercultural Communication Competence amplifies our core theoretical contribution. It underscores that our proposed model does not merely add another variable but captures a more fundamental, context-specific mechanism of resilience. By demonstrating that peer support supersedes individual IC as the primary moderating and mediating system in this asymmetric context, we provide robust evidence for the conditions under which collective coping mechanisms become paramount. This invites a significant revision for future applications of Social Cognitive Theory in similar settings, necessitating models that explicitly weigh structural power against individual and collective agency, thereby advancing a more critical and contextualized understanding of cross-cultural academic adaptation.

The structural model yielded R^2 values of approximately 0.90 for both academic identity and academic writing self-efficacy (AWSE). While such figures are uncommon in general cross-sectional research, we argue they warrant a theory-grounded interpretation rather than dismissal, particularly given the supporting diagnostic evidence. We posit that this high explanatory power arises from a confluence of three specific factors intrinsic to our research context and design. Extreme Contextual Intensity primarily characterizes the phenomenon under study. The participant population — Chinese doctoral candidates in Malaysia — operates within a tightly bounded, high-stakes ecosystem singularly focused on thesis completion. Within this pressurized environment, the predictor variables of cross-cultural writing challenges and the peer support buffer plausibly account for the overwhelming majority of systematic variance in outcomes, as they encapsulate the dominant, all-encompassing realities of the participants' academic existence. Secondly, the model's theoretical and measurement specificity contributes to its explanatory strength. The constructs are deliberately focused on a constrained set of deeply interrelated processes within doctoral writing. Notably, the peer support measure was designed to capture context-specific buffering functions, which likely have a more direct and potent relationship with outcomes than generic support measures. Crucially, as confirmed by our bias diagnostics, these high R^2 values are not attributable to methodological artifacts such as common method variance or poor discriminant validity. Consequently, we interpret these results as indicative of a highly deterministic and context-saturated phenomenon. The model suggests that within this specific, constrained system, the mechanisms of challenge and the peer support buffer are so potent that they account for nearly all systematic variance, leaving little unexplained by other factors. This interpretation aligns with and reinforces our core theoretical proposition regarding the paramount role of culturally mediated peer support in asymmetric academic contexts. We explicitly caution, however, that this finding is profoundly context-bound. It may indicate the unique potency of the studied mechanisms for this population, but it is unlikely to generalize to less intensive or more diffuse educational settings. This invites future research to test the boundary conditions of such explanatory power by replicating the model in other high-stakes, hierarchical academic environments.

The analysis of standardized path coefficients and associated effect sizes (f^2) provides a granular understanding of the associative strengths within our proposed model. Interpreting these metrics contextually is essential for moving beyond statistical significance to substantive meaning. The dominance of peer emotional support in predicting academic identity is theoretically coherent within the specific context of our study. For Chinese doctoral candidates operating within Malaysian academia, peer networks appear to constitute a proximal, actionable, and collectively legitimized resource. This resource suggests a more direct and powerful association with key outcomes than individual perceptions of challenge or individual competency. This finding refines Social Cognitive Theory by indicating that in high-stakes, hierarchical contexts, the environmental dimension embodied by peer systems may exert a disproportionately strong influence within the triadic reciprocal framework, potentially compensating for constraints in personal agency. It is imperative to emphasize that, due to the cross-sectional design, these results demonstrate strong associative relationships, not causal effects. The data are consistent with a model in which higher levels of reported peer support are strongly associated with higher levels of reported writing efficacy and integration; however, reciprocal or reverse associations remain plausible and cannot be ruled out. Alternative explanations, including measurement specificity, restricted variance in IC, or context-dependent enactment of intercultural competence, cannot be ruled out and should be examined in future research.

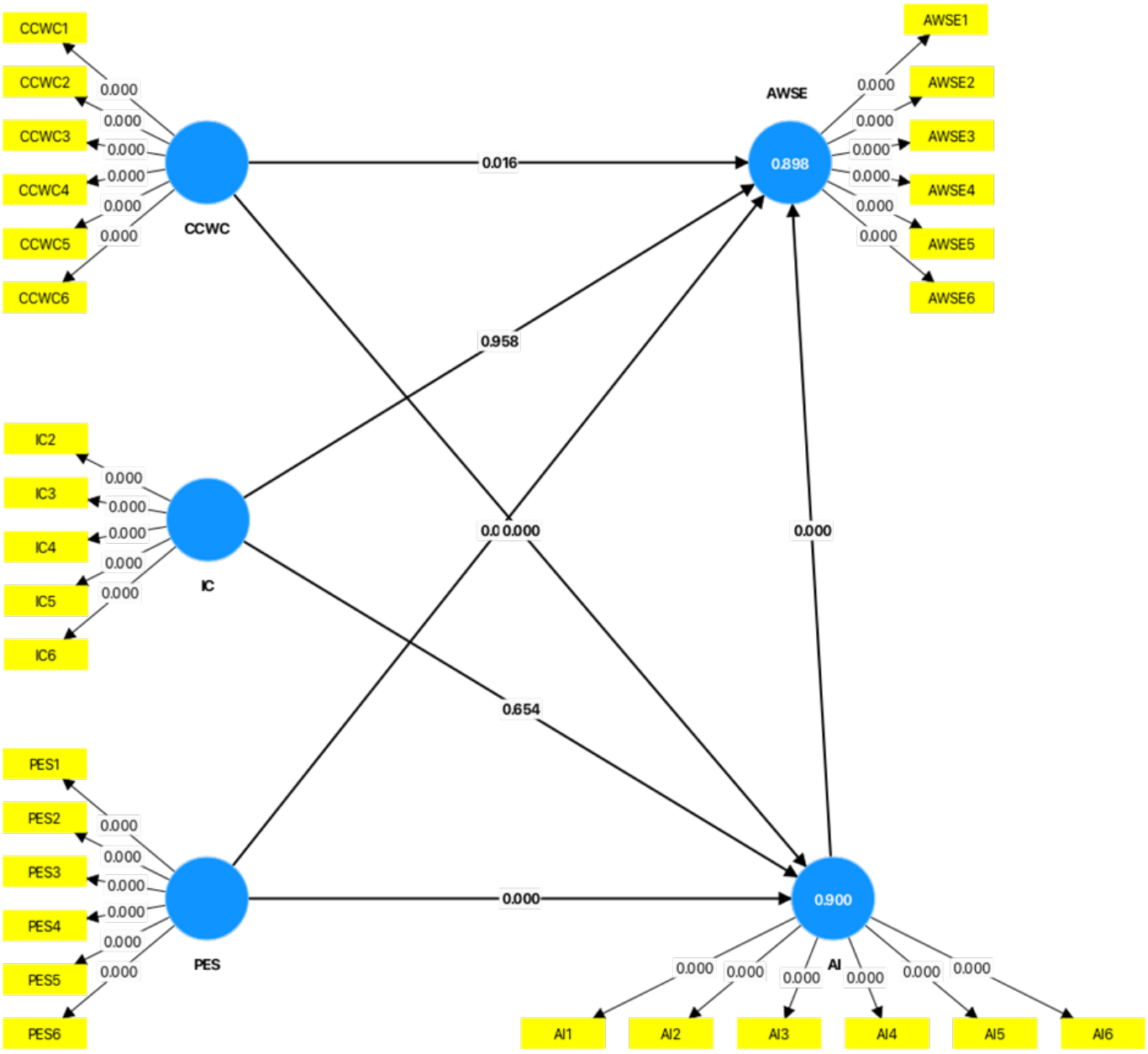

Figure 2: Graphical output (bootstrapping) showing standardized path coefficients (β), p-values, and adjusted R^2 values. CCWC = cross-cultural writing challenges; IC = intercultural competence; PES = Peer Emotional Support; AI = academic identity; AWSE = academic writing self-efficacy.

5. Conclusion

This study examined the mediating role of academic identity (AI) in the relationship between cross-cultural writing challenges, peer emotional support, intercultural competence, and academic writing self-efficacy (AWSE) among Chinese doctoral candidates in a Malaysian research context, guided by Bandura's Social Cognitive Theory. The results confirmed that both cross-cultural writing challenges (CCWC) and peer emotional support (PES) significantly influenced AI, which in turn had a strong positive effect on AWSE, establishing complementary partial mediation. These findings contribute to theory by deepening understanding of how socio-cognitive mechanisms, such as peer interaction and self-concept, shape the development of academic writing in international contexts. Practically, institutions should strengthen peer support systems and culturally responsive academic writing interventions to enhance doctoral students' academic identity and writing self-efficacy. Methodologically, this study reinforces the value of SEM-PLS in unpacking complex mediational pathways. However, limitations include the use of a specific cultural sample and a single-country context, which may affect generalizability. Future research should adopt longitudinal and cross-cultural designs to explore the temporal dynamics of academic identity formation and the role of institutional structures across diverse doctoral populations.

The findings further indicate that cross-cultural academic writing challenges, when appraised as manageable and developmental, can function as catalysts for academic identity construction and academic writing self-efficacy. Interpretations of intercultural competence should be treated cautiously, given the study's cross-sectional design and reliance on self-reported measures. The study employed non-probability sampling methods, which may introduce self-selection bias and limit the sample's representativeness.

Additionally, all data were collected via self-reported questionnaires at a single point in time, which may increase the risk of common-method variance despite procedural remedies. The findings are context-specific and should not be generalized beyond Chinese doctoral candidates studying in Malaysia without caution, as institutional, cultural, and supervisory environments may differ across national and doctoral contexts.

Within this constrained environment, the research refines SCT by identifying and testing a defensible, context-specific mechanism: the culturally-mediated peer support buffer. For Chinese doctoral candidates, peer support appears to evolve from a general facilitative factor into a specialized, agential system that provides socio-cultural translation and collective negotiation strategies, thereby actively mitigating systemic constraints. The study's novelty lies in this theoretical refinement and mechanism testing, offering a model that explains how peer support functions differently in peripheral academic contexts, thereby extending SCT's explanatory power beyond stable, symmetrical environments.

Author Contributions

Zhao Yue: Conceptualization, Methodology, Data Collection, Formal Analysis, Writing – Original Draft. **Seng Yue Wong**: Supervision, Writing – Review and Editing. **Kenny Cheah Soon Lee**: Supervision, Writing – Review and Editing.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Disclosure Statement

AI-assisted tools were used solely for language editing and clarity enhancement. All analyses, interpretations, and conclusions remain the sole responsibility of the authors.

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Ethics Approval and Consent

Ethical approval was obtained from the Research Ethics Committee of Universiti Malaya. All participants provided informed consent before participation. The study was conducted in accordance with the Declaration of Helsinki and the Personal Data Protection Act (PDPA) of Malaysia.

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Structural Model of Perceived Interdisciplinary Competency Development Through Computer Aided Engineering Drawing in Computer Science and Engineering Curricula

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Abstract

This research examines the impact of Computer-Aided Engineering Drawing (CAED) programs on the development of perceived interdisciplinary competency in engineering and computer science courses through Structural Equation Modeling (SEM), focusing on two mediating mechanisms: student attitudes toward CAED programs and the learning process within a supportive institutional environment. The structural equation model explained a substantial proportion of the variance in perceived competency ($R^2 = 0.744$) and indicated that both attitudes ($\beta = 0.787$) and learning experience ($\beta = 0.782$) were considerably influenced by CAED program design. Competency mediated by student attitudes ($\beta = 0.229$) and by learning experience ($\beta = 0.370$) had significant indirect effects, and the institutional context itself positively impacted competency ($\beta = 0.327$), likely reflecting the resources available and the promotion of interdisciplinary teamwork. Overall, the results highlight the significance of designing CAED programs in accordance with industry requirements, alongside active learning methods that foster positive student perceptions, and the importance of robust institutional support systems that equip students with the competencies required in modern engineering practice. The study is limited by its cross-sectional nature and single-institution sample. Future research can examine the long-term effects of these relationships, investigate how institutional variables may moderate them, and test the validity of the relationships across multiple institutions.

Keywords: Engineering Education; CAED; Interdisciplinary Competency; Structural Equation Modeling; Curriculum Design; Student Perception

1. Introduction

Engineering design refers to the engineering principles used in developing new products or in enhancing existing ones. Engineering design is mainly aimed at creating products that meet customer needs and expectations. Besides devising products that are well-functional, engineers must also consider functional appeal, safety, cost, reliability, and manufacturability. Over the past few years, the tendency toward using Computer-Aided Engineering Drawing (CAED) to facilitate the design process has been increasing. This has led to the creation of various advanced computer-based systems that enable designers to design, edit, and analyze engineering designs. These systems are popular across the engineering profession and significantly inform both engineering and computer science education.

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The possibility of equipping students with the capability to translate abstract theories into practical solutions is one of the main advantages of CAED. For example, CAED can assist students in acquiring a wide spectrum of engineering expertise in mechanical, civil, and electrical engineering [1]. The acquisition of such skills advances students' capabilities to engage in critical and creative thinking, and to contribute meaningfully to engineering projects. Also, the application of CAED in curricula enables students to develop greater awareness of geometric relationships, precision, computational thinking, and analytical thinking. Each of these competencies is particularly applicable to new technologies in engineering and computer science, such as Artificial Intelligence (AI) and Machine Learning (ML). In addition, CAED technologies use simulation and analysis tools, which support the design process and provide a platform where students can learn and practice advanced algorithmic and modeling building blocks [2].

1.1. Importance of interdisciplinary competencies in modern engineering and CSE AI/ML education

As technology continues to advance rapidly in both engineering and computer science education, educators need to emphasize the teaching and promotion of interdisciplinary skill sets. Both AI and ML require engineering principles and computational thinking; the use of interdisciplinary skill sets will therefore become even more prevalent in the future [3]. Interdisciplinary skill development enables students to think about problems holistically and develops the communication and leadership skills required for effective teamwork. When students participate in interdisciplinary projects, they are often more motivated and produce better-quality project outcomes [4]. The global move toward sustainable, ethically responsible engineering highlights the importance of curricula that blend CAED, AI, and ML, empowering students to devise innovative, socially conscious solutions and prompting a reexamination of teaching methodologies to meet workforce demands. Integrated frameworks that encourage collaboration across engineering, computer science, environmental studies, and social sciences enhance critical thinking, adaptability, and innovative problem-solving skills; research shows digital literacy and flexible learning environments further strengthen these competencies [5, 6]. The effectiveness of integrated curricula is evidenced by enrichment strategies that bridge achievement gaps and foster talent development, supporting the case for ongoing curriculum redesign to prepare graduates for the evolving technological landscape [7].

1.2. Rationale for studying the development of interdisciplinary skills through CAED

There are many reasons why it is important to develop interdisciplinary skills through Computer-Aided Engineering Drawing (CAED). Most notably, modern engineering tasks involve a broad range of expertise and knowledge. CAED is a unique means for students to learn technical drawing while gaining an appreciation for some of the fundamental computational concepts behind much of modern engineering [8]. Integrating CAED into curricula can also enhance students' ability to apply abstract ideas to real-world problems and provide opportunities for them to develop critical thinking and problem-solving abilities [9]. The literature suggests that early exposure to CAED, including at the K-12 level, is positively related to students' STEM interests and aspirations and prepares them for future engineering and technological work [10]. Moreover, CAED combines theoretical knowledge with practical experience and thereby contributes to the acquisition of skills used in engineering disciplines such as mechanical design, electrical systems, and fluid dynamics [11]. Finally, studies have shown that CAED experiences build communication and collaboration skills necessary for interdisciplinary team-based work, facilitate the creation of a systems-thinking perspective among students when working on project-based activities that bring together computer science and architecture [12], and create new and innovative ways to think about problems that cross disciplinary boundaries [13]. It is increasingly important for educators to integrate CAED into engineering education to prepare students for industry's increasing reliance on integrated and interdisciplinary approaches to engineering and technology innovation [6].

1.3. Objectives and significance of the research

The primary goals of this research are to determine whether CAED enhances educational outcomes by enabling students to develop interdisciplinary skills, and to identify how CAED tools assist students in developing these skills. The purpose of this research is to examine the relationship between students' engagement with CAED practices and their academic performance in Science, Technology, Engineering, and Mathematics (STEM) courses, and to identify best practices for incorporating CAED practices into current curricula. In addition to enhancing students' educational performance, this study provides a framework for developing curricula that educate future professionals capable of navigating complex digital and engineering environments, and contributes to the development of curricula that address an integrated approach to engineering and computer science education. This study also emphasizes the need to adapt present teaching methods to generate innovative and ethically grounded engineering design methods that enable graduates to meet the challenges of the 21st century [14].

1.4. Overview of the use of structural equation modeling (SEM) to explore competency development

Structural Equation Modeling (SEM) is a useful analytical tool for analyzing educational data and investigating the relationships among complex variables, such as competency development in engineering and computer science education. Specifically, SEM models the direct and indirect effects of using CAED practices on students' computational thinking and design skills. Additionally, the inclusion of latent variables in SEM models enables researchers to control for unobserved variables such as students' prior knowledge and attitudes toward interdisciplinary learning [15, 16]. The integration of SEM into research provides a comprehensive framework for understanding the mechanisms involved in the development of interdisciplinary skills, and informs the development of curricular revisions and instructional strategies that address the changing needs of the engineering profession [12]. SEM has been used successfully to evaluate the effectiveness of experiential learning, perceived employability, and the impact of e-learning on students' engagement and achievement, thus providing a basis for the continuous improvement of curricula and for the evaluation of educational methodologies [12].

1.5. Theoretical frameworks related to competency development and pedagogy

Fig. 1 illustrates the growing number of theoretical frameworks employed to support competency development through interdisciplinary pedagogy in engineering and computer science. These include Systems Thinking, which facilitates an understanding of the interconnections among engineering disciplines to solve complex problems [17]; Experiential Learning, which emphasizes the acquisition of knowledge through hands-on experience and increases both technical and interdisciplinary comprehension of students engaged in CAED [18]; and Collaborative Learning, which highlights the value of peer interaction in creating the teamwork and communication skills needed for success in engineering [19]. Digital technologies also influence these pedagogical approaches by enabling collaboration on projects and by increasing student outcomes, thereby supporting a student-centered learning environment that meets the requirements of multidisciplinary engineering education [20].

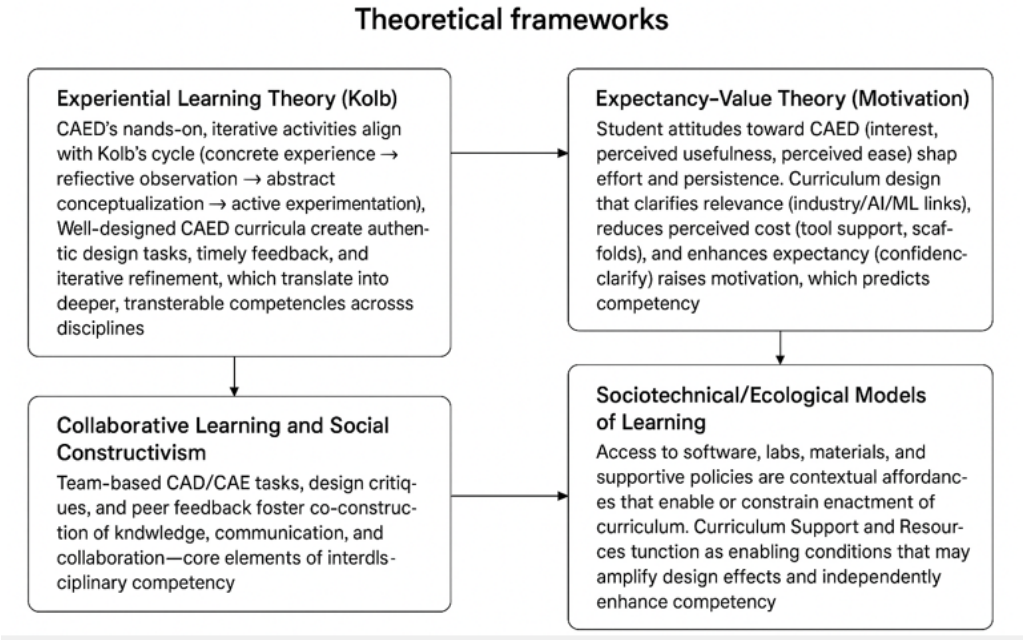

Figure 1: Theoretical foundations underpinning perceived interdisciplinary competency development through CAED, illustrating the role of systems thinking, experiential learning, and collaborative learning in engineering and computer science education.

1.6. Identification of gaps in current research that this study will address

Even though there is increasing interest in research on developing perceived interdisciplinary competency in engineering education, important gaps remain, especially regarding the ways in which CAED develops collaborative interdisciplinary work among engineering and computer science students. In addition to a focus on digital literacy and experiential learning, the empirical literature is relatively weak at identifying the specific mechanisms through which CAED promotes teamwork, problem solving, and innovation across disciplines.

There is also a relative scarcity of longitudinal assessments of student skill development in these areas over time after multiple exposures to CAED [21]; this limits the development of adaptive teaching frameworks for future engineers. Furthermore, many studies currently isolate various skill sets and do not integrate those skills into real-world contexts; therefore, they have limited utility for application in practice. This study seeks to address these limitations by employing SEM to examine the relationships between the use of CAED and the development of interdisciplinary teamwork and student skills, with the goal of providing educators with evidence-based suggestions for enhancing their curricula to meet the needs of modern engineers.

2. Conceptual Framework and Hypotheses

2.1. Construct definitions, scope, and theoretical grounding

Curriculum Design reflects intended pedagogical structure and alignment, whereas Learning Experience captures enacted pedagogy as perceived by students during course delivery. This study examines the relationship between the quality of CAED curriculum design and the perceived interdisciplinary competency of students through two primary mechanisms, student attitudes toward interdisciplinary teamwork and students' learning experience, within the context of an institution that supports curriculum and has adequate resources, as shown in Fig. 2. This framework is grounded in three theoretical foundations: Systems Thinking (competencies develop as a result of the interrelationships among curricular, pedagogical, and contextual components), Experiential Learning (the design of the curriculum influences the authenticity and hands-on nature of the learning experience, which ultimately builds competency), and Collaborative Learning (student attitudes and engagement serve as the mediator that transforms instruction into capability) [22, 23].

2.1.1 CAED Curriculum Design (CD; exogenous)

CD captures students' perceptions of the curriculum's relevance, interdisciplinarity, and pedagogical quality. It includes alignment to industry and cross-disciplinary needs, integration of modern CAD/CAE software, and active-learning methods (e.g., PBL, studios). Theoretically, high-quality design creates meaningful learning affordances that elevate motivation and engagement (Experiential Learning) and improve transfer to interdisciplinary contexts (Systems Thinking).

