

INTERNATIONAL CONFERENCE · CONFERENCE PROCEEDINGS

INSPIRE 2026

Integrating Sustainability in Policy, Innovation, Research
& Education

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JOURNAL OF REPRODUCIBLE RESEARCH (JRR)

Organised by **GIBS Business School (Global Institute of Business Studies),
Bengaluru, India**

in association with **GISMA University of Applied Sciences, Germany**

CONFERENCE DATE

22 August 2026

VENUE

GIBS Business School, Begur Campus, Bengaluru

PAPERS

14 peer-reviewed articles

JOURNAL OF REPRODUCIBLE RESEARCH (JRR) · SPECIAL ISSUE

Proceedings of INSPIRE-2026

International Conference on Integrating Sustainability in Policy,
Innovation, Research & Education

22 August 2026 · GIBS Business School, Bengaluru, India
in association with GISMA University of Applied Sciences, Germany

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About the Conference

Embracing Sustainability: Integrating Sustainability in Policy, Innovation, Research and Education (INSPIRE-2026) provides a dynamic platform for scholars, practitioners, and policymakers to rethink management paradigms through the lens of sustainability.

The conference explores the integration of sustainable principles across finance, marketing, human resources, operations, and technology. It delves into emerging themes such as green finance, circular economy, sustainable consumer behaviour, future of work, ESG integration, and AI-enabled responsible innovation, and examines how digital transformation and emerging technologies can accelerate progress toward the Sustainable Development Goals (SDGs).

INSPIRE-2026 promotes cross-sectoral dialogue among academia, industry, government, and civil society to co-create actionable solutions. It showcases contemporary research, best practices, and policy insights that bridge the gap between theory and practice, emphasising resilient and inclusive strategies for sustainable enterprises, supply chains, and smart ecosystems, and the role of ethical leadership, diversity, and future-ready workforce strategies. Ultimately, it aspires to reimagine management as a catalyst for equitable, regenerative, and technology-enabled sustainable development.

CONFERENCE OBJECTIVES

- To examine the convergence of AI, innovation, and sustainability within Industry 5.0.
- To promote research, policy insights, and best practices in sustainable management, finance, marketing, operations, and digital technologies.
- To explore the role of AI and digital transformation in achieving the SDGs.
- To encourage cross-sector collaboration for designing and implementing AI-enabled sustainable solutions.
- To enhance managerial and policy-level decision-making by integrating research with actionable strategies.

THEMES & TRACKS

Finance

Marketing

Human Resource

General Management

Operations

Technology

Finance track topics included financial inclusion; sustainable / green investing and green accounting; cryptocurrency, blockchain and FinTech; digital banking practices; and circular economy financing.

CONFERENCE HIGHLIGHTS

Paper presentations

Workshops

Keynote session

Panel discussion

Journal publication

Conference proceedings

Best paper award

PhD & ECR networking forum

About the Organisers

GIBS BUSINESS SCHOOL, BENGALURU

Global Institute of Business Studies (GIBS), Bangalore, is a premier management institution committed to academic excellence, industry relevance, and global exposure. Known for its innovative pedagogy and strong industry integration, GIBS emphasises experiential learning, leadership development, entrepreneurship, and sustainability-driven management education. The institution actively promotes research, international collaborations, faculty development, and corporate engagement, with a clear focus on nurturing socially responsible and future-ready business leaders.

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GISMA University of Applied Sciences, Germany is a globally recognised institution known for its strong focus on applied learning, innovation, and internationalisation. With a diverse student community representing multiple nationalities, GISMA emphasises practice-oriented education aligned with global industry standards. The university offers programmes in business, management, data science, and related disciplines, integrating academic rigour with real-world application. Through its strong industry connections and global partnerships, GISMA promotes research, entrepreneurship, and cross-border collaboration, preparing graduates to lead in an increasingly dynamic and sustainable global economy.