2.1.2 Student Attitudes toward CAED (SA; mediator)

SA reflects motivational and affective orientations: interest and engagement, perceived usefulness, perceived ease of learning, and willingness to apply knowledge. Positive attitudes improve persistence and depth of processing, enabling higher-order skills transfer (Expectancy-Value theory; Collaborative Learning).

2.1.3 Learning Experience in CAED (LE; mediator)

LE represents the realized pedagogical experience: hands-on practice, challenge and problem-based tasks, instructor feedback, and accessible digital tools. High-quality LE operationalizes curriculum intent into situated practice that builds problem-solving and integrative skills (Experiential Learning cycle).

2.1.4 Perceived Interdisciplinary Competency Development (IC; endogenous)

IC denotes the ability to apply engineering drawing and design concepts across domains (e.g., CSE/AI/ML and other engineering fields), to reason critically about multi-domain problems, and to communicate and collaborate across disciplinary boundaries (Systems Thinking; 21st-century competencies).

2.1.5 Curriculum Support and Resources (CS)

CS captures the institutional and material context: availability of software, laboratories, learning materials, and broader institutional encouragement for interdisciplinary learning. Supportive contexts amplify how curriculum design translates into effective learning experiences (sociotechnical and ecological models of learning environments).

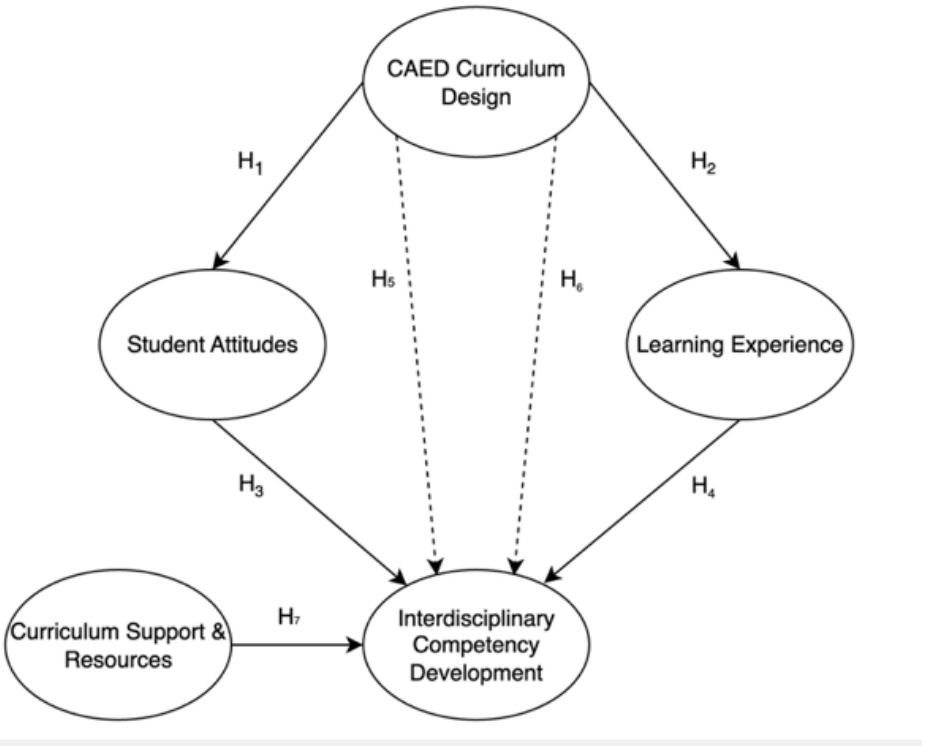

Figure 2: Conceptual framework illustrating the direct effects of CAED Curriculum Design on Student Attitudes and Learning Experience, the mediating roles of attitudes and learning experience in perceived interdisciplinary competency development, and the direct contextual effect of Curriculum Support and Resources on perceived interdisciplinary competency development.

All constructs are conceptualized as reflective latent variables: indicators are manifestations of the underlying construct (changes in the construct should shift all indicators in the same direction). This specification is appropriate because items are interchangeable, are expected to correlate, and can be dropped with minimal change to construct meaning. A formative specification for CS can be considered in future work if its facets are non-interchangeable and causally formative; in this study we retain reflective measurement for parsimony and comparability.

2.2. Structural model logic

The model posits that curriculum design is the primary lever that institutions and instructors control. Its effects on competency are not instantaneous but operate through two proximal student-level mechanisms: attitudes (why students invest effort) and learning experience (what students do and receive in the course). Institutional support and resources condition the potency of curriculum design in shaping the learning experience, because even the best-designed curriculum requires adequate tooling and support to be enacted.

Thus, the core pathways are as follows. CD positively shapes SA and LE (design, then motivation; design, then enacted experience). SA and LE in turn positively shape IC (motivation and experience, then competence). CS exerts a direct positive influence on IC (contextual resource effect).

We therefore evaluate direct effects (CD→SA, CD→LE, SA→IC, LE→IC), two mediations from CD to IC through SA and LE, and a direct contextual path from CS to IC. Optionally, a direct path CD→IC can be specified to test partial versus full mediation; our empirical results support full mediation in the specification without a direct CD→IC path.

2.3. Hypotheses

Direct effects from curriculum design to proximal drivers:

H1: CAED Curriculum Design positively influences Student Attitudes toward CAED (CD→SA > 0). Rationale: relevance, alignment, and active methods increase perceived value and interest.

H2: CAED Curriculum Design positively influences Learning Experience in CAED (CD→LE > 0). Rationale: well-designed courses more reliably deliver hands-on, feedback-rich, tool-integrated learning.

Proximal drivers to competency:

H3: Student Attitudes positively influence Perceived Interdisciplinary Competency Development (SA→IC > 0). Rationale: motivated students persist, transfer, and engage in deeper integrative practice.

H4: Learning Experience has a positive effect on Perceived Interdisciplinary Competency Development (LE→IC > 0). Rationale: authentic practice and feedback build transferable skills.

Mediated mechanisms from curriculum design to competency:

H5: Student Attitudes mediate the relationship between CAED Curriculum Design and Perceived Interdisciplinary Competency Development (CD→SA→IC). A significant indirect effect is expected, with partial or full mediation depending on whether a direct CD→IC path is modeled.

H6: Learning Experience mediates the relationship between CAED Curriculum Design and Perceived Interdisciplinary Competency Development (CD→LE→IC). A significant indirect effect is expected; learning experience is theorized to be a stronger mediator than attitudes when extensive hands-on work is present.

H7: Curriculum Support and Resources directly facilitate students' perceived interdisciplinary competency development by ensuring access to software, laboratory infrastructure, instructional materials, and an environment conducive to interdisciplinary learning. Rather than conditioning curriculum enactment, institutional support is modeled as an independent contextual predictor that contributes directly to competency outcomes alongside curriculum design and pedagogical mechanisms.

2.4. Measurement specification and validity expectations

All constructs are modeled reflectively with five to seven indicators each on a Likert scale (e.g., 1 = Strongly disagree to 5 = Strongly agree). Reflective specification aligns with the expectation that indicators are interchangeable manifestations of the same latent trait and should covary. Expected measurement properties and evaluation plan: indicator reliability with outer loadings ≥ 0.70 preferred, retaining items between 0.40 and 0.70 if AVE and content warrant; internal consistency with Cronbach's alpha and composite reliability (ρ_c) in the 0.70 to 0.95 range; convergent validity with AVE ≥ 0.50; discriminant validity with HTMT < 0.85 to 0.90 and Fornell-Larcker criterion satisfied; and collinearity with indicator VIFs < 5 and inner VIFs < 5. Procedures to mitigate and assess common method bias include anonymity, neutral wording, psychological separation of predictors and outcomes, and statistical checks (full collinearity VIFs $<$ 3.3; Harman's single-factor test).

3. Methodology

This study employed a cross-sectional, quantitative survey design and analyzed the proposed model using Partial Least Squares Structural Equation Modeling (PLS-SEM) in SmartPLS 4. PLS-SEM is appropriate here due to its prediction-oriented focus, robustness to non-normal data, and ability to estimate complex models with multiple latent constructs, mediations, and contextual variables. The analysis followed a two-step approach: first assessing the measurement model for reliability and validity, then evaluating the structural model for hypothesized relationships, mediation, and explanatory power. The target population comprised undergraduate students from engineering programs who had taken a CAED course. The sample included students from CSE/AIML/ISE, EEE/ECE, and CV/ME streams. A total of N = 271 valid responses were analyzed, exceeding recommended minimums from power analysis for models with up to three to four predictors per endogenous construct (for medium effects, $\alpha = 0.05$, power = 0.80, minimum N $\approx$ 77 to 129). This sample size provides adequate power to detect hypothesized effects and supports robust estimation in PLS-SEM. The path-weighting scheme was employed for model estimation, as it is recommended for prediction-oriented models with multiple endogenous constructs. Statistical significance of path coefficients, indirect effects, and total effects was assessed using non-parametric bootstrapping with 5,000 subsamples. Bias-corrected and accelerated (BCa) 95% confidence intervals were used to assess the significance and robustness of parameter estimates. All hypothesis tests were evaluated using two-tailed tests at the 5% significance level.

3.1. Data collection procedures and ethics

Data were collected via online and in-class administration to maximize coverage across departments and years. Participation was voluntary with informed consent, anonymity, and confidentiality clearly communicated. Procedural remedies were implemented to mitigate common method bias, including neutral item wording, psychological separation of predictors and outcomes within the instrument, and assurances of anonymity to reduce evaluation apprehension.

The study adhered to institutional ethics guidelines, with approval obtained prior to data collection. Data were stored securely with access restricted to the research team.

3.2. Data screening and preparation

Data were screened for completeness and plausibility. Given the robustness of PLS-SEM to non-normality, distributional diagnostics were reported descriptively while relying on non-parametric bootstrapping for inference. No excessive missingness was identified; standard handling procedures (e.g., case-wise deletion for rare missing items or mean imputation when appropriate) were applied conservatively. Outliers were evaluated at the indicator level via boxplots and at the construct level via standardized scores; no cases were removed solely based on extremity. Multicollinearity was examined via outer and inner VIFs. Harman's single-factor test was conducted to evaluate the presence of common method bias. All measurement items were entered into an unrotated exploratory factor analysis. The results revealed that the first factor accounted for 34.7% of the total variance, substantially below the threshold of 50%, indicating that common method bias is unlikely to affect the results. In addition to procedural remedies, statistical assessment of common method bias was conducted using the full collinearity approach proposed by Kock (2015). This method involves regressing each latent construct on all other constructs in the model and examining the resulting variance inflation factor (VIF) values shown in Table 10.

4. Results

The results are reported in two stages in accordance with the PLS-SEM procedure: (i) evaluation of the reflective measurement model (reliability, validity, collinearity), and (ii) assessment of the structural model (path estimates, explanatory power, mediation). All estimates were obtained with SmartPLS 4 using the path-weighting scheme and 5,000-subsample bias-corrected bootstrapping.

4.1. Descriptive statistics and sample profile

Table 1 summarizes respondent characteristics (N = 271). The sample is balanced by gender, predominantly in the 19 to 21 age range, and largely drawn from computing disciplines (CSE/AIML/ISE). Most students report at least some familiarity with digital tools and ample access to learning resources, supporting the relevance of CAED in their programs.

Table 1: Demographic sample profile (N = 271).

Variable	**Category**	**n**	**%**
Age group	Below 18	4	1.5
	19 to 21	229	84.5
	22 to 25	38	14.0
Gender	Male	128	47.2
	Female	143	52.8
Department	CSE/AIML/ISE	176	64.9
	EEE/ECE	73	26.9
	CV/ME	22	8.1
Year of study	1st	92	33.9
	2nd	96	35.4
	3rd	17	6.3
	4th	66	24.4
Familiarity with digital tools	Not familiar	32	11.8
	Somewhat familiar	163	60.1
	Very familiar	76	28.0
Access to resources	Yes	238	87.8
	No	33	12.2

The final sample (N = 271) was predominantly aged 19 to 21 (84.5%), with 1.5% below 18 and 14.0% aged 22 to 25. Gender distribution was balanced (47.2% male, 52.8% female). Departmental representation was 64.9% CSE/AIML/ISE, 26.9% EEE/ECE, and 8.1% CV/ME. Year of study included 33.9% first year, 35.4% second year, 6.3% third year, and 24.4% fourth year. Digital tool familiarity was reported as 11.8% not familiar, 60.1% somewhat familiar, and 28.0% very familiar. Access to learning resources was high (87.8% yes; 12.2% no).

4.2. Measurement model evaluation

4.2.1 Indicator reliability

Outer loadings (Table 2) range from 0.790 to 0.915, comfortably above the 0.70 guideline, confirming that all items are strong manifestations of their latent constructs.

4.2.2 Internal consistency and convergent validity

As presented in Table 2, Cronbach's α (0.899 to 0.944) and composite reliability (ρ_c = 0.926 to 0.957) exceed the 0.70 threshold without surpassing 0.95, indicating excellent yet non-redundant internal consistency. Average variance extracted (AVE) values are all greater than 0.70, evidencing strong convergent validity. Table 2 reports indicator loadings, internal consistency reliability, and convergent validity for all reflective constructs. All outer loadings exceed the recommended threshold of 0.70, indicating strong indicator reliability. Cronbach's alpha and composite reliability values are within the acceptable range (0.70 to 0.95), confirming internal consistency. AVE values exceed 0.50 for all constructs, supporting convergent validity.

Table 2: Indicator loadings, construct reliability, and convergent validity.

Construct	**Item**	**Loading**	α	ρ_c	**AVE**
CAED Curriculum Design (CD)	CD1	0.827	0.912	0.935	0.741
	CD2	0.860			
	CD3	0.845			
	CD4	0.888			
	CD5	0.883			
Curriculum Support and Resources (CS)	CS1	0.879	0.944	0.957	0.817
	CS2	0.908			
	CS3	0.905			
	CS4	0.912			
	CS5	0.915			
Perceived Interdisciplinary Competency (IC)	IC1	0.886	0.934	0.950	0.791
	IC2	0.908			
	IC3	0.889			
	IC4	0.855			
	IC5	0.908			
Learning Experience (LE)	LE1	0.827	0.902	0.927	0.719
	LE2	0.857			
	LE3	0.836			
	LE4	0.887			
	LE5	0.831			
Student Attitudes (SA)	SA1	0.835	0.899	0.926	0.714
	SA2	0.840			
	SA3	0.896			
	SA4	0.790			
	SA5	0.860			

4.2.3 Discriminant validity

Table 3 shows that the square root of each construct's AVE (diagonal) is greater than its highest inter-construct correlation, satisfying the Fornell-Larcker criterion. Discriminant validity was also measured using the Heterotrait-Monotrait (HTMT) ratio, as shown in Table 4. The HTMT values were below the threshold of 0.90, providing sufficient evidence of discriminant validity for each of the constructs. The Curriculum Support and Learning Experience pair (0.900) and the Perceived Interdisciplinary Competency and Learning Experience pair (0.899) were close to, but did not exceed, the 0.90 threshold and thus remain within an acceptable range. The relatively high construct HTMT values are theoretically defensible because the constructs are related conceptually within CAED's learning environment, particularly with respect to instructional support and experiential learning. Therefore, discriminant validity exists. Additionally, bootstrapped HTMT confidence intervals did not include the value of 1, further confirming discriminant validity.

Table 3: Discriminant validity: Fornell-Larcker criterion.

	CD	**CS**	**IC**	**LE**	**SA**
CD	0.861				
CS	0.707	0.904			
IC	0.697	0.799	0.889		
LE	0.782	0.830	0.830	0.848	
SA	0.787	0.720	0.769	0.822	0.845

Table 4: Discriminant validity: Heterotrait-Monotrait (HTMT) ratio.

	CD	**CS**	**IC**	**LE**	**SA**
CD					
CS	0.763				
IC	0.752	0.847			
LE	0.860	0.900	0.899		
SA	0.866	0.782	0.836	0.811	

4.3. Structural model evaluation

4.3.1 Path estimates and hypothesis testing

Table 5 reports unstandardized path coefficients, bootstrapped standard errors, t-statistics, p-values, and bias-corrected 95% confidence intervals. All hypothesized direct effects (H1 to H4) are positive and significant ($p < 0.05$). Curriculum Support, specified as a direct predictor, also exerts a significant positive influence on Perceived Interdisciplinary Competency. Inner collinearity was within acceptable limits: VIFs were 1.000 for CD→SA and CD→LE, 3.129 for SA→IC, 3.260 for CS→IC, and 4.849 for LE→IC (below the threshold of 5), indicating no critical multicollinearity among predictors of endogenous constructs. Path coefficients were statistically significant in the expected directions. CAED Curriculum Design had strong positive effects on Student Attitudes ($\beta = 0.787$, $t = 19.665$, $p < 0.001$) and Learning Experience ($\beta = 0.782$, $t = 14.785$, $p < 0.001$). Both Student Attitudes ($\beta = 0.229$, $t = 2.205$, $p = 0.028$) and Learning Experience ($\beta = 0.370$, $t = 3.230$, $p = 0.001$) positively predicted Perceived Interdisciplinary Competency. Curriculum Support and Resources exerted an additional direct positive effect on Perceived Interdisciplinary Competency ($\beta = 0.327$, $t = 2.991$, $p = 0.003$). The model demonstrated substantial explanatory power: R^2 was 0.619 for SA and 0.612 for LE (moderate to substantial), and 0.744 for IC (substantial), indicating that the predictors collectively explained a large proportion of variance in the focal outcome. Bias-corrected 95% confidence intervals for all direct, indirect, and total effects did not include zero, confirming the statistical significance and robustness of the estimated relationships.

Table 5: Structural path coefficients and hypothesis testing.

H	Path	VIF	β	SE	t	p	LCI	UCI	Supp.
H1	CD → SA	1.000	0.787	0.040	19.665	< 0.001	0.708	0.862	✓
H2	CD → LE	1.000	0.782	0.053	14.785	< 0.001	0.677	0.870	✓
H3	SA → IC	3.129	0.229	0.104	2.205	0.028	0.032	0.423	✓
H4	LE → IC	4.849	0.370	0.115	3.230	0.001	0.142	0.585	✓
H7	CS → IC	3.260	0.327	0.109	2.991	0.003	0.114	0.540	✓

LCI and UCI are the 2.5% and 97.5% bounds of the bias-corrected 95% CI.

4.3.2 Explained variance

Table 6 shows that the model explains 61.9% of the variance in Student Attitudes, 61.2% in Learning Experience, and a substantial 74.4% in Perceived Interdisciplinary Competency. Although in-sample predictive relevance was supported by substantial R^2 values, out-of-sample prediction using PLSpredict was not conducted in the present study. Future research should employ PLSpredict to evaluate case-level predictive accuracy across multiple institutions and instructional contexts.

Table 6: Coefficient of determination (R^2).

Endogenous construct	R^2	Adjusted R^2
Student Attitudes (SA)	0.619	0.617
Learning Experience (LE)	0.612	0.610
Perceived Interdisciplinary Competency (IC)	0.744	0.741

4.3.3 Effect sizes

Table 7 details f^2 values. Curriculum Design exhibits very large effects on both mediators ($f^2 > 1.5$). Effects on IC are smaller but meaningful; Curriculum Support contributes a small-to-moderate effect. Effect size estimates (f^2) indicated that CAED Curriculum Design had very large effects on both Student Attitudes ($f^2 = 1.622$) and Learning Experience ($f^2 = 1.577$), corroborating the central leverage of curriculum design. Effects on Perceived Interdisciplinary Competency were smaller but meaningful: $f^2 = 0.066$ for SA, 0.111 for LE, and 0.128 for CS, consistent with mediation where proximal outcomes transmit curriculum influence to competency.

Table 7: Effect sizes (f^2).

Predictor → Criterion	f^2	Interpretation
CD → SA	1.622	Very large
CD → LE	1.577	Very large
SA → IC	0.066	Small
LE → IC	0.111	Small
CS → IC	0.128	Small to moderate

4.3.4 Mediation analysis

Bootstrapped specific indirect effects (Table 8) confirm that Student Attitudes and Learning Experience both significantly mediate the influence of Curriculum Design on Perceived Interdisciplinary Competency (H5 and H6). Because no direct CD→IC path was modeled, mediation is full: the total effect equals the sum of indirect effects.

Table 8: Specific indirect effects.

Indirect path	β	**SE**	**t**	**p**	**LCI**	**UCI**	**Mediation**
CD → SA → IC	0.180	0.082	2.208	0.027	0.021	0.347	✓(H5)
CD → LE → IC	0.290	0.092	3.138	0.002	0.118	0.472	✓(H6)

LCI and UCI are the 2.5% and 97.5% bounds of the bias-corrected 95% CI.

Bootstrapped indirect effects supported dual mediation of the CAED Curriculum Design effect on Perceived Interdisciplinary Competency. The indirect effect via Student Attitudes was 0.180 (t = 2.208, p = 0.027) and via Learning Experience was 0.290 (t = 3.138, p = 0.002), both statistically significant. The total effect of CAED Curriculum Design on Perceived Interdisciplinary Competency was 0.470 (t = 5.209, p < 0.001). In this model specification, no direct CD→IC path was estimated; the total effect equaled the sum of the two indirect effects, indicating full mediation through attitudes and learning experience. This pattern is theoretically consistent with the premise that curriculum influences competency largely through motivational and experiential mechanisms.

4.4. Total effects

Table 9 aggregates direct and indirect effects. The largest total impact on Perceived Interdisciplinary Competency stems from Curriculum Design ($\beta = 0.470$), underscoring its strategic importance.

Table 9: Total effects on Perceived Interdisciplinary Competency.

Predictor	**Total** β	**t**	**p**	**LCI**	**UCI**
CAED Curriculum Design (CD)	0.470	5.209	< 0.001	0.294	0.639
Learning Experience (LE)	0.370	3.230	0.001	0.142	0.585
Curriculum Support (CS)	0.327	2.991	0.003	0.114	0.540
Student Attitudes (SA)	0.229	2.205	0.028	0.032	0.423

LCI and UCI are the 2.5% and 97.5% bounds of the bias-corrected 95% CI.

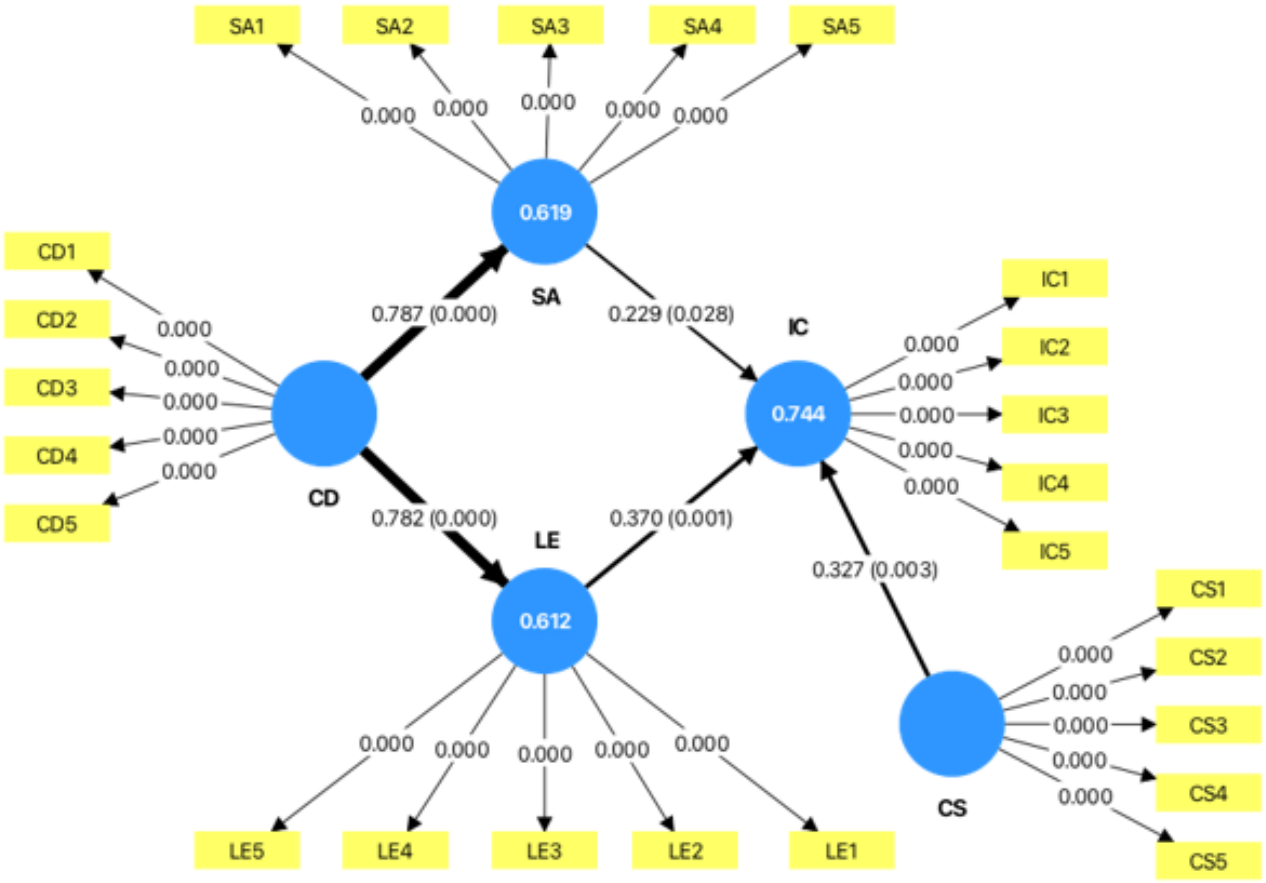

Figure 3: Total effects of CAED Curriculum Design, Student Attitudes, Learning Experience, and Curriculum Support and Resources on Perceived Interdisciplinary Competency Development based on PLS-SEM estimation.

4.5. Common method bias assessment

All reliability and validity criteria are met or exceeded by the measurement model, thus validating the subsequent structural analyses. As shown in Table 10, full collinearity VIF values for all constructs are below the 3.3 threshold proposed by Kock (2015), confirming the absence of substantive common method bias in the structural estimates.

Table 10: Full collinearity VIF (common method bias assessment).

Construct	**VIF**
CAED Curriculum Design (CD)	2.41
Student Attitudes (SA)	2.78
Learning Experience (LE)	2.95
Perceived Interdisciplinary Competency (IC)	2.63
Curriculum Support and Resources (CS)	2.52

In addition, support from institutions generates competency independent of curriculum design, and warrants additional study as an external contextual moderator in future work. Ultimately, the results indicate that curriculum design quality, meaningful learning experiences, and institutional support are interdependent strategies for developing students' capacity for interdisciplinary capabilities through CAED education.

4.6. Predictive relevance

Table 11: Predictive relevance (Q^2) using blindfolding.

Endogenous construct	**Q^2**
Student Attitudes (SA)	0.421
Learning Experience (LE)	0.398
Perceived Interdisciplinary Competency (IC)	0.512

The predictive relevance of the model was assessed using the cross-validated redundancy (Q^2) measure obtained through blindfolding. As shown in Table 11, all Q^2 values were greater than zero, indicating that the model demonstrates strong predictive relevance for Student Attitudes, Learning Experience, and Perceived Interdisciplinary Competency.

4.7. Summary of hypothesis testing

Table 12: Summary of hypothesis testing.

H	**Statement**	**Result**
H1	CD positively → SA	Supported
H2	CD positively → LE	Supported
H3	SA positively → IC	Supported
H4	LE positively → IC	Supported
H5	SA mediates CD → IC	Supported
H6	LE mediates CD → IC	Supported
H7	CS positively → IC	Supported

5. Discussion

The results of this research suggest that CAED curriculum design is the principal factor enabling students to achieve competence in interrelated disciplines. Two main factors, students' views regarding their studies and their learning experiences, mediated the relationship between curriculum design and perceived competency within a supportive institutional setting, explaining nearly three-quarters ($R^2 = 0.744$) of the variance in competency. The findings also indicate that the design of the curriculum has a strong impact on both students' views regarding their studies (CD → SA $\beta = 0.787$) and students' learning experiences (CD → LE $\beta = 0.782$), which in turn have a strong relationship to competency (SA → IC $\beta = 0.229$; LE → IC $\beta = 0.370$). These findings support the use of a dual-mediation model, indicating that the influence of curriculum design on competency is indirect, through affective engagement and experiential learning, rather than direct. This is consistent with prior theories such as Experiential Learning Theory, Expectancy-Value Theory, and Systems Thinking Theory, which describe the interaction of curriculum, pedagogy, and context.

Institutional support directly impacts competency ($\beta = 0.327$) by enabling student access to needed tools, reducing obstacles encountered during practice, and promoting students' ability to work together to solve problems across disciplines, although the potential moderating role of institutional support in the design-to-experience pathway may be worth investigating further. This study (i) validated a robust measurement model for the five constructs related to CAED, (ii) clarified a dual-mediator mechanism in which the learning experience exhibits the larger effect size, and (iii) illustrated institutional support as a separate predictor of competency, demonstrating how the curriculum can be translated into capabilities through affective and experiential channels within supportive contexts.

The very large effect sizes should be interpreted cautiously, as curriculum design and learning experience are conceptually proximate constructs and were measured via self-report, which may inflate associations. The results indicate strong predictive associations rather than causal effects, given the cross-sectional, self-reported design. Additionally, the use of self-reported measures may introduce common method bias and social desirability effects, which should be considered when interpreting the findings. The recommendations emphasize CAED design aligned with industry and interdisciplinarity, hands-on problem-based pedagogies rich in feedback, the fostering of positive student attitudes through relevance framing and scaffolding, and continued institutional support in software, labs, and policies, reflecting the leverage order of design quality, authenticity of learning, student attitudes, and institutional resources.

The findings extend previously established relationships of relevance, active learning, digital integration, and engagement to the outcome of perceived interdisciplinary competency in CAED, with reliable, valid, and predictive assessment. Because causal interpretations are limited by the cross-sectional, self-report nature of the study and the single-institution sample, subsequent research should examine moderation effects, test mediation models that include direct paths, employ longitudinal or experimental designs, assess performance-based competency measures, and replicate at multiple institutions with subgroup and invariance analyses.

6. Conclusions

This paper presents model-based evidence that CAED curriculum design is one of the strongest levers for building interdisciplinary perceived competencies in engineering and CSE programs. The findings should be interpreted as context-specific and not directly generalizable across institutions or disciplines. The impact of curriculum design is mediated by two proximal pathways, students' attitudes toward CAED and students' learning experience, with the latter being the stronger mediator. Institutional support also contributes to perceived competency separately, strengthening the case for the use of software, lab access, and policies that are supportive of students. The measurement model demonstrates good psychometrics, and the structural model explains nearly three-quarters of perceived interdisciplinary competency variance, with theoretical predictive relevance.

Practically, the findings of this study suggest four priority areas: first, establishing CAED curricula that respond to industry needs and exhibit an explicitly interdisciplinary approach; second, implementing pedagogies that provide hands-on and problem-based learning experiences with regular feedback; third, instilling positive attitudes toward engineering by making its relevance and usefulness visible; and fourth, investing in the infrastructure needed to create learning environments that approximate real-world experiences.

This study provides practical recommendations to educators and program directors interested in applying CAED to enhance the skills of students preparing to work as effective interdisciplinary professionals. Future investigation should incorporate longitudinal, experimental, and multi-institutional designs using objective measures of performance, to advance the causal understanding of how design is converted to capability and to examine the propositions made in this study, in order to determine whether the recommendations generalize across settings for educating the next generation of engineers capable of effectively applying design, computational, and systemic thinking.

Author Contributions

N. Sudharshan: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft. **M. Shreyas**: Conceptualization, Methodology, Validation, Writing – Review and Editing. **K. B. Vinay**: Data Curation, Investigation, Software, Visualization. **T. R. Praveen Yadav**: Investigation, Resources, Visualization, Writing – Review and Editing.

Declaration of Competing Interests

The authors declare no conflict of interest related to this study.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request, subject to institutional and ethical guidelines.

AI Disclosure Statement

Artificial intelligence tools were used solely for language refinement and editorial assistance. No AI tools were used for data collection, statistical analysis, model estimation, or interpretation of results. All analytical decisions and interpretations remain the responsibility of the authors.

Funding Declaration

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Ethics Approval and Consent

The study was conducted in accordance with institutional ethical standards for research involving human participants. Ethical approval was obtained from the Institutional Ethics Committee of Vidyavardhaka College of Engineering, India (Approval No.: 0064/IEC/VVCE/2025, Date: 23 Aug 2025). The committee reviewed the study protocol, survey instrument, and data-handling procedures prior to data collection. Participation in the study was voluntary. Prior to completing the questionnaire, all participants were informed about the purpose of the study, the nature of their involvement, and their right to withdraw at any time without penalty. Informed consent was obtained electronically, and no personally identifiable information was collected, ensuring participant anonymity and confidentiality.

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Appendix A. Survey Instrument

Overview

This study employed a structured, self-administered questionnaire to measure students' perceptions of CAED curriculum design, attitudes, learning experience, perceived interdisciplinary competency development, and institutional support. All construct items were measured using a five-point Likert scale unless otherwise stated.

Scale anchors: 1 = Strongly Disagree; 2 = Disagree; 3 = Neutral; 4 = Agree; 5 = Strongly Agree.

Section A: Demographic and Contextual Information

Age group: Below 18 / 19 to 21 / 22 to 25. Gender: Male / Female / Prefer not to say. Department: CSE / AIML / ISE / EEE / ECE / CV / ME. Year of study: First / Second / Third / Fourth. Familiarity with digital tools and software: Not familiar / Somewhat familiar / Very familiar. Regular access to required learning resources (software, labs, internet): Yes / No.

Section B: CAED Curriculum Design (CD)

Construct definition: Students' perceptions of the relevance, interdisciplinarity, and pedagogical quality of the CAED curriculum. *Adapted from:* engineering design education and curriculum quality literature (contextualized for CAED).

Table 13: CAED Curriculum Design (CD) items.

Code	Item
CD1	The CAED curriculum is well aligned with industry and interdisciplinary requirements.
CD2	The curriculum incorporates relevant digital tools and software effectively.
CD3	Course materials and activities adequately cover essential engineering drawing concepts.
CD4	The CAED curriculum encourages integration of knowledge across computer science and engineering domains.
CD5	The teaching methods used in CAED courses are innovative and support active learning.

Section C: Student Attitudes toward CAED (SA)

Construct definition: Students' motivational and affective orientations toward learning CAED. *Adapted from:* Expectancy-Value and technology acceptance literature.

Table 14: Student Attitudes toward CAED (SA) items.

Code	Item
SA1	I find CAED an interesting and engaging subject.
SA2	I believe that learning CAED will benefit my future career.
SA3	I feel motivated to learn CAED concepts and skills.
SA4	The CAED course content is easy to understand.
SA5	I am willing to apply the knowledge gained from CAED in practical projects.

Section D: Learning Experience in CAED (LE)

Construct definition: Students' perceptions of enacted pedagogy and instructional experiences during CAED courses. *Adapted from:* experiential learning and active learning frameworks.

Table 15: Learning Experience in CAED (LE) items.

Code	Item
LE1	The CAED course provided sufficient hands-on practice opportunities.
LE2	The use of gamification or problem-based learning enhanced my learning experience.
LE3	The instructor provided timely and helpful feedback during the CAED course.
LE4	Learning CAED helped me develop critical thinking and problem-solving skills.
LE5	The digital tools and resources used in the course were easy to access and use.

Section E: Perceived Interdisciplinary Competency Development (IC)

Construct definition: Students' perceived ability to apply CAED knowledge across disciplines and to collaborate effectively. *Adapted from:* perceived interdisciplinary competency and engineering education literature.

Table 16: Perceived Interdisciplinary Competency Development (IC) items.

Code	Item
IC1	I am confident in applying engineering drawing skills in interdisciplinary projects.
IC2	The CAED course improved my ability to communicate technical ideas across disciplines.
IC3	Thanks to CAED, I can better collaborate with peers from engineering and computer science.
IC4	CAED helped me develop skills relevant to both AI/ML and engineering fields.
IC5	The course enhanced my problem-solving skills in interdisciplinary contexts.

Section F: Curriculum Support and Resources (CS)

Construct definition: Students' perceptions of institutional and infrastructural support for CAED learning. *Adapted from:* institutional support and learning environment studies.

Table 17: Curriculum Support and Resources (CS) items.

Code	Item
CS1	The institution provides adequate learning materials and software tools for CAED.
CS2	The availability of labs and technology supports effective learning of CAED.
CS3	Institutional support encourages interdisciplinary learning in CAED courses.
CS4	I have access to sufficient technical help when using digital tools for CAED.
CS5	Resources provided meet the requirements for mastering CAED concepts and skills.

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Mapping the Landscape of Street Food Research: A PRISMA-Guided Bibliometric Review

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Abstract

Street food has experienced considerable growth, particularly in developing countries, and has become an important component of destination marketing and the tourist experience. Its increasing popularity has attracted significant interest from researchers across various fields, including tourism and marketing. Guided by the PRISMA framework, this study examines the structure and evolution of the street food research landscape through a bibliometric approach. A total of 186 articles from the Dimensions database were analyzed using VOSviewer software. The analysis encompassed author networks, influential journals, contributing countries and institutions, and thematic keyword clusters. The findings reveal substantial growth in research on this topic, with Indonesia, India, and Turkey emerging as key contributors. Major journals publishing research on street food include the Journal of Hospitality and Tourism Management and the British Food Journal. Vikas Gupta and Raj Kumar Gupta are among the most active researchers in this area. Thematic analysis identifies three main clusters: cultural and tourism studies, marketing and consumer behavior, and behavioral theories and intentions.

Keywords: Street Food; Food Tourism; Culinary Tourism; Destination Branding; Tourist Experience; Bibliometric Analysis

1. Introduction

Street food generally refers to food that is cooked or processed and sold in public areas such as streets, parks, and shopping malls [1–3]. It includes both food and beverages sold by hawkers or food handlers [4] and is typically consumed on-site or taken away [5]. Most street food vendors use temporary setups or mobile carts to serve their offerings [6]. Street food represents a region's culinary attraction and reflects its culture [7]. It is important for food security, cultural expansion, and the growth of the informal economy, particularly in regions such as Asia, Latin America, and Africa. Its popularity has increased substantially in developing economies [8]. Street food has been considered a viable option for sustainable tourism development in emerging economies [9], as the experiential quality of street food positively influences destination image [10]. Moreover, variation in street food experiences directly shapes tourists' perceptions of authenticity [11]. This reflects that street food has become a significant component of the travel experience and a useful tool for tourist destinations to build their brand, which is why it has attracted considerable scholarly attention.

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Tourism experts regard street food as a powerful tool for showcasing authentic culture and offering travelers a rich, sensory experience that fosters a connection with the local area [12]. In a context where tourist destinations are seeking differentiation, street food is viewed as a key cultural asset [13] and a marketing tool that enhances destination competitiveness [14]. Countries such as India have used street food as a means of spreading their culture and influence [15]. According to a 2024 report by Innova Market Insights, at least one in four people worldwide consumed street food in the previous year, and 55 percent of those individuals visited street food stalls at least twice a month [16]. As this popularity and commercial activity have grown, so has scholarly interest in studying street food [10, 14]. This growing body of research underscores the need for a comprehensive understanding of what is being studied about street food. Although some studies have been conducted previously, they primarily used limited databases such as Scopus and Web of Science [10, 14]. These databases restrict access through costly subscriptions and provide selective coverage. Such limitations can introduce bias in capturing the full breadth of research scholarship. In contrast, the Dimensions database offers broader and more inclusive open-access scholarly literature without accessibility restrictions, providing a comprehensive view of the research landscape [17]. By adopting a Dimensions-only approach, this study addresses these limitations and provides a broader and more meaningful perspective on the evolution of street food research, with direct relevance to the tourism and marketing fields.

The study aims to answer the following research questions:

1. What are the growth trends in street food research indexed in the Dimensions database?
2. Which journals are the most influential in street food research in terms of citations and bibliographic linkages?
3. Who are the most productive authors contributing to street food scholarship?
4. How is street food research distributed across countries and institutions?
5. Which are the most influential documents in street food research based on citations?
6. What are the dominant thematic keyword clusters in street food research?

2. Review Methodology

2.1. Bibliometric Approach

The term bibliometrics was first used by Alan Pritchard in 1969 [18] to describe the application of mathematical and statistical techniques for analyzing scholarly publications. Over time, this method has gained popularity in business and management research [19, 20], and it is widely used to conduct quantitative assessments of existing literature [21]. This technique helps in understanding knowledge creation, dissemination, and accumulation in a particular field of study [22]. Bibliometric methods are frequently employed to identify influential authors, articles, countries, institutions, and journals, which aids in understanding the structure of knowledge and research trends [23]. Bibliometric analysis has been applied in many different research areas, including the Russia–Ukraine war [24], smart cities [25], service quality and customer satisfaction in the hotel industry [26], reviews of bibliometric studies [27], and the study of behavioral intentions in tourism and hospitality [28]. Building on this established methodological foundation, this study adopts a bibliometric approach to systematically analyze and map the existing scholarly literature on street food.

2.2. Database Selection and PRISMA Framework

Previous bibliometric studies on street food used the Web of Science database [13] or a combination of Scopus, Web of Science, and PubMed [29]. These databases require subscription-based access and may impose coverage limitations. In contrast, this study utilizes the Dimensions database, which is openly accessible and reduces biases [19] while improving transparency and reproducibility in knowledge mapping studies. The Dimensions database indexes over 110 million research outputs, including journal articles, preprints, book chapters, edited volumes, and reports, providing broader and more inclusive coverage of scholarly literature. The Dimensions database offers strong metadata integration and citation linkage, which ensures methodological rigor and analytical consistency [30–32]. To the best of the authors' knowledge, no prior bibliometric study in the field of street food has employed the Dimensions database, thereby offering a novel methodological contribution. The data for this study were extracted using the keyword "street food" in the title and abstract. The study adopts the PRISMA framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [33], as illustrated in Figure 1, for identification, screening, eligibility assessment, and inclusion of studies to ensure transparency and methodological rigor in the record selection process. The initial database search yielded 2,164 records for the period 1987 to 2025.

In the filtering stage, preprints, chapters, monographs, edited books, and proceedings were excluded in the first phase, resulting in 1,803 records. The time duration was then restricted to 2015 to 2025, yielding 1,532 records. To ensure disciplinary alignment, the dataset was further restricted using the field-of-research classification system based on the ANZSRC 2020 taxonomy. Records were limited to classifications under "3508 Tourism" and "3506 Marketing" fields of research. Records classified under other fields of research, such as Environmental Sciences, Public Health, and Food Sciences, were excluded, yielding 186 records for analysis. The inclusion and exclusion criteria along with filtering outcomes are presented in Table 1.

Table 1: Study Filtering Criteria and Outcome

Screening Stage	**Inclusion Criteria**	**Exclusion Criteria**	**Retained (n)**	**Excluded (n)**
Identification	Records retrieved from Dimensions using "street food" in title/abstract (1987 to 2025)	Records not indexed in Dimensions or without keyword in title/abstract	2,164	–
Filtering – Document type	Peer-reviewed journal articles	Book chapters, monographs, edited books, proceedings, preprints	1,803	361
Filtering – Publication period	Records published 2015 to 2025	Records published before 2015	1,532	271
Eligibility – Subject classification	Records classified under 3508 Tourism and 3506 Marketing (ANZSRC 2020)	Records classified under other fields of research	186	1,346
Final dataset	Records meeting all inclusion criteria	–	186	–

2.3. Data Cleaning and Analytical Tool

Following PRISMA-based identification and filtering, the exported file was manually inspected for metadata accuracy and structural consistency. No duplicate records were identified. Author names and institutional affiliations were standardized to reduce variation. Country information was extracted from metadata, and a full counting approach was applied to multi-country publications. Essential metadata (title, publication year, etc.) were verified for completeness before analysis. Van Eck and Waltman (2007) developed a method for visualizing similarities between objects [34] and later, in 2010, developed VOSviewer, a freely available computer program for constructing and visualizing bibliometric data [35]. This tool facilitates the analysis of authorship, citations, co-occurrence, and the geographical landscape of research and has been widely used by researchers conducting bibliometric studies [36–40]. This study used VOSviewer to visualize the authorship network, citation network, and keyword analysis.

3. Bibliometric Findings

3.1. Growth of Publications

As presented in Figure 2, publications in the street food domain have grown substantially from 2015 to 2025. The data were collected on June 1, 2025, with seven months remaining in 2025 and 26 articles already published; it can be expected that the number of documents will exceed that of 2024. In 2015, three articles were published, a figure that increased more than 14-fold to 43 in 2024. The trend shows steady growth, except for a slight decline in 2022. This growth indicates increasing researcher interest in the street food domain.