JOURNAL OF REPRODUCIBLE RESEARCH (JRR)

The Journal of Reproducible Research (e-ISSN 2948-5282) is a double-blind peer-reviewed quarterly journal published by Vally Links Sdn. Bhd. as an initiative of the World Research Union. JRR publishes original research, systematic reviews, and meta-analyses across the social sciences, STEM, and arts, with an emphasis on work whose datasets or algorithms can be made available for verification, and favours practical, innovative, and substantive contributions.

CONFERENCE TIMELINE

Submission open	09 March 2026
Last day for abstract submission	15 May 2026
Notification of acceptance of abstracts	01 June 2026
Extended abstract / full paper submission	01 July 2026
Conference (GIBS Business School, Begur Campus, Bengaluru)	22 August 2026

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Preface

It is our pleasure to present this special issue of the Journal of Reproducible Research, which brings together 14 papers presented at INSPIRE-2026, the international conference organised by GIBS Business School, Bengaluru, in association with GISMA University of Applied Sciences, Germany, on 22 August 2026.

The conference set out to examine how sustainability can be built into the everyday practice of policy, innovation, research and education rather than treated as a separate agenda. The papers collected here reflect that ambition. In finance, authors examine digital public infrastructure and financial self-reliance, the centralisation of the finance function in digital banking, digital payments, the governance of intellectual capital, the links between technological innovation and external debt, and the bibliometric evolution of FinTech for sustainable finance. In marketing, contributions address value-driven purchasing among Gen Z consumers and patient relationship management as a strategic capability for traditional health-care providers.

The general management papers consider Indo-German collaboration in green technology and the role of coworking spaces in sustainable entrepreneurship, while the operations papers assess stone paper as a circular-economy material and geopolymer concrete for mitigating urban heat islands. The technology track closes the issue with empirical evidence on AI-enabled personalised language learning and a framework for integrating AI, analytics and automation for sustainable development.

All papers were presented at the conference and accepted by the Scientific Committee before being prepared in the journal's format. We thank the authors for their contributions, the reviewers and session chairs for their time and judgement, the leadership of GIBS and GISMA for their support, and the conveners and committee members whose work made the conference possible. We hope these papers encourage further reproducible, sustainability-focused research and practice.

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Guest Editors, INSPIRE-2026 Special Issue

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Digital Transformation of an Organization's Finance Function: Centralization vs Decentralization

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ABSTRACT

The rapid evolution in the field of digital banking practices has brought about a change in the very nature of finance functions in banking organizations, where companies are now compelled to restructure their financial processes to achieve better efficiencies and decision-making capabilities. Advanced technologies, including artificial intelligence (AI), enterprise resource planning (ERP) and centralized digital treasury systems have all contributed to the digital integration of finance functions. In this context, the present research paper seeks to explore how the centralized and decentralized finance functions affect organizational performance in a digital banking context.

A comparative case study design is adopted for the purpose of the study, wherein the secondary financial data of JPMorgan Chase India and Deutsche Bank India are analyzed for the period of FY2022–FY2024. Financial statements and ratio analysis data from the Capitaline database are employed to analyze the following aspects: capital allocation, efficiency, liquidity, cost control, profitability and revenue diversification.

The results suggest that there is excellent performance in terms of cost effectiveness, capital allocation, liquidity management, and profit generation in JPMorgan Chase, where the use of the digitally integrated and centralized finance system proves to be highly effective. On the other hand, there is more flexibility, better credit deployment locally, and greater response to market conditions in the decentralized structure of Deutsche Bank, despite the higher costs involved in it. It can be said from this study that although digitized banking systems increase the effectiveness of centralized finance by means of automation, standardization of processes, and financial control, the decentralized structure offers certain strategic advantages.

This study makes a valuable contribution to the existing research on digital banking, digital integration and flexibility.

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1. Introduction

The fast-changing nature of digital banking has brought about the way financial organizations operate and run their finance function. The growing use of technology, including Artificial Intelligence (AI), Enterprise Resource Planning (ERP), centralization of treasury management system and process automation, has helped banks to increase financial control, decision-making ability and improve operations efficiency. As a result of digital transformation, the finance function is no longer confined to the area of accounting and financial statements but becomes the tool for capital allocation, risk management, liquidity planning and value creation.

The design of the finance function in the digital world has become a critical decision in a company's strategy. Financial institutions opt for one of the two options of organizational structure, either centralized or decentralized, in order to allocate their financial resources and achieve their goals. While digital technologies help to create a single information flow and real-time reporting, the successful operation of these technologies greatly depends on the way financial power, decision-making and operations are organized in an organization.

On the other hand, decentralization of finance function implies decentralization of financial authority through geographical or business unit dispersion of financial management authority which allows local managers to take decisions in line with the market conditions and customers' demands. Digital banking technologies help in achieving decentralized finance function through provision of quick financial information and coordination among geographically dispersed operations. Decentralization increases flexibility and adaptability and makes decision-making process quicker but at the same time causes duplication of activities and increase in operating expenses and inconsistencies in financial governance.

Thus, the choice of centralization or decentralization of finance function is not only an organizational design issue but also a strategic decision-making task in the context of digital banking. While centralized finance function may be enhanced by digital banking technologies for achieving greater cost efficiency, effective capital management and financial control, decentralized finance function provides greater flexibility and quick adaptation to regional market conditions and customer needs. The banking sector is one of the areas where such relationships can be examined since digitization has greatly affected the mobilization of deposits, credit allocation, liquidity management, financial risks monitoring, and delivery of financial services by banks. The structure of the finance function has a great impact on how digital banking technologies support financial performance and organizational efficiency and effectiveness.

The research will compare JPMorgan Chase India and Deutsche Bank India which are global banking organizations that have quite different finance function structures in the context of digital banking. Thus, JPMorgan Chase India has a highly centralized finance function structure while Deutsche Bank India has a relatively decentralized finance function structure. This study will allow comparing two companies within one industry and the same legal and regulatory framework to understand the impact of finance function structure on organizational performance.

The fundamental aim of this research is to study the impact of centralized and decentralized finance functions on organizational performance in the context of digital banking practices. Secondary financial data from FY2022 to FY2024 is used in this study for evaluating the different dimensions including capital structure, efficiency, liquidity, cost, profitability, and income diversification. The results provide practical insights on how digitally aligned finance functions enable organizational performance and at the same time point out the inherent trade-offs of efficiency and flexibility in finance functions. In view of the increasing role of digital transformation in banking processes, it has become necessary for the financial organizations to explore the link between digital banking practices and finance functions.

2. Literature Review

(Xiaojun Fan, 2022) analyzed the link between centralization in firms and their performance using threshold regression in Chinese listed firms. Results show that centralization is effective depending on the size of the firm, having strong positive effects on ROA and ROE in small and medium-sized firms but not for large firms. Centralization is effective in enhancing efficiency in the allocation of cost, reducing agency costs, and R&D activities through reduction of information asymmetry. Too much centralization may be ineffective due to managerial constraints and information overload. The study also found that centralization is more effective in privately-owned firms.

(Fory A. N Away, 2021) studied the impact of centralization, decentralization, and the quality of human resources on organizational performance in Indonesian rural banks through multiple linear regression. It has been found that centralization and the quality of human resources have positive effects on the performance of the organization, but decentralization does not have any statistical significance on its own. All these variables help in improving the performance of the organizations. The research stresses on the point that centralization will help in ensuring effective financial control, credit decision, risk management, and regulation.