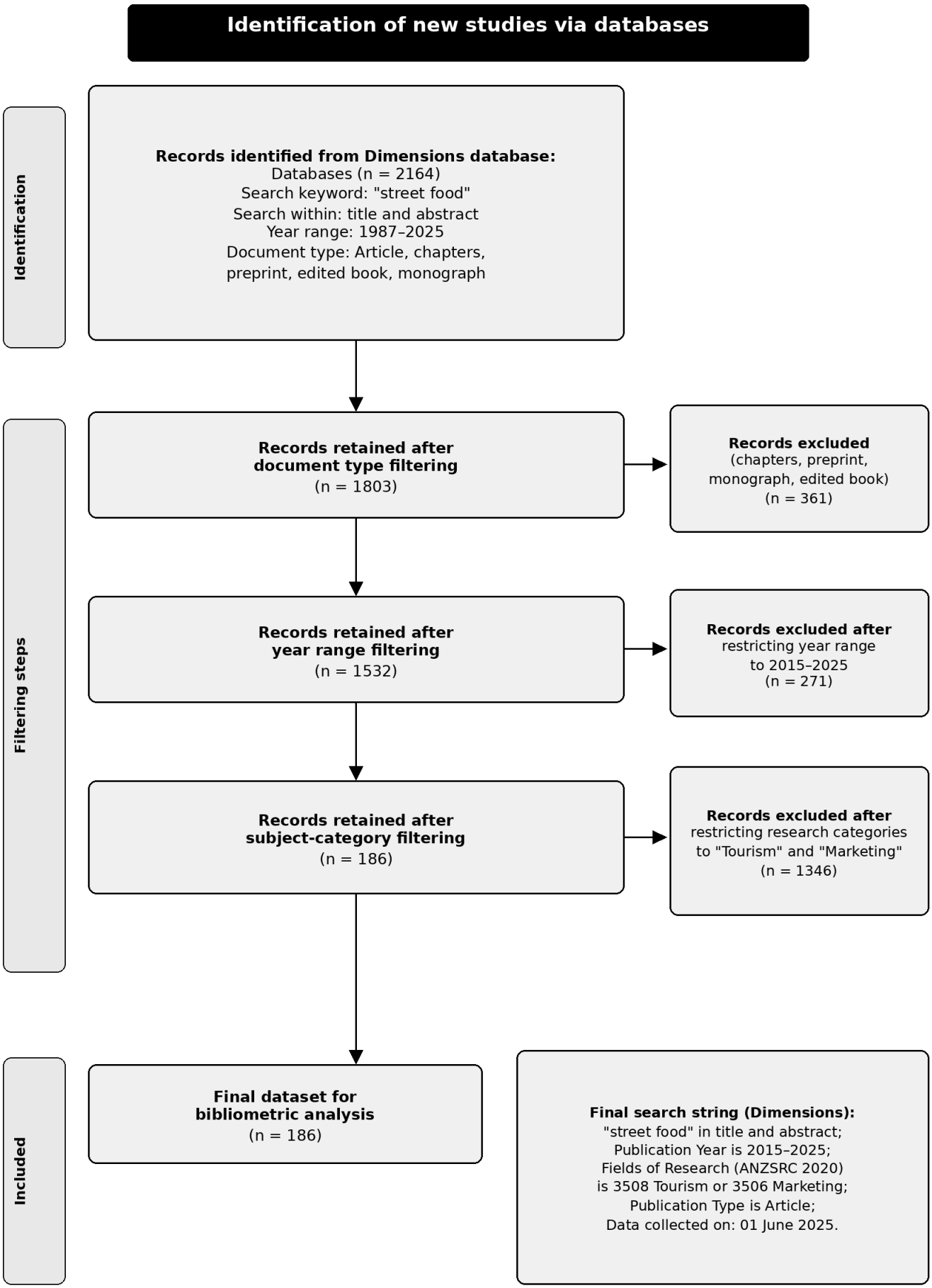

Figure 1: PRISMA-guided flow diagram of record identification and filtering steps for the bibliometric review.

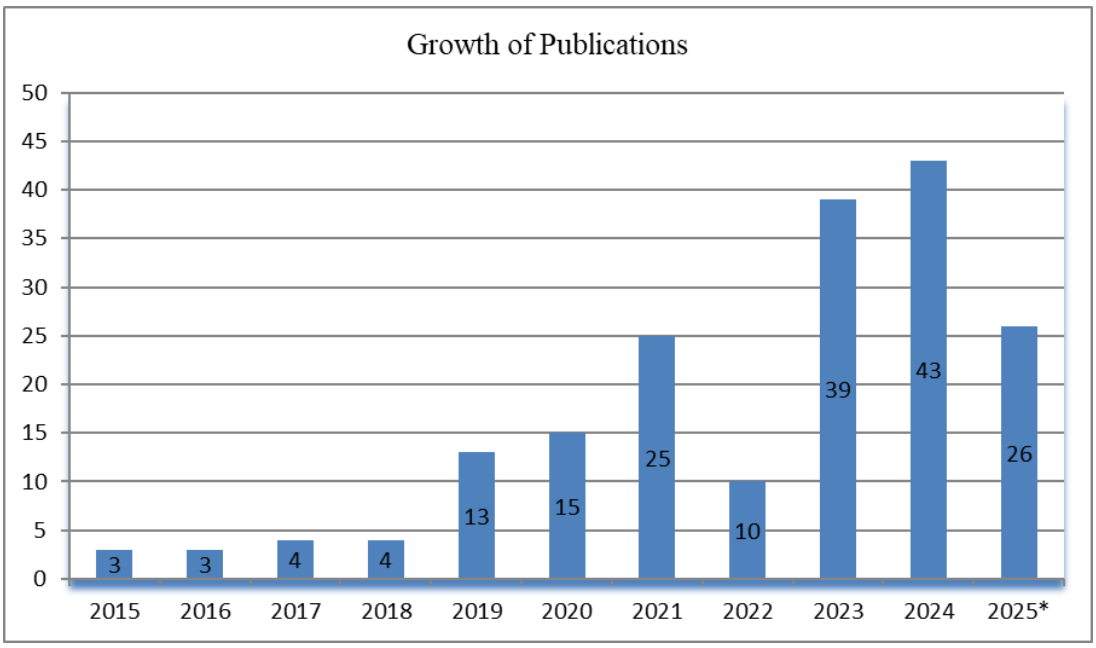

Figure 2: Growth of publications (* As of June 1, 2025).

3.2. Influential Journals

Citation analysis can serve as an indicator of the influence of journals and authors. Using VOSviewer, the analysis was conducted using citation links with a criterion of two documents and 19 citations. The journal analysis presented in Table 2 shows that the Journal of Hospitality and Tourism Management is the most influential journal with 219 citations, followed by the British Food Journal with 208 citations and the International Journal of Environmental Research and Public Health with 83 citations. To enable comparison across journals, citation density, defined here as the average number of citations per document, was also examined. The Journal of Hospitality and Tourism Management has the highest citation density at 54.75 citations per document, followed by the International Journal of Environmental Research and Public Health with 41.5 citations per document. An analysis of source productivity reveals that the British Food Journal is the most productive journal with eight documents, followed by the International Journal of Gastronomy and Food Science with six documents, the Journal of Hospitality and Tourism Management with four documents, and the International Journal of Tourism Cities and Sustainability with three documents each.

Table 2: Most Influential Journals

Source	**Documents**	**Citations**	**Total Link Strength**
Journal of Hospitality and Tourism Management	4	219	20
British Food Journal	8	208	33
International Journal of Environmental Research and Public Health	2	83	13
International Journal of Tourism Cities	3	72	7
International Journal of Gastronomy and Food Science	6	69	11
Journal of Foodservice Business Research	6	69	18
International Journal of Consumer Studies	2	66	1
Sustainability	3	32	1
International Journal of Hospitality Management	2	29	2
Journal of Quality Assurance in Hospitality & Tourism	2	19	10

To examine relationships among journals, a bibliographic coupling analysis was conducted and presented in Figure 3 as a density map containing two clusters of five sources each. Warmer colors in the map indicate higher concentrations of publications and citations. The British Food Journal emerges as the most prominent research outlet, reflecting its central role and strong influence in the field of street food. Other journals with notable density include the International Journal of Gastronomy and Food Science, the Journal of Hospitality and Tourism Management, and the Journal of Foodservice Business Research.

This highlights the strong integration of food science, hospitality, and tourism perspectives. The presence of journals such as Sustainability and the International Journal of Environmental Research and Public Health reflects the focus of studies on the environmental and health dimensions of street food, indicating that research on this topic spans multiple domains.

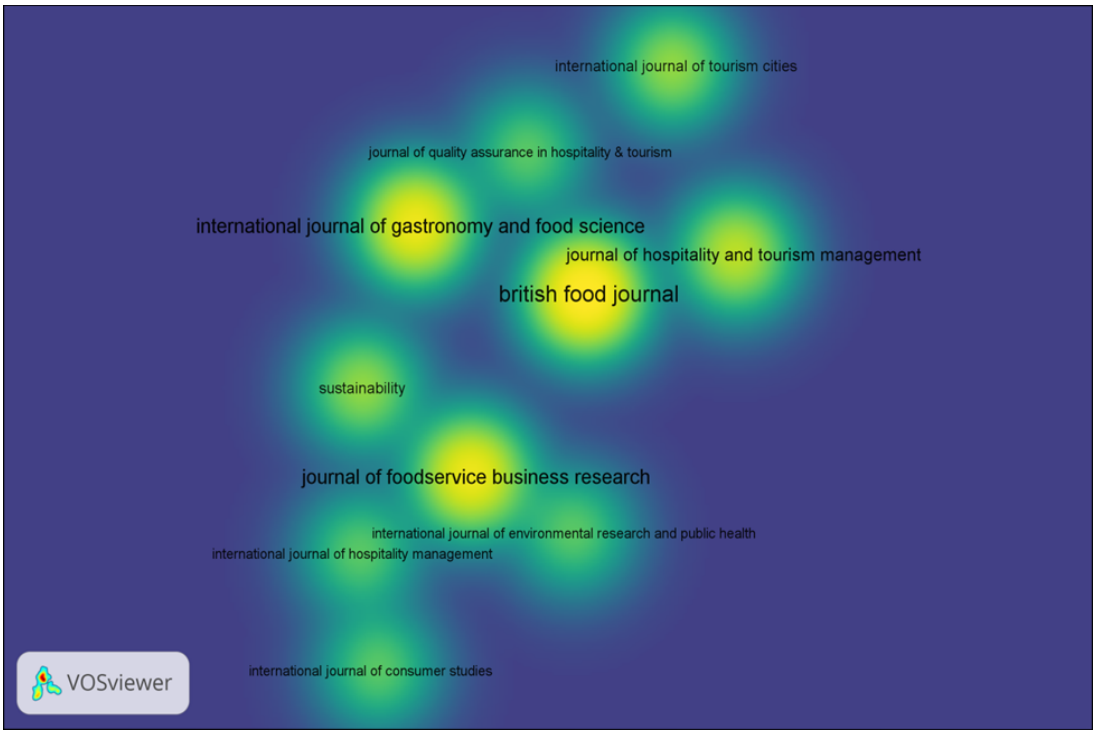

Figure 3: Density visualization map of bibliographic coupling of journals.

3.3. Contributing Authors

An analysis of author productivity and citation performance provides insight into the concentration and influence of scholarly contributions within a field. Author analysis was conducted using a citation-links approach in VOSviewer, with minimum thresholds of two documents and 25 citations. Table 3 presents the ten most productive and influential authors in the street food domain identified through this procedure. Contributions are presented in terms of the number of documents, citations, and total link strength (TLS), where TLS reflects shared citation relationships within the constructed network using the dataset and chosen threshold.

Vikas Gupta emerges as the leading contributor, with the highest number of documents (8), citations (291), and TLS (58). This indicates that Vikas Gupta is not only central to the field of street food but has also helped shape research in this domain through interconnections across different studies. The second-most-cited author is Raj Kumar Gupta, with three documents and 156 citations and the second-highest TLS of 34 in the group. Kavita Khanna, with two documents, has the highest citation density at 65 citations per document. Heesup Han, with two documents, has received 96 citations but with a low TLS of only 3, suggesting that his work has been cited but is less closely connected with the research cluster. Other authors such as Manohar Sajnani, Ibrahim Cifci, and Tita Deitiana display moderate citation levels and TLS values, reflecting meaningful engagement within the street food domain. Conversely, Adeola A. Ayodele and Taufik Abdullah, despite having two publications each, show no link strength (TLS = 0), which may indicate less integration with the dominant citation network. The affiliation of leading authors with developing nations in Asia and Africa reflects the dominance of developing economies in street food scholarship.

Table 3: Most Contributing Authors

Author	Documents	Citations	Total Link Strength
Vikas Gupta	8	291	58
Raj Kumar Gupta	3	156	34
Kavita Khanna	2	130	25
Heesup Han	2	96	3
Manohar Sajnani	2	76	26
Ibrahim Cifci	2	56	24
Adeola A. Ayodele	2	38	0
Tita Deitiana	2	28	8
Wasisto Ruswidiono	2	28	8
Taufik Abdullah	2	26	0

3.4. Research Output Across Countries and Institutions

In mapping research output across countries, it was revealed that document output in the street food domain from 2015 to 2025 originated from 34 countries, of which 12 countries contributed single documents, nine countries contributed two documents each, and three countries produced three documents each. A list of the top ten document-producing countries based on citation links is presented in Table 4. From the table, it is evident that Indonesia, Turkey, and India lead research production in the street food domain with 16, 11, and 10 documents, respectively. India leads in citations with 327, followed by Thailand (291 citations) and South Korea (286 citations). Turkey has the highest TLS. From the table, it can also be inferred that street food is not only popular in developing nations [8] but that developing nations are also leading research output in this domain. However, this pattern should be interpreted with caution, as it may be influenced by the Dimensions database's coverage characteristics, which can favor countries with greater representation in indexed journals, thereby shaping the observed scholarly patterns.

Table 4: Research Output Across Countries (Top Ten)

Country	Documents	Citations	Total Link Strength
Indonesia	16	48	11
Turkey	11	113	78
India	10	327	58
Malaysia	9	115	26
China	8	157	21
South Korea	6	286	46
Thailand	6	291	31
Australia	4	118	15
South Africa	4	50	11
United States	4	76	7

In a similar analysis based on organizational citations, it was revealed that research output between 2015 and 2025 was published by 151 organizations, of which 132 were involved with only one document each and 14 were involved in two documents each. A list of the top five institutions based on research output, with a threshold of three documents, is presented in Table 5.

Table 5: Most Contributing Institutions

Organization	Documents	Citations	Total Link Strength
Amity University	6	278	14
Sejong University	3	134	8
Istanbul University	3	83	18
Indonesia University of Education	3	26	0
Universiti Putra Malaysia	3	24	0

Amity University from India is the most productive institution with six documents and the highest number of citations (278), followed by Sejong University, Istanbul University, Indonesia University of Education, and Universiti Putra Malaysia, each contributing three documents with 134, 83, 26, and 24 citations, respectively.

3.5. Influential Documents

An examination of the most cited documents from the dataset of 186 documents, based on citations received in the Dimensions database as of the date of data extraction (June 1, 2025), was conducted. The analysis indicates a strong inclination toward data-driven research in street food scholarship, as 14 of the top 15 articles are empirical in nature, while one is a review article. An analysis of metadata reveals that the most influential empirical studies predominantly focus on behavioral intentions, experiential authenticity, perceived risk, and service quality, highlighting the central role of these constructs in understanding street food consumption within tourism and marketing contexts.

As presented in Table 6, several studies emphasize the role of factors such as affection, taste value, emotional value, and authenticity in shaping tourists' attitudes, satisfaction, and behavioral intentions toward street food. Other highly cited documents examine the moderating and mediating roles of risk perception, place attachment, and perceived value, suggesting a complex understanding of consumer decision-making. Service quality is another recurrent theme, with multiple studies demonstrating its influence on destination image, satisfaction, and positive word of mouth. Collectively, these influential documents highlight the extensive use of behavioral and experiential models in street food research and reveal academic interest in consumer-centric and theory-driven approaches.

Table 6: Most Influential Documents

Sr. No.	Citation	Article Type	Key Findings
1	[41] (100)	Empirical	Affection is the most important predictor of tourists' behavior toward street food in Phuket among hygiene, affection, food quality, service quality, satisfaction, and value.
2	[42] (97)	Empirical	Proposed a model for street food tourism based on Kotler's marketing mix factors.
3	[43] (90)	Empirical	Risk and benefit perceptions are interlinked and influence consumer attitudes toward street food. Reducing risk perception and increasing benefit perception can positively influence consumer attitudes.
4	[44] (87)	Empirical	Street food attributes are positively significant in understanding tourists' behavior. Risk perception acts as a potential moderator in predicting consumer behavior.
5	[45] (80)	Empirical	Analysis of images and text revealed that food vending is one of the most prominent components of place brand identity.
6	[46] (71)	Empirical	70% of respondents wanted to know ingredients used in street food but were more concerned with taste than health aspects.
7	[47] (59)	Empirical	Taste value has the most influence on tourists' attitudes toward street food in Penang, followed by emotional value. Place attachment mediates the relationship between attitudes and revisit intention.
8	[11] (50)	Empirical	Perceived authenticity and cultural disparity positively influence experiential perception of foreign tourists.
9	[48] (48)	Review	Consumers in developing countries are aware of health risks associated with street food and are willing to pay more for safer options. A lack of regulatory framework for street food was also identified.
10	[49] (45)	Empirical	Service quality positively influences both utilitarian and hedonic values, which in turn positively influence repurchase intention. Risk perception moderates the link between food quality and utilitarian value but not hedonic value.

4. Thematic Analysis

A keyword co-occurrence analysis was performed using VOSviewer based on keywords extracted from titles and abstracts, ignoring structured abstract labels and copyright statements. A binary counting method was used to avoid over-representation of keyword-dense publications. This yielded a total of 4,917 keywords. A thesaurus file was used to unify synonymous terms, and further filtration using a minimum of 10 occurrences as the criterion resulted in 106 documents meeting the threshold. The 64 most relevant keywords were analyzed and presented in Figure 4. From this figure, it is evident that three keyword clusters were formed, as summarized in Table 7.

Table 7: Keyword Clusters

Cluster	Color	Main Keywords	Interpretation
Cultural and tourism studies	Blue	Culture, destination, culinary tourism, interview, case study, observation, promotion, authenticity, originality value, Thailand	Qualitative and field-based research in culinary tourism studies focusing on authenticity
Marketing and consumer studies	Green	Price, marketing strategy, decision, information, location, place, social media, consumer behavior, taste, Indonesia, pandemic, COVID	Marketing and consumer-oriented studies focusing on pricing, information sources, and consumer behavior in street food markets
Behavioral theory and intentions	Red	Intention, behavioral intention, attitude, perceived risk, service quality, food quality, value, health, TPB, street food consumption, street food experience	Application of the Theory of Planned Behavior model to explain street food consumption, behavioral intention, and perception

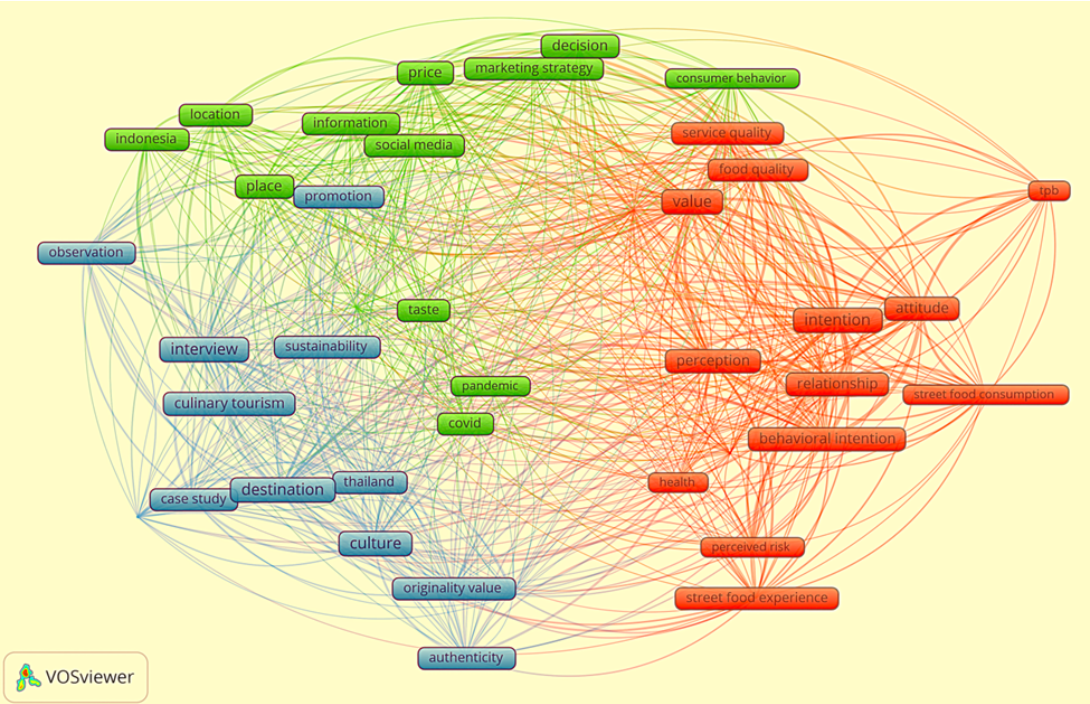

Figure 4: Keyword network visualization.

4.1. Cultural and Tourism Studies

Cluster 1 (blue) represents cultural and tourism studies and includes keywords such as culture, destination, culinary tourism, interview, case study, authenticity, originality value, and observation. This cluster reflects the qualitative nature of street food studies. Keywords such as authenticity and originality value highlight the role of street food as an experiential tourism resource. The interconnectivity of these keywords positions street food as a medium through which tourists engage with local culture and seek authentic experiences. This is consistent with earlier studies that explain street-food-based tourist experiences [8, 12].

4.2. Marketing and Consumer Studies

Cluster 2 (green) represents marketing and consumer-oriented perspectives. The central keywords in this cluster, namely price, marketing strategy, promotion, social media, information, location, place, consumer behavior, and decision, indicate a focus on pricing and marketing communication strategies. The inclusion of keywords such as social media and observation suggests the application of digital and observational techniques in street food research. Indonesia's presence as a geographical marker also suggests a concentration of street food scholarship in developing economies, where street food plays a significant role in consumer markets, as noted by Malhotra [8].