(Polak, 2024) has examined the utilization of artificial intelligence (AI) in centralization of finance activities through the digital transformation of Chinese businesses. The research shows that the main technologies used for finance transformation are AI-enabled ones such as automated reconciliation, intelligent financial reporting, big data

analytics, RPA, OCR, and LLMs. They help to improve the quality of reporting, operational efficiency, and decision making and reduce information asymmetry and risk management. However, it should be mentioned that finance functions which are integrated via digitization provide better control over finances, although corporate ownership structure influences the process of digital transformation.

(Ming Jin, 2025) examined the effect of financial decentralization on firm-level risks employing a multi-period Difference-in-Differences (DID) approach through the process of reforming the Rural Credit Cooperatives to Rural Commercial Banks in China. The results show that financial decentralization leads to higher corporate risks as a result of the tightening of financing constraints and decrease in financial flexibility. The paper found that the crowding out effect of financial institutions and corporate loans is one of the key mechanisms through which capital allocation is affected. This effect is especially apparent for small, non-state owned, and low profitability firms.

(Sokheang Men, 2025) A study of 879 Scopus-based articles was conducted on organizational restructuring and decentralization through CiteSpace. Results show that corporate governance, ownership structure, coordination, and organizational performance are the major themes that have been studied extensively. It has been noted that the decisions taken about centralization and decentralization affect agency costs, capital budgeting, resource allocation, and shareholders' monitoring. Ownership structure plays an important role in organizational performance and governance helps in improving financial efficiency.

(Tavares, 2024) The effects of decentralization in the decision-making process within organizations have been explored by Maria C. Tavares (2024). Specifically, the impact of low-level managers in financial and operational decisions is investigated. The results reveal that decentralization helps improve resource management and the responsiveness of the organization in relation to the utilization of local knowledge and expertise. On the other hand, the lack of governance system can lead to inconsistencies in financial planning and performance evaluation. In this case, there is a balance between organizational control and flexibility, which requires effective governance systems to ensure financial performance of an organization.

(Wenlong, 2022) studied fiscal and financial decentralization from the perspective of macroeconomic governance with particular emphasis on their impact on capital allocation, financial stability, and resource distribution. It was found that misalignments of revenue and expenditure decentralization affect financial management negatively and create financial risks in the system. The research suggests that coordinated financial systems help to enhance efficiency of capital allocation, risk management and financial governance.

(Eva Labro, 2023) Predictive Analytics, Organizational Centralization, Corporate Governance and Financial Decision-Making have been analysed by Eva Labro in relation to each other. The results show that predictive analytics decreases information asymmetry, increases the power of control over finances in the hands of headquarters and increases the accuracy of forecasts and financial decisions. Moreover, the research shows that data-based analytics increases performance measurement, managerial control systems and incentive structures. The results show the significance of using predictive analytics to improve allocation of resources, financial control, operational efficiency and overall performance.

(Li, Zhong, & Yang, 2024) analysed the effect of digital transformation of commercial banks on corporate financial constraints using data of listed Chinese companies. The results show that digital transformation has significant effects on lowering down the information costs and information asymmetry that allows banks to perform better in credit allocation, lending efficiency, and finance. Moreover, the use of technologies like big data, artificial intelligence, and digital information processing helps in risk assessment, financial decisions, and capital allocations. In summary, digital transformation of banks enhances financial efficiency, mitigates corporate financing constraints, and helps in sustainable growth of organizations and economy.

(Papathomas, 2024) investigated the digital transformation process for financial organizations and suggested a framework comprising adaptation, growth, and transformation as three stages. This review shows that digital transformation is not only the use of technology but also the alignment of organization's strategy, leadership, people, innovation, and customer value. In addition, the research proposes the use of measurable Progress Tracking

Indicators (PTIs) to evaluate digital maturity at each stage. According to the results, financial organizations may improve their efficiency and competitiveness implementing digital transformation programs.