4.3. Behavioral Theory and Intentions

Cluster 3 (red) represents behavioral theories and intention studies, featuring keywords such as intention, behavioral intention, attitude, perceived risk, value, service quality, food quality, health, and TPB. This cluster presents the application of existing behavioral frameworks such as the Theory of Planned Behavior (TPB). The connectivity among keywords such as behavioral intention, perception, service quality, and food quality indicates a correlation between consumer perception and decision-making processes in recent street food scholarship.

5. Discussion and Future Directions

This study employs a bibliometric approach to provide an overview of the evolving research landscape in the street food domain within the tourism and marketing categories. The analysis is based on data sourced from the Dimensions database and visualized using VOSviewer. The findings indicate steady growth in research output over the decade 2015 to 2025, reflecting increasing scholarly interest in street food as a cultural and experiential phenomenon. Journal analysis reveals that the British Food Journal has published the highest number of articles on street food, whereas the Journal of Hospitality and Tourism Management has received the most citations. The analysis of influential authors indicates that Vikas Gupta, Raj Kumar Gupta, and Kavita Khanna are the most cited contributors in street food research. Indonesia, Turkey, and India emerge as the leading countries in terms of research output, while Amity University is identified as the most productive institution. The article by Chavarria and Phakdee-auksorn (2017) is the most cited document in the dataset. Furthermore, keyword analysis reveals three major clusters, demonstrating the multidimensional nature of street food research. Street food scholarship is dominated by developing economies in Asia and Africa.

In terms of academic contributions, this study advances knowledge by systematically mapping the intellectual structure of street food scholarship and demonstrating its interdisciplinary orientation across cultural and tourism, marketing and consumer, and behavioral theory and intentions clusters. The prominence of keywords such as authenticity, originality value, and culinary tourism within the cultural and tourism cluster, together with attitudes, behavioral intentions, perceived risk, and service quality in the behavioral cluster, highlights the continued relevance of established behavioral theories such as the Theory of Planned Behavior (TPB). Moreover, the intersection between these clusters indicates that price, information, and service quality shape consumption intentions by moderating perceived risk and value perceptions. Collectively, these findings highlight the need for integrative frameworks that combine behavioral, experiential, and cultural perspectives in street food research. Methodologically, the use of the openly accessible Dimensions database offers broader and more inclusive representation of scholarly output, particularly capturing contributions from developing economies more effectively and complementing earlier bibliometric studies based on subscription-based databases such as Scopus and Web of Science.

From a practitioner's perspective, the study shows that street food promotes a destination through distinct yet interconnected mechanisms, as identified through keyword clusters. The cultural and tourism studies cluster highlights authenticity and experiential value, suggesting that destination marketers should integrate street food into destination branding as a symbol of local culture. The marketing and consumer studies cluster underscores the role of social media as a promotional tool, enabling operators to communicate in real time. The behavioral theory and intention cluster highlights service quality, food quality, perceived risk, and health considerations, indicating that hygiene standards and quality assurance are critical for strengthening tourist trust and consumption intentions.

Bibliometric analysis is useful for identifying research gaps and guiding future research directions. Based on the findings of this study, future research may integrate social media variables with behavioral frameworks, and comparative longitudinal studies could be conducted to examine the long-term impact of the COVID-19 pandemic. As this study is limited to data sourced from the Dimensions database, future research incorporating multiple major databases may provide deeper and more comprehensive insights into the street food research landscape. As the present study is limited to the "tourism" and "marketing" fields of research (FoR) only, research from other FoR categories such as public health and sustainability may have remained underrepresented; future studies may include additional FoR to obtain a broader

perspective on scholarly output.

6. Conclusions

This bibliometric review systematically maps the intellectual landscape of street food research within tourism and marketing scholarship. The analysis of 186 articles from the Dimensions database reveals substantial growth in research output over the period 2015 to 2025, with developing economies, particularly Indonesia, India, and Turkey, emerging as leading contributors. The British Food Journal and the Journal of Hospitality and Tourism Management serve as the primary publication outlets, while Vikas Gupta, Raj Kumar Gupta, and Kavita Khanna are identified as the most influential authors. Thematic analysis through keyword co-occurrence reveals three distinct research clusters: cultural and tourism studies emphasizing authenticity and experiential value; marketing and consumer studies focusing on pricing, social media, and consumer behavior; and behavioral theory and intentions applying frameworks such as the Theory of Planned Behavior. These findings underscore the multidimensional and interdisciplinary nature of street food scholarship and highlight the need for integrative research frameworks. The study contributes methodologically by demonstrating the utility of the Dimensions database for inclusive bibliometric analysis and offers practical insights for destination marketers seeking to leverage street food as a cultural and promotional asset.

Author Contributions

Anirudh Thakur: Conceptualization, Methodology, Data curation, Formal analysis, Writing: original draft, Visualization. **Sanjeeb Pal**: Supervision, Writing: review and editing. **Rakesh Ahlawat**: Methodology, Validation, Writing: review and editing. **Manish Verma**: Writing: review and editing, Supervision.

Declaration of Competing Interests

The authors declare that they have no competing interests that could have influenced this work.

Data Availability Statement

The bibliometric records analysed in this study were retrieved from the Dimensions database (https://app.dimensions.ai). The dataset is available from the corresponding author upon reasonable request.

AI Disclosure Statement

The authors used generative AI tools (specifically ChatGPT version 5.2) only to improve language quality and manuscript presentation. Generative AI was not used to generate research data or perform analyses. The authors confirm that all results and conclusions are their own and accept full responsibility for the content of the manuscript.

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Ethics Approval and Consent

This study used publicly available bibliometric metadata from the Dimensions database. No human participants, animal subjects, or sensitive personal data were involved; ethics approval was therefore not required.

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Digitalized Organizational Career Management Systems: A Dual-Lens Examination of Functional and Experiential Dimensions

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Abstract

This study investigates Digitalized Organizational Career Management Systems (DOCMS) through two complementary perspectives: functional design and user experience. A systematic literature review was conducted on 87 peer-reviewed articles published between 2010 and 2024, applying PRISMA guidelines to ensure transparency and rigor. Braun and Clarke's six-phase thematic analysis framework was employed for synthesis. The study first developed a bibliometric mapping as a pre-analysis step and then identified six emergent themes: career management strategies, information technology integration, organizational career management, job satisfaction and organizational commitment, career self-management, and career motivation. The review contributes to the literature by combining both bibliometric and thematic approaches, thereby providing a structural overview of the field while enabling a deeper thematic interpretation. The findings indicate that DOCMS research has matured considerably along functional sense-making dimensions (i.e., functional design) while remaining fragmented with respect to experiential aspects (i.e., experience design), thereby necessitating greater integration between the two. Significant contradictions were identified within the literature: between algorithmic objectivity and organizational politics, between system-driven guidance and individual autonomy, and between functional design criteria and relational evaluation processes. A dual-lens framework is proposed to integrate these perspectives through a socio-technical lens. The review offers both theoretical explanations of the socio-technical structure of DOCMS—in terms of organizational functionality—and practical implications for the development of DOCMS that balance organizational efficiency and employee career development. The framework provides organizations with a diagnostic tool for identifying functional-experiential gaps and understanding the underlying contradictions that may limit DOCMS effectiveness regardless of technical sophistication.

Keywords: Digitalized Career Management; Organizational Career Systems; Digital Transformation; Human Resource Technology; Employee Experience; Socio-Technical Systems

1. Introduction

The digital evolution of organizational career management represents one of the most significant changes in human resource management over the past decade [1]. As technology continues to transform the workplace, traditional methods of career development are being redefined through digital platforms and intelligent systems [2].

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Digitalized Organizational Career Management Systems (DOCMS) enable career paths that are more strategic and responsive than ever before. Building on prior conceptualizations of digital HRM and career management, a DOCMS is operationally defined here as a socio-technical system that digitally enables career planning, monitoring, and development through data-driven, interactive, and personalized digital platforms. DOCMS differs from traditional Organizational Career Management (OCM) through its reliance on digital integration and from HR digitalization more broadly by focusing specifically on employee–organization career co-creation. Through the dual-lens perspective, DOCMS can be examined from a functional dimension—focusing on system design, digital integration, and analytics—and an experiential dimension—comprising employee-level perceptions, agency, and relational value.

This framing builds upon Strohmeier's [3] view of digital HRM as a socio-technical system integrating technological and human dimensions and is consistent with Wiblen and Marler's [4] insights regarding the balance between the efficiency of digitalized talent management systems and the experience of employees using them. DOCMS applies this logic specifically to career development contexts by integrating advanced technology solutions such as analytics and artificial intelligence with platform-based applications [5, 6]. Amid rapid changes in career management, the challenge lies in creating a balance between managing the talent pipeline and meeting employee expectations for engaging career development experiences [7, 8].

To respond to this dual-sided pressure, organizations must improve process efficiencies while also creating career management systems that feel relevant to individual employees. Implementing this integrated approach requires organizations to move from a single-function perspective based on conventional thinking to a more holistic view of career management [9]. A comprehensive study of system design, integration capacities, and automation aspects—alongside personalization, engagement levels, and user empowerment outcomes—therefore serves a critical purpose [10].

1.1. Literature Gap and Research Question

Existing research is fragmented across different streams, providing only a partial view. While studies have addressed turnover reduction [5], knowledge worker development [6], and career involvement by sector [8], a cohesive synthesis of how the functional capabilities of systems directly affect user experience remains lacking. Recent systematic and bibliometric reviews have assessed both talent management and employee experiences with digital HRM. Some reviews treat digitalization solely as a technology tool, while others view it only as a managerial concept related to employee experience. Only a few bring both approaches together, thereby highlighting the need for improvement in future research. To clarify this positioning and identify gaps that directly informed the present research question, Table 1 summarizes key reviews published between 2022 and 2025.

To address this gap, the following research question was formulated: *"What are the salient functional and experiential dimensions of DOCMS, as outlined in the current academic literature?"*

This study utilizes a dual-lens framework [11] based upon the emerging digital career competencies concept to create a comprehensive content analysis and synthesis of 87 peer-reviewed articles within the DOCMS domain. Prior reviews on organizational career management have provided useful contributions but also exhibit significant limitations. Certain studies conceptualized their reviews from traditional career management and talent perspectives, with only peripheral attention to digital aspects [12, 10]. Recent bibliometric reviews consider HR digitalization and mention career management but do not provide a systematic synthesis of DOCMS as a conceptual construct.

The present review differs in three distinct ways: (1) timeframe—spanning from 2010 to 2024, reflecting the full movement from early digitization to AI-based systems; (2) scale—studying 87 peer-reviewed articles, providing a broader evidentiary base than prior career management reviews; and (3) focus—applying a dual-lens framework that integrates functional system capabilities and employee outcome experiences.

Previous systematic reviews [10, 12, 13] were primarily focused on organizational career management and talent management frameworks, with limited synthesis of digitalized employee experience perspectives. Lou et al. [13] examined HR digitalization for sustainable performance, and John et al. [14] explored employee experience management in hybrid work contexts; however, these studies tended to view functionality and experience as independent constructs. The present review synthesizes a socio-technical understanding, connecting functional and user-centric DOCMS dimensions.

1.2. Objectives

The objectives of this study are as follows:

1. To investigate DOCMS using a dual-lens framework that combines both functional and experiential perspectives.
2. To identify and analyze the key thematic dimensions emerging from the DOCMS literature.

Table 1: Comparative summary of recent reviews. Source: Authors' compilation.

Study	Dataset	Timeframe	Method	Specific Gap Related to Digitalized Career Management
Sakib et al. (2025)	532 documents from Scopus and Web of Science	1984–2024	Systematic Review and Bibliometric Analysis	Research largely emphasizes operational and relational digital HR activities, overlooking how integrated digital career systems can strategically transform employee development. This absence of a socio-technical synthesis directly motivates examining DOCMS functional dimensions.
Indroputri & Sanjaya (2024)	19 key studies selected from 306 unique records	2020–2024	Systematic Literature Review	Highlights an experiential gap concerning digital-native employees' perceptions of organizational digitalization. Indicates a need for frameworks that integrate user experience and digital system functionality—a core DOCMS objective.
Marin (2023)	Literature from Web of Science and Scopus	Varied	Literature Review and Bibliometric Analysis	Demonstrates weak conceptual linkage between talent management and digitalization. This functional fragmentation shows the need for models that unify digital career infrastructure and human experience—central to the DOCMS inquiry.
Moganadas & Goh (2022)	17 articles plus grey literature and snowballing sources	2016–2022	Content Analysis and Comprehensive Review	Identifies dispersed definitions of Digital Employee Experience and a lack of measurable constructs. This absence of cohesive experiential modeling supports the need to explore experiential DOCMS dimensions.
Zhao et al. (2022)	85 highly influential OCM-related papers	1978–2021	Systematic Review	Finds that organizational career research is still grounded in pre-digital hierarchies. Calls for exploration of digitally enabled career agency and perception, aligning with the experiential perspective of DOCMS.

3. To contribute theoretical insights into socio-technical career management systems and practical guidance for organizations seeking to optimize their digital career systems.

2. Literature Review

2.1. Evolution of Career Management in Organizations

Recent years have witnessed major changes in organizational career management. The field has shifted from manager-dominated processes to complex technology-powered platforms focused on employee agency and personalization [15]. Earlier, organizational career management was a fragment of general human resource management activities, characterized by standardized processes, formal succession planning procedures, and high levels of managerial intervention [6, 16].

These systems were mainly based on internal labor market philosophy and organizational hierarchies [17]. Career advancement was previously defined by set performance metrics and managerial discretion—a definition largely centered on processes, procedures, and control rather than individual development or employee satisfaction [18]. The only opportunity for career advancement was through the traditional promotion ladder, with rare opportunities for lateral or alternative career paths [9].

As employees demanded flexibility and autonomy in managing their own career development, these rigid structures began to erode [19]. Employees also sought employer support for self-directed learning, valued contracted responsibilities, and expected ongoing development of their career identity [20]. This change represents a general shift in the employment relationship, where job security has been traded for increased opportunities for learning and career adaptability [12].

Within knowledge-driven industries and among the younger workforce, older career management systems hold little appeal. These employees value rich learning experiences and professional development over upward mobility within organizational hierarchies [21]. Organizations have begun to realize that managing employee career trajectories cannot simply be a mechanical process. Instead, systems that enable the management of multiple individual career aspirations while aligning those aspirations with overall strategic business goals are now sought.

2.2. The Emergence of Digital Career Platforms

The introduction of digital technologies marked an important shift in career management. Digital technologies offer greater opportunities for scalability, accessibility, and customization than traditional methods. Digital career platforms eliminated many difficulties associated with traditional career management and manager-centric systems by providing greater transparency regarding job opportunities and increased feedback regarding career progression. Prior studies indicate that digital career platforms are able to meet the growing demand of employees for self-directed career growth [7, 22], thereby aligning with evolving employee expectations.

Early digital platforms provided a way of automating existing processes without fundamentally changing how careers were managed. Over time, technology progressed to offer more advanced automation, including the ability to create personalized development pathways and to facilitate mentorship relationships within both the hospitality and higher education industries [23]. Additionally, functional integration increased through technology enabling seamless data transfer between talent analytics, learning management, and performance tracking systems [24, 25], thereby paving the way for digitally driven strategic human resource management [26].

Virtual learning platforms have also created new ways of learning collaboratively, fostering career growth. Social learning and mentoring tools have increased the importance of developing careers through informal peer networks rather than solely through traditional hierarchical supervisor–subordinate relationships [27].

2.3. Digitalization vs. Digital Maturity

A Career Management System (CMS) has evolved from one that merely converts paper-based processes into electronic formats to a digitally mature system. A digitally mature CMS utilizes advanced, integrated technologies that promote the creation of a Digital Workplace Environment where each employee's career path is informed by data-driven feedback and peer interaction [28, 29].

A digitally mature CMS demonstrates that the current career management system is a combination of social and technical components, maintaining a balance between organizational financial success and employee personal development. By considering both factors, a digitally mature CMS supports the goals of increasing overall organizational efficiency while also meeting individual employee goals through digital workplace technologies. These technologies allow a digitally mature CMS to develop anticipatory career interventions and create tailored career development paths. Machine learning algorithms review employee competencies, performance patterns, and career goals to provide tailored recommendations on learning interventions, likely occupational transitions, and development priorities. Such systems can identify impending skill gaps before they become critical and suggest anticipatory development programs to address them.

However, research indicates that technological sophistication alone is no assurance of system effectiveness. Technologically advanced but poorly designed systems have been found to lead to employee alienation, incongruence between personal objectives and system suggestions, and reduced trust in organizational career counseling [30]. The implication is that DOCMS must be strong at the functional level while also being experientially capable from the user's perspective.

2.4. The Need for Combined Perspectives

Although great progress has been made with DOCMS development, practice and research remain split into two areas: technology development and human experience. The major trends in career management research proceed from two different perspectives. The first focuses on the technological capability of systems, such as usability, automation capabilities, and analytic support systems. The second is centered on user behavior toward DOCMS, including user satisfaction, engagement, and identity construction. Research has addressed both perspectives, but they have rarely been examined together, even though they are often intertwined [24, 31].

By separating the understanding of DOCMS into technology and user behavior, a knowledge gap has emerged regarding how to properly design and implement DOCMS to achieve optimal system performance while enhancing user experience. Organizations attempting to leverage automation and analytics for increased productivity must simultaneously create a DOCMS that meets the needs of employees by providing personalized and meaningful career support. Due to these divergent approaches, it is not uncommon for a DOCMS to excel in one capacity while being deficient in another.

The functional versus experiential dichotomy demonstrates the conflicting theories present in DOCMS scholarship. Baruch and Vardi [32] describe "Doublethink" as a set of contradictions within career management literature that utilizes overly optimistic language regarding digitalized systems while failing to consider the complexities of employee experience with instability and risk. Although such systems allow career choice through self-directed tools, the algorithms behind them can limit true autonomy. De Vos and Cambré [33] also identified the "Career Management Paradox," which holds

that while organizations need predictable talent pipelines, the contemporary workforce is more individualized and less likely to adhere to a standardized model of talent development. Institutional systems have made this paradox even more prevalent, creating solutions that provide opportunities for empowerment while limiting actual choices.

A growing body of literature advocates for a more integrated approach examining how DOCMS function best when system and engagement characteristics are combined rather than examined independently. Guan et al. [31] concluded that career adaptability is influenced by both DOCMS characteristics and individual psychosocial development. Salleh et al. [24] added that technical capability alone is never sufficient, as users also need to feel emotionally engaged with the system.

These findings serve as the basis for the dual-lens methodology used in this review. Specifically, DOCMS are assessed on two interrelated levels: the outcomes achieved by system users and the design of the system itself as a functional entity. This dual evaluation recognizes that long-term DOCMS utility depends on both functional performance and the degree to which the system is valued by employees. The review therefore incorporates both perspectives to address the long-standing fragmentation in DOCMS research.

3. Review Methodology

This research utilized a systematic thematic literature review to explore DOCMS in human resource management. The purpose was to determine the most significant functional and experiential drivers of workplace career management digitalization. The literature scope was broad, with stringent inclusion and exclusion criteria applied to ensure the highest possible quality and pertinence of sources.

3.1. Search Strategy and Inclusion Criteria

Peer-reviewed journal articles were systematically retrieved from Scopus on 7 May 2025. The search approach complied with PRISMA guidelines [34] to enable replicability and transparency. A systematic Boolean search syntax employing wildcards (e.g., "digitali*ed," "organi?ational") and truncation operators was used to accommodate terminological variation across international scholarly settings [35, 36]. Scopus was selected as the primary database because of its comprehensive coverage of management and HRM journals, proven reliability, and suitability for bibliometric analysis [37]. The review period was 2010–2024, encompassing early digitization efforts along with more recent AI-driven platforms. The database search was conducted in May 2025, applying a time filter from 2010 to 2025 to ensure full coverage of recent studies. However, the final eligible corpus comprised 87 publications from 2010 to 2024, and all analyses, results, and reporting correspond exclusively to this 2010–2024 period. The base year (2010) was selected because it reflects the initial emergence of digitized career systems in the scholarly literature.

The broad search query employed was as follows: ("digitali*ed organizational career management system" OR "organi?ational career management" OR "Digital* career management system" OR "Technolog* career management system" OR "E-career management system" OR "Digital career management platform" OR "HR tech career management system" OR "organi?ational career Development" OR "OCM" OR "career management" OR "career management framework" OR "E-career management system" OR "career management tool"). The broad initial yield reflected the intentional inclusiveness of this Boolean search, which combined both explicitly digitalized and traditional career management terms using OR logic. Including non-digital descriptors (e.g., "OCM," "career management") was deliberate to capture transitional and foundational studies where organizational career systems have evolved toward digitalization. This approach follows construct-evolution logic [3, 4] and ensured conceptual completeness. Multi-stage PRISMA screening subsequently refined the dataset for relevance to digitalized or technology-enabled career management, maintaining methodological rigor.

Articles were limited to English-language journals within Business, Management, and Accounting. Only articles and review papers were considered to ensure analytical richness and specificity. Table 2 summarizes the search parameters.

Table 2: Summary of search parameters. Source: Authors, based on PRISMA [34] protocol.

Parameter	Description
Database	Scopus, selected for comprehensive coverage of management and HRM journals and suitability for bibliometric analysis [37].
Search Date	7 May 2025
Search Terms (Boolean Syntax)	Using TITLE-ABS-KEY: ("digitali*ed organizational career management system" OR "organi?ational career management" OR "Digital* career management system" OR "Technolog* career management system" OR "E-career management system" OR "Digital career management platform" OR "HR tech career management system" OR "organi?ational career Development" OR "OCM" OR "career management" OR "career management framework" OR "E-career management system" OR "career management tool")
Timeframe	Search timeframe: 2010–2025 (from early digitization to AI-based systems); final included studies: 2010–2024.
Document Type / Language	Peer-reviewed journal articles and review papers; English only
Subject Area	Business, Management, and Accounting
Inclusion Criteria	Studies addressing digitalized or technology-enabled organizational career management; HR digitalization linked to career systems; conceptual or empirical works meeting DOCMS scope
Exclusion Criteria	Non-peer-reviewed sources, conference papers, books, reports, and grey literature (excluded during Identification). Conceptual exclusions applied during Screening: studies focused solely on traditional organizational career management or individual career behavior with no digital or technology component; studies on HR digitalization or HR technology without explicit linkage to career management or employee career experience; macro-level labor policy or historical career studies unrelated to organizational digital systems.
Screening Stages (per PRISMA)	Identification: 5,011 records retrieved from Scopus. Filters (timeframe, subject, document type, and language) reduced the set to 408 records. Duplicate removal, exclusion of one medical journal entry, and removal of records with missing author names and DOIs reduced the corpus to 369. Screening: 282 records were excluded based on title and abstract review against inclusion/exclusion criteria. Eligibility: 87 reports met eligibility criteria. Inclusion: 87 articles were included for final synthesis.