2.1 Research Gap

Existing literature has provided ample discussions on the topics of centralization, decentralization, corporate governance, artificial intelligence, and digital transformation separately. Studies by (Xiaojun Fan, 2022) and (Fory A. N Away, 2021) primarily focus on the influence of centralized and decentralized organization structures on financial performance, cost efficiency and governance while (Ming Jin, 2025), (Tavares, 2024) and (Wenlong, 2022) emphasise the implications of decentralisation for capital allocation, financial flexibility and risk management. However, there is no comparative study on the joint relationship of digital transformation and design of centralized and decentralized finance function in the banking industry. There is a paucity of empirical analysis on the way that these finance functions impact cost efficiency, capital allocation, operational efficiency, financial control, and overall performance of the organization.

Furthermore, research by (Polak, 2024), (Eva Labro, 2023), (Li, Zhong, & Yang, 2024) and (Papathomas, 2024) highlights the growing role of Artificial Intelligence (AI), predictive analytics, digital banking technologies and enterprise-wide digital transformation in improving financial decision making and operational efficiency. Nevertheless, limited empirical evidence exists regarding how these digital technologies influence the effectiveness of centralized versus decentralized finance functions in terms of cost efficiency, capital allocation, financial control, operational performance, and risk management.

In addition, while studies such as (Sokheang Men, 2025) discuss organizational restructuring and governance, comparative evidence from global commercial banks operating under different finance structures, particularly within the Indian Banking Sector remains scarce. Therefore, the present study addresses these research gaps through a comparative analysis of **JPMorgan Chase India** and **Deutsche Bank India**, providing insights into how **digital banking practices** and finance function design jointly influence organizational performance.

3. Research Methodology

Research Design: This research will use a comparative approach to examine the effect of finance functions that are more centralized and those which are decentralized on the performance of organizations. This will be done by comparing JPMorgan Chase India and Deutsche Bank India, the former has more centralized finances while the latter has decentralized finances. The areas of financial performance, capital deployment, operational efficiency, liquidity and risk management are examined in light of digital transformation.

Source of Data: The research uses secondary data obtained from Capitaline AWS through PES University. Capitaline assures accuracy and reliability of financial data since it uses the same format for all the companies. The study makes use of financial data from Balance Sheet, Profit and Loss Statement, Cash Flow Statement and Key Financial Ratios.

Sampling technique: JPMorgan Chase India is chosen for the purpose of studying since it provides an example of a rather centralized finance function with centralized treasury management, uniform financial processes and integrated global governance. Deutsche Bank India is chosen as it is characterized by rather decentralized finance function with more autonomy of regions in providing loans and making decisions. Such companies serve as appropriate samples for the analysis of impact of the structure of finance function on organizational performance in the banking industry.

Data analysis: Performance of companies will be analysed with the help of ratio analysis which will facilitate the process of comparing companies based on the categories of profitability, liquidity, efficiency and capital structure. In order to enhance internal validity, firms from the same industry will be compared, financial data will be obtained from a single source and will be analysed for a certain period of time.