3.2. PRISMA Flow and Screening

The initial search query returned 5,011 articles. Timeframe, subject area, document type, and English language filters reduced the corpus to 408. One duplicate (identified by title) was removed, and one entry from a medical journal was excluded, leaving 406 distinct articles. Data cleaning eliminated 33 entries with missing DOIs and 4 entries with missing author information, as these fields are essential for reliable bibliometric mapping and cross-referencing in R-based Bibliometrix analyses, resulting in a final dataset of 369 articles with complete metadata.

Title and abstract screening was conducted to remove studies that did not align with the DOCMS scope. Two reviewers jointly performed the screening and conceptual exclusion process to ensure that only studies linking digital or technology-enabled systems with organizational career management were retained. To assess reviewer consistency, 20% of the full-text papers (74 out of 369) were independently cross-checked, resulting in 91% agreement on inclusion decisions [38]. Any discrepancies were resolved through discussion until consensus was achieved. This process yielded 87 articles for full inclusion. A summary of the systematic search process is shown in Fig. 1.

3.3. Sample and Source Characteristics

Bibliometric and co-word analyses were performed in RStudio (R version 4.5) using the Bibliometrix R package via its Biblioshiny interface [39]. The Scopus dataset was imported and structured using `convert2df()`. Descriptive bibliometric indicators were generated with `biblioAnalysis()` and `summary()`, as shown in Figs. 2 and 3. Co-word networks were created using `biblioNetwork()` and visualized through `thematicMap()`, as shown in Figs. 4 and 5. The keyword co-occurrence network and thematic map were generated using Biblioshiny with author keywords (field = DE). Terms occurring at least twice (minfreq = 2) were retained, resulting in a 250-node co-occurrence network normalized using the association strength method. Labels were automatically generated and positioned by the software without manual adjustment to maintain analytical objectivity. Keyword clusters were identified using the default community-detection routine implemented in Bibliometrix [39]. All analytical parameters were verified from the exported BiblioshinyReport-2025-05-19.xlsx, ensuring reproducibility consistent with bibliometric reporting standards [40].

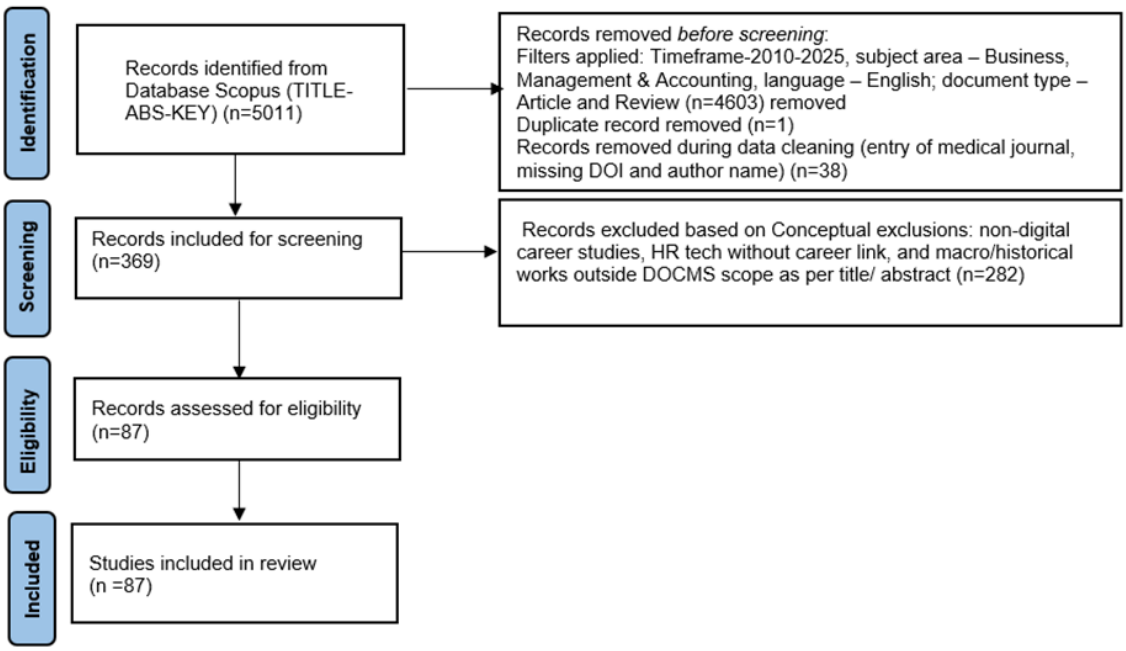

Figure 1: PRISMA flow diagram (search timeframe: 2010–2025; final included studies: 2010–2024). Source: Authors, adapted from PRISMA protocol [34].

The final pool comprised 87 articles across 55 journals authored by 217 scholars, with an average of 2.8 co-authors per document and 14 single-authored papers over the period 2010 to 2024. Fig. 2 shows the bibliometric analysis conducted with Bibliometrix, which revealed an annual growth rate of −4.83% for DOCMS-related studies, suggesting a temporary plateau in scholarly output rather than a decline in relevance. This pattern may reflect thematic consolidation or a shift toward practice-oriented work that is less visible in academic publishing [39]. International co-authorship accounted for 32.18% of output, indicating extensive international collaboration, particularly from India and China [22, 31].

Figure 2: Overview of the sample ($n = 87$). Source: Authors, using Bibliometrix R package.

The leading outlets were the *International Journal of Human Resource Management* (11 articles) and *Career Development International* (8 articles), as shown in Fig. 3. These outlets mirror the field's two major orientations: functional and experiential DOCMS studies. HRM journals largely highlighted technical system features, while the *Journal of Vocational Behavior* focused on user-level career constructs [20].

3.4. Data Analysis Approach

In line with the bibliometric analysis method, this study visualizes how research in the field has developed and uncovers the structural patterns behind it. The literature was thematically analyzed using Braun and Clarke's [41] six phases to identify and interpret themes. Combining these two types of analysis provides a review that integrates an overview of publication trends with deeper thematic insights. DOCMS is an emerging construct, and thus this review incorporated studies that used digital and/or technology-enabled career management approaches to illustrate the development of the DOCMS concept. The use of digital technology in HRM has been viewed as a continuum from traditional HRM practices through to advanced digital systems, according to previous research [42, 43]. Additionally, numerous calls have been made for theory regarding digital HRM to be extended into more specific areas, such as DOCMS [3, 4]. The bibliometric results provided the "what" of the research landscape, while the thematic synthesis provided the "so what"—integrating descriptive evidence with theoretical understanding.

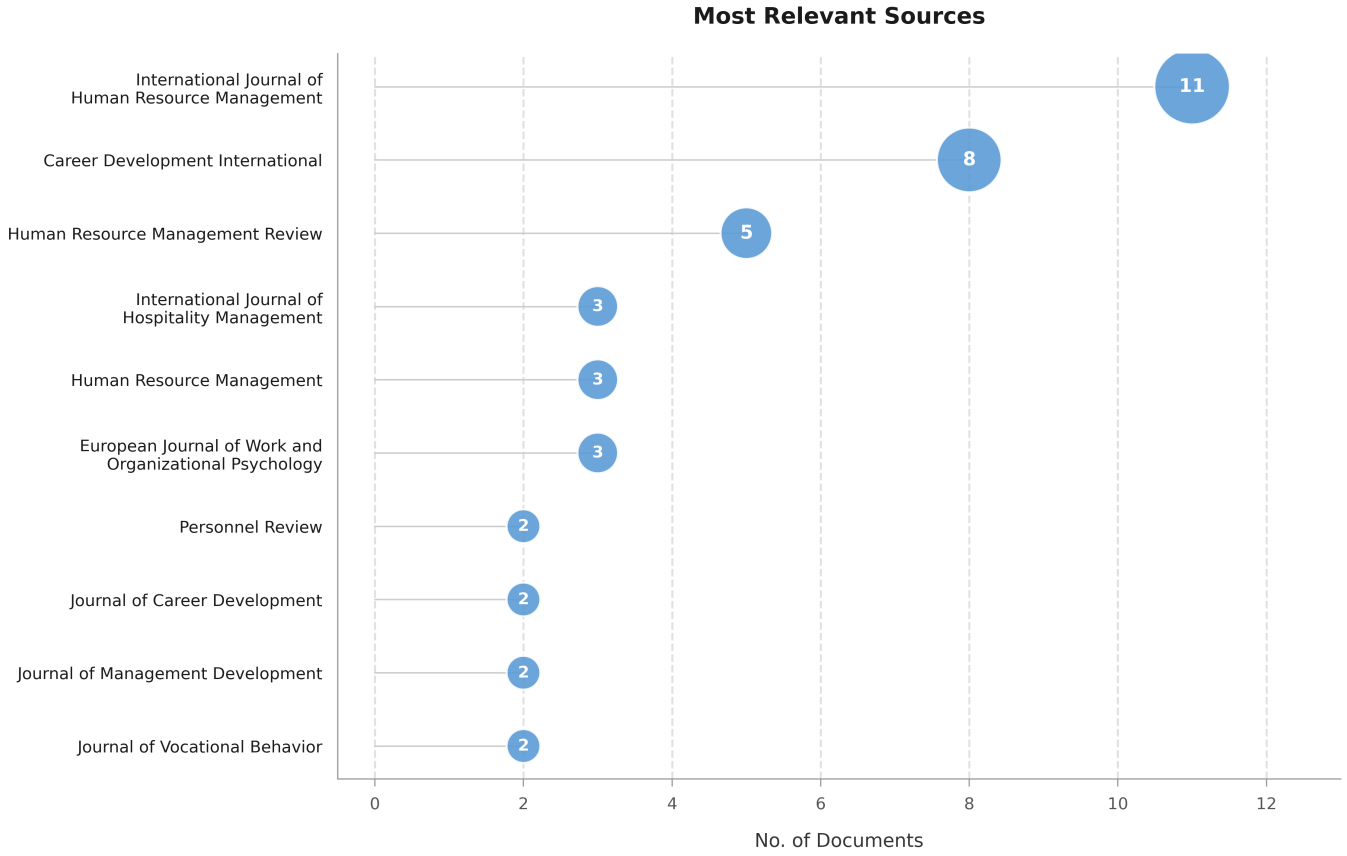

Figure 3: Most relevant journal sources in DOCMS research. Source: Authors, using Bibliometrix R package (Biblioshiny).

3.5. Thematic Analysis Framework

To enhance analytical transparency and methodological rigor, this review adopts Braun and Clarke's [41] six-phase thematic analysis framework as a guiding scaffold for interpreting bibliometric outputs. While the literature analysis employed bibliometric tools (Bibliometrix in R), the conceptual abstraction logic, theme development, and interpretation followed qualitative research best practices, particularly for synthesizing conceptual patterns from diverse sources.

In the first phase (familiarization), all 87 included studies were read in full and revisited multiple times to develop interpretive immersion in the dataset. During this phase, the titles, abstracts, and author keywords of all included papers were also revisited as reference points to support full-text interpretation and ensure consistency with the bibliometric dataset. This reading differed from the earlier eligibility screening, focusing on conceptual understanding rather than inclusion verification.

To identify and refine themes, a hybrid methodology was employed linking bibliometric co-occurrence analysis with interpretive thematic quadrant mapping generated using Bibliometrix (R). Based on the mapped quadrants, two reviewers independently compared the mapped clusters and associated literature and interpreted and labeled the identified themes through discussion until consensus was reached, consistent with the reflexive thematic analysis approach of Braun and Clarke [41]. The 91% agreement reported in Section 3.2 applied only to inclusion decisions, while theme abstraction relied on collaborative interpretation and iterative discussion rather than quantitative coding.

The interpretation process was inductive and concept-driven. Both reviewers independently identified recurring constructs and conceptual phrases (e.g., "career adaptability," "user control," "internal mobility," "digital integration") from titles, abstracts, and author keywords. These constructs were then treated as conceptual codes within Braun and Clarke's [41] framework and refined through iterative discussion to ensure interpretive consistency. The repeated appearance of key concepts—including career management strategy, IT integration, and career self-management—across various articles confirmed the stability of the clusters. The convergence between the bibliometric quadrant map and the qualitative interpretation established six themes, providing comprehensive coverage of the functional and experiential aspects of DOCMS through the dual-lens approach. Functional dimensions represent system-level, data-driven, or technological mechanisms (e.g., predictive analytics, IT integration, algorithmic feedback), while experiential dimensions reflect employee-level perceptions, agency, and relational value (e.g., autonomy, trust, motivation, fairness).

In the second stage, conceptual abstraction was supported mainly through identifying recurring conceptual structures. Keyword co-occurrence data were noted but used as an anchoring point rather than as a basis for coding. This approach aligns with established protocols for integrative and systematic reviews that merge bibliometric structure with qualitative synthesis [44]. In the theme search phase, themes were developed using thematic mapping (Fig. 5), which arranges concepts by density (internal development) and centrality (prominence across the literature).

In the fourth phase (reviewing themes), both reviewers revisited the mapped clusters and literature sources to ensure that the themes accurately reflected the underlying conceptual patterns. Consistency with the dual-lens DOCMS model was applied as a review criterion, and theme boundaries were refined through joint discussion, in line with qualitative synthesis standards [38]. In naming and defining themes (phase five), six core themes were synthesized and clearly categorized under functional and experiential dimensions.

This hybrid design integrates quantitative co-occurrence mapping with qualitative conceptual abstraction, allowing the six themes to emerge both from data structure and interpretive convergence across studies. As DOCMS research is conceptually emergent, not all reviewed studies employed explicit AI, gamification, or predictive analytics frameworks. Accordingly, references to such technologies are used in a general, integrative sense to represent the broader digital or data-driven career management mechanisms identified across the corpus.

3.6. Visual Theme Mapping

A co-occurrence network of keywords in DOCMS literature is shown in Fig. 4. The network was generated using Biblioshiny (field = DE; minfreq = 2; association strength normalization) and includes 250 keywords meeting the frequency threshold. Node size represents keyword occurrence, and edge thickness represents co-occurrence strength.

Larger, centrally located nodes (e.g., "career management," "career development," "organizational career management") represent established functional research clusters focused on organizational processes and interventions. In contrast, smaller peripheral nodes (e.g., "job satisfaction," "career success," "employee retention") reflect emerging experiential dimensions related to individual employee outcomes. Evidence of fragmentation is observed in isolated peripheral keywords (e.g., "career self-management," "person–job fit") and in the limited connections between functional and experiential dimensions, indicating a significant research gap around the mechanisms linking organizational career practices to employee outcomes.

The thematic quadrant map (Fig. 5) was generated using Biblioshiny (field = DE; $n = 250$; minfreq = 2; association strength normalization). Quadrants represent motor (upper right), niche (upper left), basic (lower right), and emerging (lower left) themes. The thematic map analysis identifies dominant motor themes in the top right quadrant: career management strategy and information technology, organizational career management, organizational commitment and job satisfaction, career motivation, and career self-management. The experiential core appears in the bottom right quadrant, consisting of career management, career development, and career success themes. These experiential themes are highly applicable but still disconnected and need to be better integrated with system-level design thinking. The analysis demonstrates that functional capabilities are highly developed but experiential aspects are under-integrated, which justifies the dual-lens approach.

4. Results and Discussion

4.1. Motor Theme Integration in DOCMS: Dual-Lens Analysis Framework

The evolution of digital career platforms has changed the nature of job postings from basic job boards to complete ecosystems that include performance management, learning management systems, and workforce analytics. Kong et al. [45] noted that job postings and 360-degree feedback systems became key tools for promoting internal mobility through open and transparent pathways. Through this integration, organizations are able to align employee development with strategic goals while providing employee-controlled, accessible career resources [6, 16, 45].

Thematic content analysis identified six significant areas of focus for how DOCMS have evolved. While functional dimensions demonstrate increasing convergence around technological integration and analytic capability [24, 29, 46], the experiential dimensions remain comparatively fragmented. Constructs such as user trust, autonomy, motivation, and perceived fairness are discussed across several studies [31, 30, 20, 47] yet without a unified theoretical framing. Functionally, DOCMS studies increasingly align around system-level analytics and predictive models, whereas experiential perspectives are dispersed among psychological, relational, and motivational subfields, reflecting a fragmented theoretical foundation. These six areas are presented below.

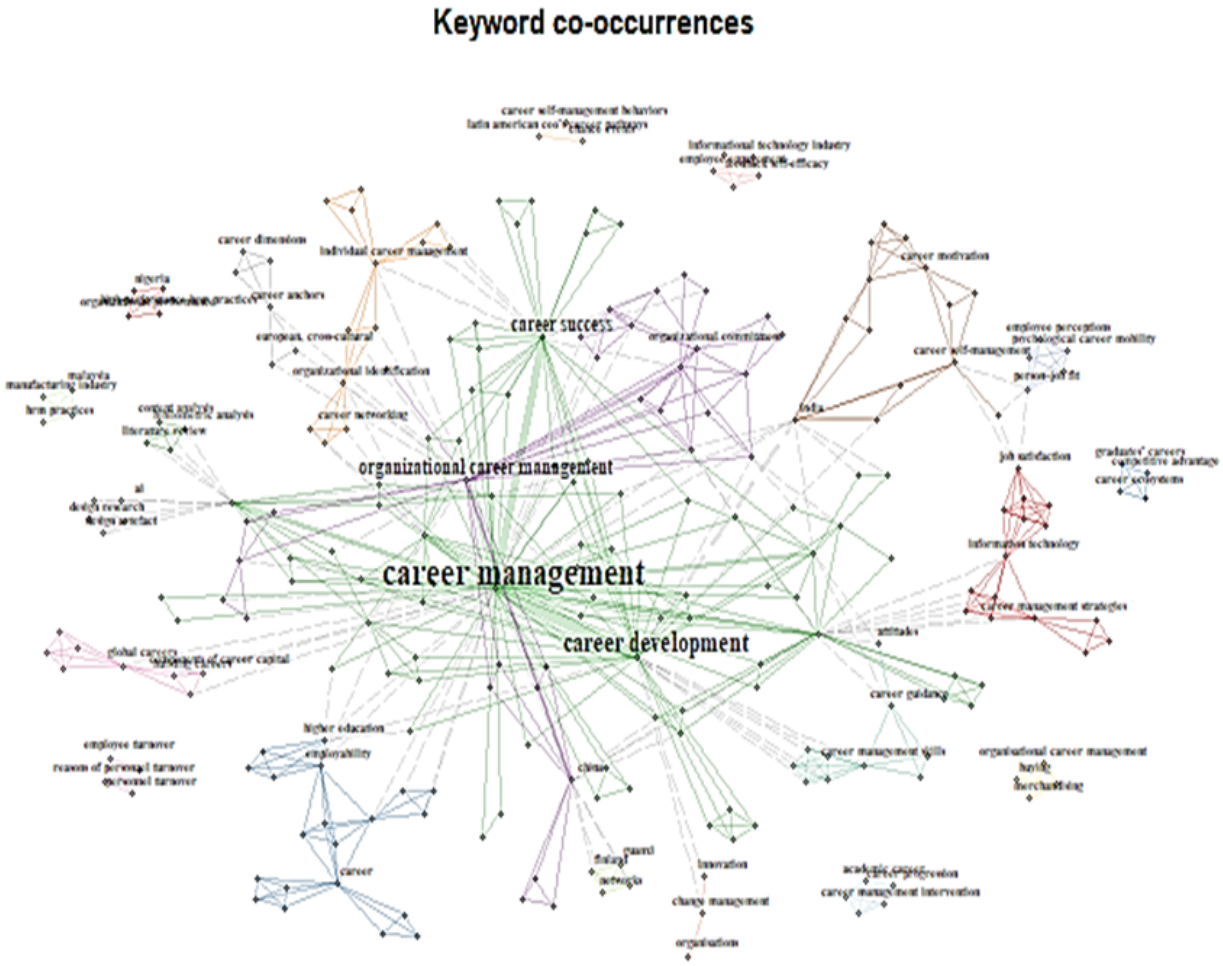

Figure 4: Keyword co-occurrence network in DOCMS literature. Source: Authors, generated in Biblioshiny.

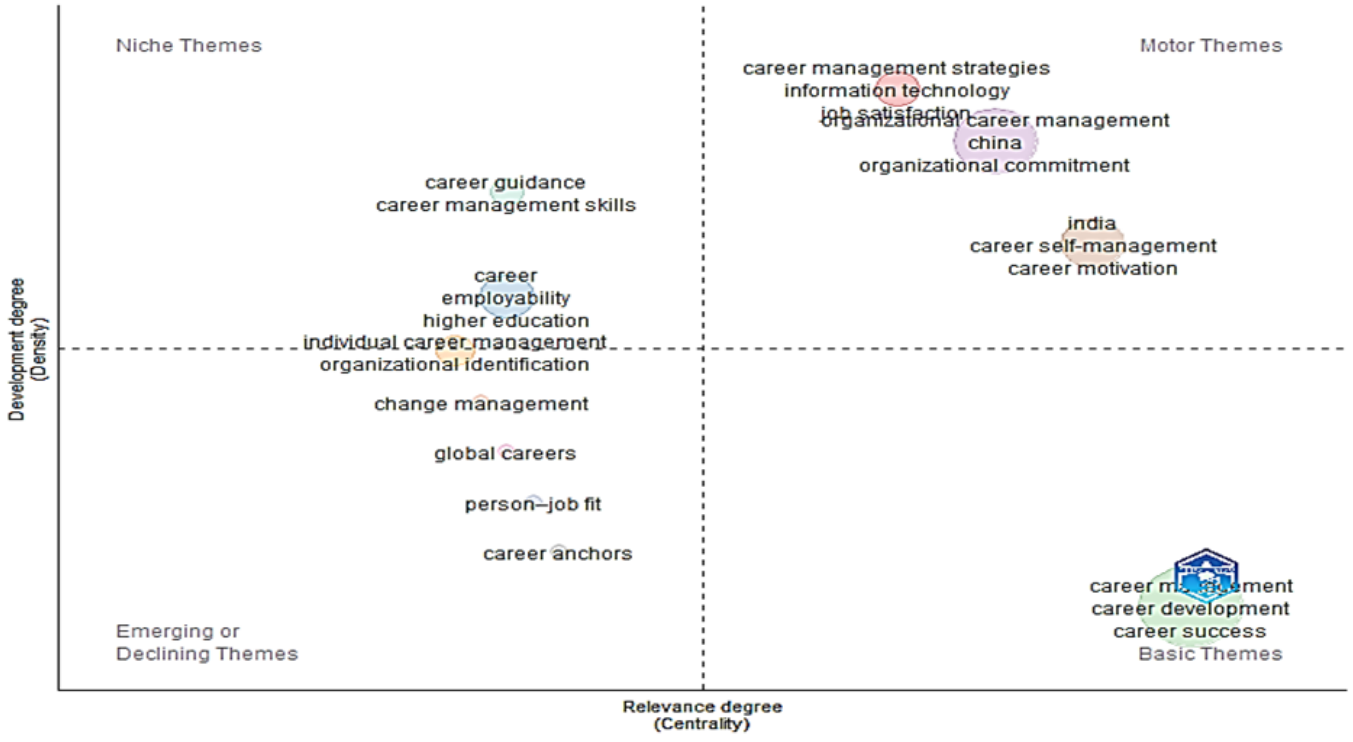

Figure 5: Thematic quadrant mapping of DOCMS literature. Source: Authors, generated in Biblioshiny.

4.2. Career Management Strategies

This theme refers to the algorithmic and analytics-based structuring of career pathways within DOCMS, through which progression options are generated, ranked, and recommended.

Functional focus: Continuous performance data, predictive analytics, and algorithmic job matching are used to construct career ladders and mobility pathways.

Experiential focus: Employees calibrate trust and acceptance of algorithmic career recommendations within predefined system logic.

4.2.1 Functional Dimensions

The incorporation of continuous performance feedback into a career identity framework through advanced analytics is changing how career identity is created and digitally structured. Studies illustrate the increasing importance of algorithmically based job matching, upskilling, and mobility pathways [24, 29]. Such systems lead employees to rely less on direct human decision-making and to make career advancement decisions based on the transparency of organizational succession plans while aligning growth objectives with the changing industry landscape [46, 48]. Contemporary career management platforms (e.g., SAP SuccessFactors, Oracle HCM Cloud) illustrate the real-world manifestation of DOCMS functionalities, using machine learning and predictive analytics to personalize career pathways. These examples are illustrative rather than drawn from the reviewed corpus, as they embody comparable mechanisms reported in the reviewed studies [46, 48]. Such platforms provide organizations with customized learning pathways and structured career ladders, while machine learning systems observe and assess career trajectories to identify optimal career paths and predict probable future skill shortages [1].

4.2.2 Experiential Dimensions

The reviewed studies highlight the importance of balancing algorithmic support with individual user autonomy. Tools that provide real-time feedback and enable self-evaluation of career progress help users gain a better understanding of their careers through iterative processes [31]. On the other hand, excessive automation can erode trust, reduce engagement, and limit the perceived value of recommendations [49]. Several authors [30] emphasize the embedding of career management within daily work routines so that employees may take advantage of data-driven recommendations while maintaining the authority to make their own career decisions.

The literature also reveals significant contradictions regarding algorithmic career recommendations. While DOCMS provide ostensibly equitable means of determining job suitability through algorithms, Darling and Cunningham [19] found that many of these systems operate by "procedural merit" rather than "real merit." Furthermore, Hoffmann et al. [50] found that perceived equality of advancement diminished significantly when employees demonstrated high levels of self-direction—one of the key attributes DOCMS seek to foster. This finding suggests that the most agentic employees may derive the least satisfaction from formalized digital career advancement systems.

4.3. Information Technology Integration

This theme captures the technological infrastructure that enables the operation and accessibility of DOCMS.

Functional focus: Cloud technologies, APIs, real-time data access, and interoperability connecting DOCMS with learning and performance systems.

Experiential focus: User engagement and usability outcomes derived from intuitive design and social learning affordances.

4.3.1 Functional Dimensions

The literature indicates that DOCMS function most effectively when supported by advanced IT systems [25]. These systems provide managers with access to real-time data, mobile connectivity, and assistance in connecting to learning and performance management platforms [25, 24]. Cloud technologies and APIs enable DOCMS users to access global talent pipelines from any region [28]. The integration of these systems allows for a centralized resource that combines employee performance reviews, training history, and skill updates, enabling organizations to track career development paths that directly link to strategic objectives and individual employee growth.

4.3.2 Experiential Dimensions

Usability plays a key role in the successful user experience, even with technological advances. Social learning features and responsive design provide higher engagement than traditional function-driven systems [46]. User-centered designs, including social learning features, enable DOCMS users to discover new opportunities, receive timely feedback, and internalize career insights. Across the reviewed studies, the alignment of technological capabilities with user engagement mechanisms contributes to experiential success, emphasizing that sophisticated functionality cannot guarantee positive career development outcomes without a strong user experience.

4.4. Organizational Career Management

This theme encompasses the organizational-level structuring and governance of careers enabled by DOCMS.

Functional focus: The use of performance data, learning information, and workforce analytics within DOCMS to proactively align individual career paths with organizational objectives, succession planning, and long-term capability development.

Experiential focus: Employee perceptions of organizational support and relational alignment as shaped by career dialogue, clarity of mutual expectations, and the maintenance of the psychological contract.

4.4.1 Functional Dimensions

Career management within organizations has changed from static, hierarchical structures to dynamic, analytics-based systems. Organizations use DOCMS to link individual career paths to organizational objectives by relating performance data, individual learning preferences, and career aspirations [8, 16]. This integration enables HR practitioners to transition from reactive to proactive career management—anticipating and mitigating risk, developing succession plans, and strategically investing in employee development [7].

4.4.2 Experiential Dimensions

Employees derive the most benefit from CMS when their personal goals align with organizational expectations. Cappellen and Janssens [9] posit that digital tools enabling structured "career dialogues" assist in this alignment by clarifying mutual expectations and sustaining the psychological contract between employees and employers. Conversely, without meaningful dialogue and customized development plans, employees may view DOCMS as monitoring tools rather than enablers of growth, leading to dissatisfaction and disengagement [20, 31].

An inherent conflict exists between how DOCMS are functionally designed and how employees evaluate relational career support. Van Vianen et al. [47] found that employees determine whether they are fairly supported by comparing themselves to colleagues rather than by evaluating DOCMS functional capabilities. This creates a challenge particularly for knowledge workers, who tend to distrust supervisor-led career development and rely instead on peer-based learning and interaction [51].

4.5. Job Satisfaction and Organizational Commitment

This theme concerns the affective and attitudinal outcomes associated with employee interactions with DOCMS.

Functional focus: The use of analytics dashboards and predictive models within DOCMS to monitor, assess, and anticipate levels of employee satisfaction, organizational commitment, engagement patterns, and retention risk.

Experiential focus: Employee emotional evaluations of their career development experience, including perceived value, trust, and affective commitment, as outcomes of DOCMS use.

4.5.1 Functional Dimensions

Analytics dashboards integrated with modern DOCMS provide organizations with the opportunity to assess employee satisfaction and organizational commitment in real time. By providing detailed analysis of engagement patterns and possible signs of retention risk [48], DOCMS can identify relationships between satisfaction/commitment metrics and employee performance reviews, participation in learning activities, and career advancement opportunities [52]. Predictive analytics within DOCMS can identify early signs of disengagement, allowing timely organizational intervention.

4.5.2 Experiential Dimensions

Job satisfaction and organizational commitment cannot be fully captured with quantitative metrics alone. Research shows that systems providing meaningful feedback, autonomy, and career clarity are more likely to create and maintain higher levels of organizational commitment [30, 23]. When DOCMS are perceived as monitoring tools rather than development tools, employee trust in the system decreases and affective commitment declines [20, 46]. Systems that succeed in building satisfaction and commitment do so by enhancing the quality of career development experiences rather than merely tracking satisfaction measures.

4.6. Career Self-Management

Career self-management refers to the employee-initiated use of DOCMS to plan, monitor, and adjust career development.

Functional focus: AI-enabled guidance, personalized dashboards, and analytic tools supporting self-directed learning, competency tracking, and career exploration while maintaining linkage to the organizational talent system.

Experiential focus: Employees' perceived control and trust in using DOCMS as a supportive aid for informed career decisions, rather than as an automated or controlling career mechanism.

4.6.1 Functional Dimensions

DOCMS has integrated various tools enabling career self-management, including AI-based career guidance systems, integrated career dashboards, and personalized development planning tools. Through DOCMS, employees can plan, track, and reflect on their careers more autonomously, in addition to enhancing self-directed learning, competency tracking, and applications for internal movement [24, 29]. Using machine learning modules, DOCMS assess learning readiness, recommend professional networks, and identify potential career paths based on employee behavior and progress data.

4.6.2 Experiential Dimensions

Functional capabilities alone are insufficient to create a rich career self-management experience. Research indicates that when organizations offer employees access to digital tools supporting self-directed learning, those employees are more motivated to pursue personal growth [31]. Allowing employees to select training programs and career paths (choice) enables the belief that they possess the ability to make meaningful career decisions (empowerment). However, if a digital system limits authority or second-guesses decisions, employees will likely disengage.

The DOCMS literature regularly presupposes that career capital transfers seamlessly across organizational contexts. However, Dickmann and Cerdin [53] demonstrated that employees at humanitarian field stations build "know-how" and "know-whom" skills that cannot be effectively transferred to organizational headquarters, creating "un-intelligent careers" for employees who forgo upward mobility in commitment to organizational mission. Digital systems designed on the assumption that career capital transfers uniformly between contexts are likely to provide inadequate guidance in specialized sectors.

4.7. Career Motivation

Career motivation refers to the processes through which DOCMS sustain employee engagement in career development activities over time.

Functional focus: Machine learning–driven motivational systems, including gamification features, adaptive feedback, and personalized incentives that respond to users' behavioral patterns and motivational styles.

Experiential focus: Employees' intrinsic motivation, including feelings of mastery, purpose, and relevance, shaped by the perceived developmental value of DOCMS rather than by short-term rewards or control mechanisms.

4.7.1 Functional Dimensions

Several studies anticipate that machine learning–based motivational systems are increasingly central to sustaining career engagement among employees. These platforms use algorithms that continuously improve their ability to motivate users by learning from their behaviors [25]. Gamification features (e.g., badges, leaderboards, achievements) engage users with career development activities [46]. The most sophisticated DOCMS identify different motivational styles

using characteristics identified through behavioral psychology, delivering personalized nudges, feedback, and incentives based on intrinsic motivation patterns.

4.7.2 Experiential Dimensions

Individual career motivation varies considerably. Employees report the strongest connection and engagement with DOCMS when systems adapt to their specific preferences, recognize their accomplishments, and align career development activities with their values and future goals [20]. Because individuals respond differently to encouragement, standardized motivational methods prove inadequate; motivation can degrade rapidly if gamified features do not support real career progression [48, 30]. Sustainable motivation is created when digital systems provide meaningful career growth experiences while demonstrating value based on perceived relevance and developmental benefit rather than merely through gamification models.

4.8. Integrative Framework

To delineate the conceptual boundaries and linkages among the six emergent themes, Fig. 6 presents the Integrative Dual-Lens Framework of DOCMS Themes. It indicates how each theme operates concurrently in a functional (system design) and an experiential (user perception) capacity through various bridging mechanisms, including usability, relational alignment, and empowerment. While certain constructs such as analytics or performance data may recur across themes, this reflects their operation at different analytical levels—systemic, organizational, and individual—rather than conceptual redundancy.

4.9. Practical and Theoretical Implications

The evidence presented indicates that, for any DOCMS to be successful, both technical capability and user-centered design must be combined. Elements that facilitate personalized career support, provide intuitive ease of use, and include opportunities for social interpersonal relationships result in increased user engagement and organizational ownership when used in conjunction with analytics and strategic workforce planning [7, 24]. The dual-lens framework reveals where systems might be unbalanced—strong in function but weak in experience—and exposes a similar divide in the academic literature. DOCMS extends beyond HR digitalization or e-HRM by focusing on career enablement rather than HR automation, integrating both technological and experiential dimensions. It represents a distinct, career-specific evolution of digital HRM that emphasizes co-created digital career value.

4.10. Future Research Directions

Most empirical studies on DOCMS focus on large organizations in Western contexts, and limited attention has been paid to DOCMS use within SMEs, not-for-profit organizations, and developing economies [22, 31]. Future research should examine the minimum viable configurations of DOCMS applicable in resource-limited environments and assess how cultural and infrastructural factors affect system success in Asia, Africa, and Latin America.

Longitudinal studies are also critical. Research designs spanning 3–5 years would allow mapping of DOCMS usage pathways, trust development, and system use patterns, while 5–10 year cohort studies would provide means to measure long-term consequences such as internal career mobility, career adaptability, and retention—aspects not adequately captured by current cross-sectional designs.

Theoretical contradictions associated with DOCMS also require empirical testing, including the paradox of autonomy and control in digital career management [33], the transferability of career capital across contexts [53], and the divergence between DOCMS rhetoric and actual employee experience [32]. Ethical issues requiring attention include conducting audits of bias in algorithmic systems and ensuring equitable access to career opportunities for digitally excluded populations [19]. Finally, further investigation is needed on how algorithmic tools can enhance rather than replace human mentoring and informal mechanisms of career support [30, 31].

4.11. Limitations

Limitations are acknowledged at methodological, disciplinary, and conceptual levels. Methodologically, only Scopus-indexed, English-language publications were searched; therefore, relevant studies may have been missed from regional journals not indexed by Scopus, grey literature, and scholarly material in other languages. Conference proceedings, dissertations, and book chapters were excluded, potentially omitting early-stage research.

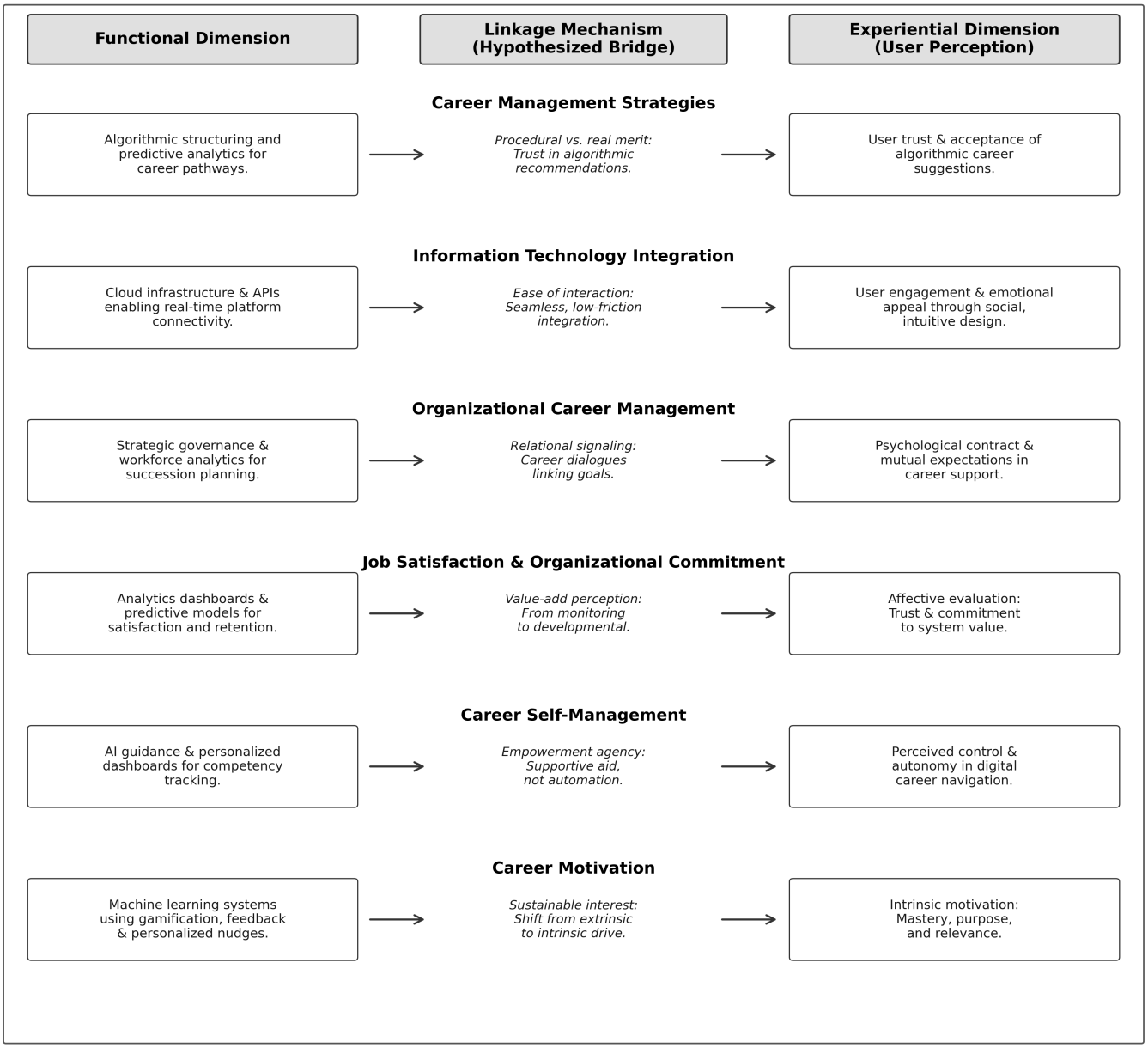

Figure 6: Integrative dual-lens framework of DOCMS themes. Source: Authors' conceptual synthesis, based on thematic and bibliometric integration.

At the disciplinary level, only studies published within Business, Management, and Accounting were reviewed. Studies from information systems, organizational psychology, sociology, and human–computer interaction may offer valuable perspectives for understanding DOCMS as socio-technical systems.

Conceptually, the dual-lens framework does not integrate emerging domains with limited theoretical development in current scholarship, such as algorithmic bias and fairness mechanisms, affective trust in AI-mediated guidance, digital well-being and technology-induced anxiety, and equity of access. The majority of reviewed studies employed cross-sectional designs, which limited the synthesis of longitudinal effectiveness and longer-term career outcomes. Publication bias may also exist, whereby studies yielding positive results are more likely to be published than those yielding null or negative findings.

5. Conclusions

This systematic literature review examines and synthesizes existing research on DOCMS, providing an integration of bibliometric and thematic synthesis rather than proposing a new theory or conducting empirical research. The review offers a thematic analysis of DOCMS through a novel dual-lens framework that integrates functional and experiential dimensions, bridging disparate research streams and providing an integrated picture of effective DOCMS implementation for contemporary organizations.

The six motor themes that emerged—career management strategies, information technology integration, organizational career management, organizational commitment and job satisfaction, career self-management, and career motivation—reveal both the socio-technical promise and inherent tensions of modern career management systems. While DOCMS offer unprecedented functional capabilities, the literature exposes significant contradictions: between algorithmic objectivity and political realities, between system-driven guidance and individual autonomy, and between functional design and relational evaluation. These contradictions indicate that successful DOCMS implementation requires organizations to look beyond efficiency and satisfaction to critically analyze whether digitalization-driven changes are truly transformative or simply the formalization of pre-existing career management contradictions. The dual-lens framework provides organizations with a means to identify functional-experiential gaps and understand the underlying contradictions that may ultimately limit DOCMS effectiveness regardless of technical sophistication.

Author Contributions

Timsy Kakkar: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization. **Bharti**: Conceptualization, Supervision, Methodology, Writing – Review and Editing, Project Administration.

Declaration of Competing Interests

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The Scopus database was searched using the Boolean search method described in Section 3.1 on 7 May 2025. The final set comprised 87 peer-reviewed articles within the Business, Management, and Accounting subject areas. Data were cleaned and screened following PRISMA guidelines. Due to Scopus licensing restrictions, the raw exported file cannot be made publicly available; however, the complete list of 87 included studies with DOIs and titles is available from the corresponding author upon reasonable request.

AI Disclosure Statement

The authors used an AI-based language tool to improve grammar and readability during manuscript preparation. The scientific content, analysis, and conclusions were reviewed and validated by the authors. The AI tool was not involved in the design, conduct, or interpretation of the research.

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Ethics Approval and Consent

Not applicable. This study is a systematic literature review of published scholarly articles and did not involve human participants, animals, or sensitive data.

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Workload-Specific Performance Evaluation of Python Just-in-Time Compilers: A Comparative Study of Numba and Cython

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Abstract

The persistent performance gap in dynamic languages like Python has driven the development of numerous compiler solutions. This paper presents a comparative performance analysis of two prominent Python compilers, Numba and Cython, across distinct computational workloads: recursive (Fibonacci series) and arithmetic-intensive (Euclidean distance). Addressing a gap in existing literature, this study provides an evidence-based framework that maps compiler performance directly to workload types. Experiments conducted in a controlled environment measured execution time, speedup ratios, and memory usage. Results demonstrate that Numba achieves a speedup of up to 6.18× over pure Python for arithmetic-intensive tasks, while Cython performs better in deep recursion cases. The study concludes by offering a workload-to-compiler decision framework, which serves as a practical tool and a contribution to the literature on scenario-based compiler recommendations.

Keywords: Just-In-Time Compilation; Numba; Cython; Python Optimization; Performance Benchmarking

1. Introduction

The demand for high-performance computing in fields such as scientific research and data analysis has driven the need for efficient compilers, even for traditionally interpreted languages such as Python. While various tools have been developed to accelerate Python code, there remains a notable lack of comparative, workload-aware analysis to guide developers in selecting the most suitable compiler for specific tasks. This paper addresses that gap by providing a comparative performance analysis of two prominent Python compilers: Cython, an Ahead-of-Time (AOT) compiler, and Numba, a Just-in-Time (JIT) compiler.

This research explicitly evaluates these compilers' performance across two distinct workload categories: arithmetic-intensive tasks (e.g., Euclidean distance calculation) and recursion-heavy tasks (e.g., Fibonacci sequence generation). By systematically benchmarking their effectiveness on these diverse workloads, the study aims to provide a practical, evidence-based framework that helps developers make informed decisions. This framework provides illustrative guidance on how JIT and AOT compilers behave under distinct workload characteristics, rather than a universal prescription across all Python applications.

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1.1. Compilers and Just-in-Time (JIT) Compilation

A compiler is a program that translates code written in a high-level language into machine code that a computer can execute [1]. This traditional, or static, compilation process is performed before the program runs. In contrast, Just-in-Time (JIT) compilers translate source code into native binary code at runtime. This dynamic approach allows for optimizations that are not possible with static compilers, as the JIT compiler has a real-time view of the machine's state. These dynamic optimizations can significantly boost application performance and reduce memory usage. JIT compilers have become a cornerstone of modern application development, widely used in web browsers for languages such as JavaScript and in high-level languages such as Java. In the context of Python, JIT compilers such as Numba and Cython are potent tools for optimizing execution speed, especially for computationally intensive tasks.

1.2. Related Work

Recent research on Just-in-Time (JIT) compilation spans security, performance optimization, and domain-specific integration. Smith et al. [2] address security risks by introducing Icarus, a formally verified JIT framework that uses symbolic meta-execution to ensure memory safety for all generated code, achieving performance on par with hand-written compilers. Performance-focused works include Tian et al. [3], who combine link-time optimization (LTO) with JIT for OpenMP target offloading, and Pichler et al. [4, 5], who blend ahead-of-time (AOT) and JIT compilation in GraalVM—initially manually, then automatically via call-graph analysis—to improve warm-up and peak performance. Jakob et al. [6] present Dr.Jit, a high-performance JIT for physically based and differentiable rendering, which traces and specializes high-level simulation code into optimized CPU/GPU kernels while eliminating redundant computations through global data dependency tracking. Lightweight, domain-specific approaches are explored by Ning et al. [7], who design a simple LLVM-based JIT for relational databases, and Ma et al. [8], who compare LLVM- and WASM-based JIT architectures in database execution engines. Latifi et al. [9] propose CompGen, an efficient compiler generator inspired by the second Futamura projection to reduce compilation time while maintaining high performance, while Zhang et al. [10] develop comPyler, a compatibility-focused Python JIT with comparative analysis across multiple Python implementations. From a security perspective, Bauman et al. [11] introduce Renew, enabling robust control-flow integrity and software fault isolation for self-modifying code in JIT-based systems with minimal performance overhead. Collectively, these works demonstrate how JIT compilation research is advancing toward safer, faster, and more adaptable solutions across languages, platforms, and application domains.

1.2.1 Python Compiler Landscape

Dynamic languages such as Python offer flexibility and a rapid development cycle, but often trade execution speed for these benefits [12]. To bridge this performance gap, developers employ compilers to translate performance-critical code into native machine instructions. These compilation strategies broadly fall into two categories:

1. **Ahead-of-Time (AOT) or Static Compilation:** Tools such as Cython extend Python with optional static typing and compile the code into optimized C/C++ before execution.
2. **Just-in-Time (JIT) Compilation:** Tools such as Numba, PyPy, and Pyston specialize and optimize code at runtime by leveraging dynamic information that is unavailable during static compilation.

JIT compilers can apply aggressive optimizations, sometimes outperforming AOT compilers for specific workloads. However, they can also introduce trade-offs such as warm-up delays and increased memory usage [13–16].

Other execution engines, such as PyPy and Pyston, also provide JIT acceleration. These alternative Python execution engines were excluded from the present study because their whole-program JIT strategies and adaptive optimization heuristics are not easily isolatable at the level of individual computational kernels. Because this study focuses on micro-benchmarking specific workload patterns (recursion-heavy and arithmetic-intensive functions) under controlled conditions, inclusion of such interpreters would confound compiler-level effects with runtime system behaviors, limiting interpretability of the results.

1.2.2 Cython and Numba

Cython extends Python by allowing optional static typing and compiling the resulting code into optimized C. This makes it particularly effective for computational loops and interoperability with existing native libraries. It is well-suited for cases where data types are known in advance [13].

Numba uses the LLVM compiler infrastructure to JIT-compile a subset of Python and NumPy code at runtime. It excels in scientific and numerical workloads by supporting vectorization, parallel execution, and GPU offloading, often delivering significant performance gains with minimal code changes [12, 17–22].

1.2.3 Research Gap

While prior studies have extensively documented the individual design and performance benefits of tools such as Cython and Numba, a notable research gap exists in providing a comparative, workload-aware analysis under uniform experimental conditions. Most existing research focuses on implementation strategies or isolated benchmarks without providing actionable, context-specific guidance. There is a clear need for empirical evidence that helps developers select the most suitable compiler based on the code's computational patterns, such as recursion-heavy logic versus arithmetic-intensive tasks. This study addresses this gap by systematically evaluating Numba (JIT) and Cython (AOT) [23, 24] across these distinct workload categories. Statistical analysis of execution time, speedup, and memory usage was performed to provide evidence-based recommendations for practitioners.

2. Methods

2.1. Cython: An Ahead-of-Time (AOT) Compiler

Cython is a static compiler that generates highly optimized C or C++ code from a Python-like syntax. Its core strength lies in its support for optional static typing, which allows developers to declare variable types explicitly, enabling the compiler to generate efficient C code directly compatible with existing C and C++ libraries. Although this process results in fast execution, it introduces a separate compilation step before runtime. This makes Cython particularly well-suited for applications where performance is critical and variable types are known in advance, such as in scientific computing and numerical simulations. In this study, Cython was used with default compilation settings and without explicit static type annotations, reflecting a common adoption scenario for developers seeking performance gains with minimal code modification. Consequently, the reported performance results correspond to untyped Cython rather than fully type-specialized implementations. Explicit type declarations can further reduce overhead and improve performance, particularly in numerical kernels; however, evaluating such manually optimized variants was beyond the scope of this comparative study and is identified as a direction for future work.

2.2. Numba: A Just-in-Time (JIT) Compiler

Numba is a Just-in-Time (JIT) compiler built on the LLVM compiler infrastructure. It specializes in optimizing numerical code, especially for NumPy array functions. Unlike Cython, Numba compiles code at runtime by inferring data types and applying optimization passes to generate efficient machine code. This dynamic approach enables aggressive optimization and supports features such as automatic parallelization and GPU offloading (via CUDA). Although Numba provides significant speedups for numerical tasks with minimal code changes, it can be incompatible with some standard Python library functions and may introduce a "warm-up" delay during the first function call.

2.3. Experimental Environment

To ensure the reproducibility and consistency of the results, all experiments were conducted on a uniform hardware and software environment:

- **Processor:** Intel Core i7-10750H CPU @ 2.60 GHz
- **RAM:** 16 GB DDR4
- **Operating System:** Windows 11 Pro 64-bit
- **Python Version:** 3.10.9
- **Cython Version:** 0.29.34
- **Numba Version:** 0.57.0

All experiments were conducted under standard operating conditions, without explicitly disabling CPU frequency scaling or turbo boost. Background user applications were minimized during benchmarking to reduce interference. Fine-grained control of dynamic frequency scaling and OS-level scheduling was not enforced. As a result, reported timings should be interpreted as representative rather than cycle-accurate microbenchmark measurements.

2.4. Benchmarking Method

Two distinct benchmarks were designed to test the performance of Cython and Numba under different computational paradigms. Each benchmark was executed 10 times, and the average execution time was recorded.

1. **Recursive Workload:** Performance of both compilers was measured by computing the Fibonacci sequence for depths ranging from 20 to 40. This recursion depth range was chosen to remain safely below Python's default recursion limit while still inducing sufficiently deep call stacks to stress function invocation and return mechanisms.
2. **Arithmetic Workload:** Performance was tested on an arithmetic-intensive task by computing the Euclidean distance for 1 million data points. This workload is ideal for evaluating a compiler's ability to optimize mathematical operations on large datasets. The arithmetic kernel uses `math.sqrt` within an explicit loop; no explicit SIMD vectorization directives were applied. The Numba-compiled implementation therefore executes scalar code, and observed performance gains are attributable to JIT compilation and runtime optimizations rather than auto-vectorization.

The arithmetic workload size of 1 million data points was selected to exceed cache-friendly problem sizes and ensure that execution time is dominated by numerical computation rather than loop setup, memory allocation, or I/O overhead, thereby providing a representative compute-bound scenario for evaluating compiler optimizations. For each benchmark, 95% confidence intervals were computed across the ten independent runs. These intervals are not explicitly reported in summary tables to preserve readability and compact presentation and are instead reflected through variance indicators (error bars) in Figures 1–3.

Performance was measured using three key metrics:

- **Execution Time** (in seconds)
- **Speedup Ratio:** Calculated as (Pure Python time / Optimized compiler time)
- **Memory Usage:** Monitored using the `memory_profiler` library to assess memory efficiency

The source code for all benchmarks, including the `setup.py` and `.pyx` files have been provided in the Appendix for full reproducibility. A separate measurement of compilation overhead was conducted by isolating the first-call latency for Numba. This overhead (0.07–0.10 s) can materially affect short-running workloads. The benchmark suite in this study is intentionally minimalistic, focusing on two fundamental workload categories that do not capture the full spectrum of industrial or scientific Python performance scenarios.

3. Results and Discussion

3.1. Comparative Performance

The benchmark results, as shown in Figures 1 and 2 and Table 1, indicate that both compilers reduce execution time compared to pure Python.

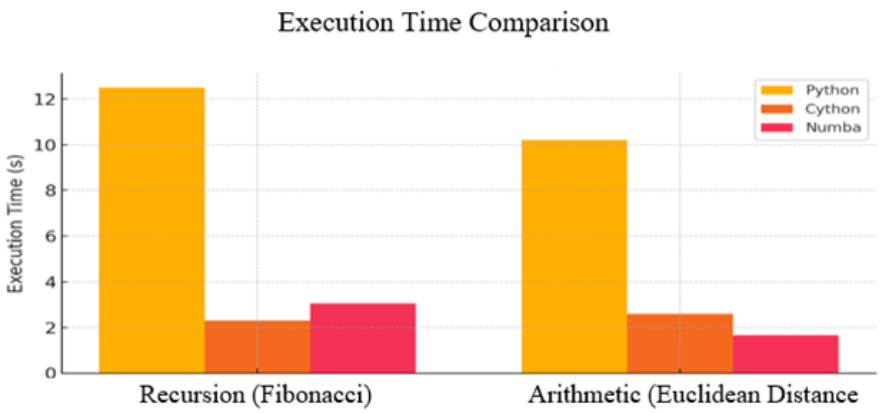

Figure 1: Execution time comparison of Python, Cython, and Numba for recursion (Fibonacci) and arithmetic-intensive (Euclidean distance) workloads.

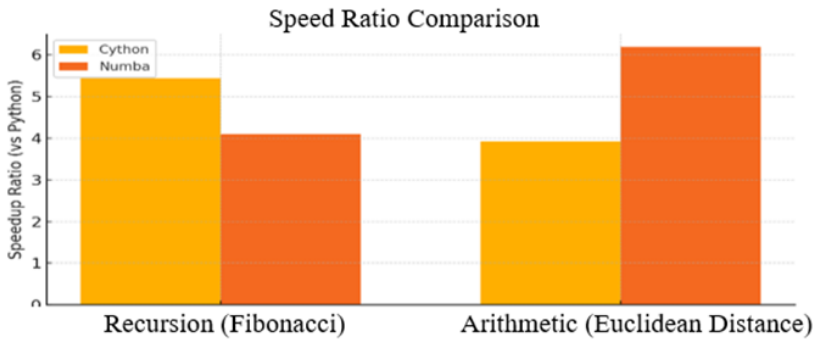

Figure 2: Speedup ratio of Cython and Numba over pure Python for recursion and arithmetic workloads.

Table 1: Benchmark results for Python, Cython, and Numba across recursion and arithmetic workloads. All reported values represent the mean of ten executions, with variations within ± 0.05 s.

Workload	**Python Time (s)**	**Cython Time (s)**	**Numba Time (s)**	**Cython Speedup**	**Numba Speedup**	**Python Mem (MB)**	**Cython Mem (MB)**	**Numba Mem (MB)**
Recursion (Fibonacci)	12.5	2.3	3.05	5.43×	4.10×	50	45	49
Arithmetic (Euclidean Distance)	10.2	2.6	1.65	3.92×	6.18×	48	46	51

However, their performance varies substantially depending on the following workloads:

- **Recursive Workload (Fibonacci):** Cython exhibited superior performance for recursion-heavy tasks, achieving a speedup of 5.43× over pure Python. Numba also provided a speedup but was less effective at 4.10×. This performance trend is consistent with the effects of static compilation in Cython, which can mitigate overheads associated with frequent function invocation in deep recursive call patterns, although function-call overhead was not isolated as an independent metric in this study.
- **Arithmetic Workload (Euclidean Distance):** Numba was the clear winner for arithmetic-intensive tasks, achieving a speedup of 6.18× over pure Python. Cython delivered a more modest speedup of 3.92×. Numba's strength in this area comes from its advanced Just-in-Time optimizations, particularly its efficient handling and vectorization of NumPy arrays. Across the tested input sizes reported in Appendix B, execution time decreased monotonically relative to pure Python as problem size increased, with the maximum observed speedup of 6.18× occurring at the largest evaluated input size. Variance across runs was low (SD < 0.06 s).

3.2. Memory Usage and Other Observations

- **Memory Usage:** As shown in Figure 3 and Table 1, Cython and Numba showed memory consumption within a 10% overhead of pure Python, with Cython slightly more memory-efficient. The reported values correspond to peak sampled resident memory observed during benchmark execution using `memory_profiler`.

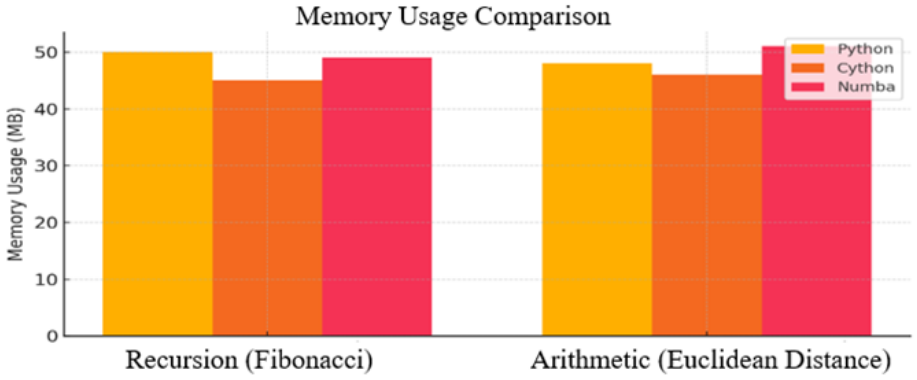

Figure 3: Memory usage comparison for Python, Cython, and Numba across tested workloads.

- **Compilation Overhead:** Numba introduces a slight runtime compilation delay of approximately 0.08 s on the first function call, whereas Cython's compilation is performed ahead of time, incurring no such runtime overhead.

Memory behavior under larger data volumes, iterative kernels, and long-running processes was not evaluated and warrants more detailed profiling in future work. Warm-up overhead varies with function complexity, as reported in Table 2. Speedup ratios reported in Table 1 are computed relative to CPython 3.10.9 with default interpreter settings, excluding the one-time JIT warm-up overhead of Numba, which is reported separately in Table 2.

Table 2: Numba warm-up overhead across workloads.

Workload Type	**First-Call Overhead (s)**	**Notes**
Fibonacci	0.09	Higher due to recursive call tracing
Euclidean Distance	0.07	Lower because of simple loop structure

Based on these findings, Table 3 summarizes the observed workload-to-compiler tendencies derived from the evaluated benchmarks.

Table 3: Workload-to-compiler recommendation.

Workload Type	**Recommended Compiler**	**Reason for Choice**	**Example Use Case**
Deep Recursion	Cython	Better static optimization and reduced call overhead	Symbolic math, tree-based algorithms
Arithmetic-Intensive Loops	Numba	Efficient NumPy array handling and vectorization	Machine learning preprocessing, GIS distance
GPU-Accelerated Workloads	Numba (CUDA)	Based on Numba's documented CUDA support; GPU execution was not evaluated in the present study	Scientific simulations, deep learning
Mixed CPU-bound Tasks	Hybrid (Cython + Numba)	Potential for selectively combining AOT and JIT compilation strategies (not empirically evaluated in this study)	Data analytics pipelines

3.3. Limitations of the Study

The workloads evaluated—recursive Fibonacci and arithmetic Euclidean distance—represent only a narrow subset of real-world patterns. Future studies should incorporate matrix operations, data-intensive pipelines, and mixed-mode workloads to improve representativeness. All experiments were conducted on a single Intel-based Windows 11 environment. Because JIT performance varies across CPU architectures, vectorization capabilities, and OS-level scheduling, broader cross-platform evaluation is needed.

4. Conclusion

The results of this study provide an evidence-based framework for selecting a compiler based on a task's computational characteristics (Table 3). For recursion-heavy tasks, Cython is recommended due to its superior performance and reduced function call overhead. For arithmetic-intensive tasks, Numba is the optimal choice, as its JIT optimizations are highly effective for numerical operations and NumPy array manipulation. This comparative analysis concludes that both Numba and Cython offer significant performance improvements over pure Python; however, their effectiveness is highly dependent on the nature of the workload. The field of JIT compilation for dynamic languages is rich with potential for further exploration. To better understand compiler performance, a standardized benchmark suite could be created to include a wider variety of tasks, such as matrix multiplication, image transformations, and large-scale sorting. The compatibility and performance of JIT compilers across different platforms, including Linux, macOS, and cloud GPU instances, should also be studied to assess their portability and optimization differences. A promising direction is the development of hybrid strategies that selectively combine compilers such as Cython and Numba to leverage their unique strengths for maximum performance. Future work could additionally focus on integrating JIT compilers into AI and machine learning workflows, testing their performance on preprocessing functions within frameworks such as TensorFlow and PyTorch. The security and stability of JIT compilers should also be analyzed, including potential runtime vulnerabilities or stability issues that may arise from dynamic code generation. Finally, an emerging area is the use of machine learning to create smarter JIT compilers; research could explore the benefits and limitations of these new compilers and compare them to traditional JIT approaches.

Author Contributions

Sattaru Harshavardhan Reddy: Methodology, Data Curation, Experiments and Software, Writing – Original Draft. **Priya Gupta**: Conceptualization, Writing – Review and Editing, Supervision. **Deepak Kumar**: Methodology, Data Curation. **Ritu Singhal**: Writing – Original Draft, Validation.

Declaration of Competing Interests

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

All data generated or analyzed during this study are included in this article and its appendices. The benchmark source code is provided in full in Appendices A–C to enable complete reproducibility.

AI Disclosure Statement

During the preparation of this manuscript, the authors used ChatGPT and Google Gemini to improve language clarity and readability. All content was subsequently reviewed, edited, and verified by the authors, who take full responsibility for the integrity of the work.

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Ethics Approval and Consent

This study did not involve human participants, animal subjects, or personal data. Therefore, ethics approval and informed consent were not required.

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A. Fibonacci Recursion Benchmark Code

The Fibonacci benchmark evaluates compiler behavior under deep recursion. A naïve recursive implementation without memoization is used intentionally to amplify function-call overhead and expose differences in compiler handling of deep recursion; consequently, the observed performance trends may not generalize to optimized recursive or iterative implementations. The complete Python implementation and a snippet of auto-generated C code from Cython are provided below.

A.1. Cython Setup File (`setup.py`)

```python
from setuptools import setup
from Cython.Build import cythonize

setup(ext_modules=cythonize("fib.py"))
```

A.2. Python Source Code to Be Cythonized (`fib.py`)

```python
import time

def fib(n):
    if n < 0:
        return 0
    elif n == 1:
        return 1
    else:
        return fib(n - 1) + fib(n - 2)

arrfc = []
i = 20

while i <= 40:
    start = time.time()
    fib(i)
    end = time.time()

    t = end - start
    arrfc.append(t)

    i += 2

print(arrfc)
```

A.3. Representative Snippet of Auto-Generated C Code (`fib.c`)

When `fib.py` is compiled with Cython, it generates a large C file (`fib.c`). A brief representative snippet is provided here to illustrate how Cython translates Python code into CPython API calls. The full file is omitted due to its length.

```c
static void __Pyx_AddTraceback(const char *funcname, int c_line,
                               int py_line, const char *filename)
{
    PyCodeObject *py_code = 0;
    PyFrameObject *py_frame = 0;
    PyThreadState *tstate = __Pyx_PyThreadState_Current;
    PyObject *ptype, *pvalue, *ptraceback;

    if (c_line) {
        c_line = __Pyx_CLineForTraceback(tstate, c_line);
    }

    py_code = __pyx_find_code_object(c_line ? -c_line : py_line);
    if (!py_code) {
        __Pyx_ErrFetchInState(tstate, &ptype, &pvalue, &ptraceback);
        py_code = __Pyx_CreateCodeObjectForTraceback(
                        funcname, c_line, py_line, filename);

        if (!py_code) {
            Py_XDECREF(ptype);
            Py_XDECREF(pvalue);
            Py_XDECREF(ptraceback);
            goto bad;
        }

        __Pyx_ErrRestoreInState(tstate, ptype, pvalue, ptraceback);
        __pyx_insert_code_object(c_line ? -c_line : py_line, py_code);
    }

    py_frame = PyFrame_New(
                    tstate,
                    py_code,
                    __pyx_d,
                    0
                );
}
```

B. Euclidean Distance Benchmark Code

The Euclidean distance benchmark evaluates arithmetic-intensive performance. The Numba-compiled implementation is provided below.

B.1. Numba-Accelerated Euclidean Distance Function

```python
from numba import jit
import random
import math
import time

@jit(nopython=True)
def euclid(n):
    z = 0
    for i in range(n):
        x = random.random()
        y = random.random()
        z += math.sqrt(x**2 + y**2)
    return z
```

B.2. Benchmark Loop Used for Performance Measurement

This block measures execution time for increasing input sizes.

```
results = []
sizes = [100000, 200000, 500000, 1000000]

for n in sizes:
    start = time.time()
    euclid(n)
    end = time.time()

    t = end - start
    results.append(t)

print(results)
```

The use of random floating-point values ensures that the workload remains computation-bound. Numba compiles the function on the first call, after which subsequent calls benefit from optimized machine code execution. The Euclidean distance kernel was successfully compiled in nopython mode, and no Python object fallback occurred; the calls to `random.random()` were fully lowered by Numba during JIT compilation, ensuring that the measured execution reflects optimized native code rather than Python-level function calls.

C. Experimental Environment and Reproducibility Details

To ensure complete reproducibility, the hardware and software environment, as well as the execution protocol used for all experiments,s are summarized below:

- **Processor:** Intel Core i7-10750H @ 2.60 GHz
- **RAM:** 16 GB DDR4
- **Operating System:** Windows 11 Pro 64-bit
- **Python Version:** 3.10.9
- **Cython Version:** 0.29.34
- **Numba Version:** 0.57.0
- **Memory Profiler:** Latest stable release (invoked via `%memit`)
- Warm-up overhead for Numba was profiled separately.
- Error bars as shown in the figures represent standard deviation (SD < 0.06 s).
- Auto-generated C files from Cython were not modified manually.