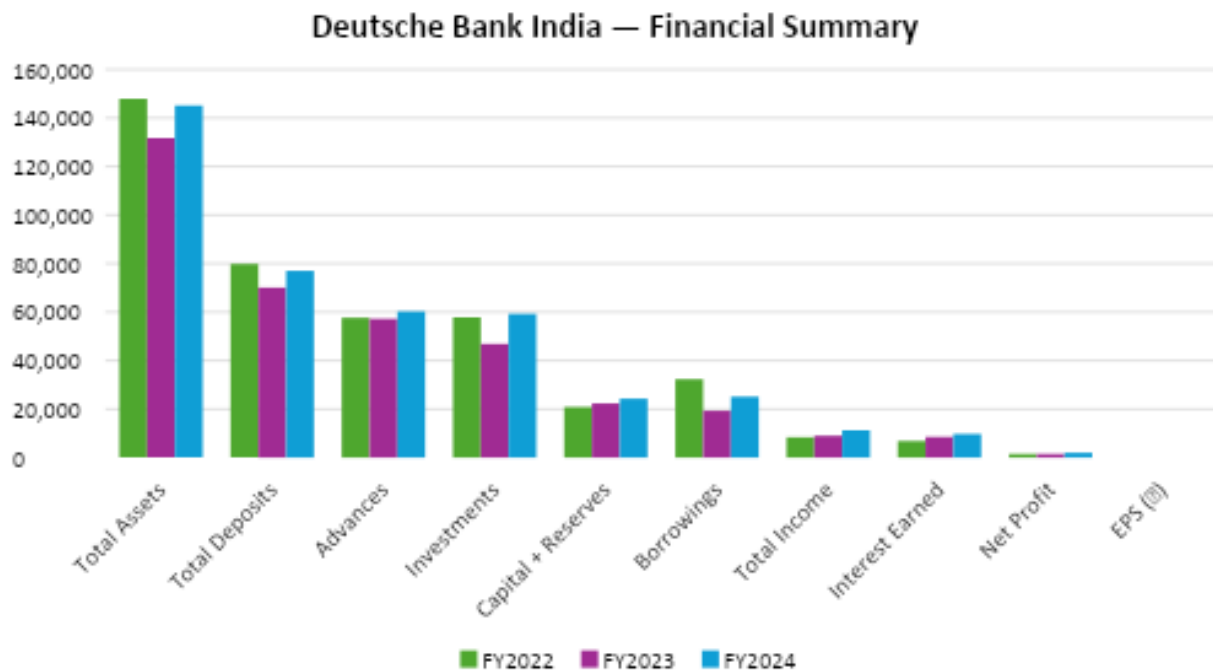
4. Data Analysis

The financial performance of JPMorgan Chase India and Deutsche Bank India is evaluated based on secondary financial data sourced from the Capitaline AWS database during the research period. The analysis focuses on the comparison of important financial indicators that represent profitability, liquidity, capital deployment, efficiency, and risk management to see how the relative centralization and relative decentralization of the finance functions affect organization performance in terms of digital transformation. The financial performance analysis employs the ratio analysis method to determine the disparities in financial results of the companies under consideration.

4.1 Data Overview

4.1.1 Deutsche Bank India – Financial Summary

Metric (₹ Crores)	FY2022	FY2023	FY2024	FY23 YOY (%)	FY 24 YOY (%)
Total Assets	1,47,955	1,31,841	1,45,235	-10.89%	10.16%
Total Deposits	79,908	70,070	76,994	-12.31%	9.88%
Advances	57,649	57,196	60,241	-0.79%	5.32%
Investments	57,813	46,839	59,236	-18.98%	26.47%
Capital + Reserves	20,845	22,312	24,289	7.04%	8.86%
Borrowings	32,313	19,286	25,109	-40.32%	30.19%
Total Income	8,382	8,994	11,234	7.30%	24.91%
Interest Earned	6,836	8,518	9,723	24.61%	14.15%
Net Profit	1,474	1,467	1,977	-0.47%	34.76%
EPS (₹)	1.75	1.74	2.34	-0.57%	34.48%



Deutsche Bank India experienced a temporary decline in its financial performance in FY2023 followed by a robust growth in FY2024. There was a reduction of 10.89% in total assets in FY2023 followed by an increase of 10.16% in FY2024. Similarly, there was a reduction of 12.31% in total deposits in FY2023 followed by a rise of 9.88% in FY2024. This shows that FY2023 was a consolidation period for the bank as it optimized its balance sheet and took a conservative approach towards risk management and liquidity management, and as a result of improvement in business environment in FY2024, there were more deposits and growth in assets. The same pattern was noticed for

advances and investments. There was just a slight decline of 0.79% in FY2023 followed by a growth of 5.32% in FY2024 in advances, and similarly there was a decrease of 18.98% followed by an increase of 26.47% in FY2024 in investments. This clearly shows that the bank reduced its risk-taking activity in terms of lending and investments.

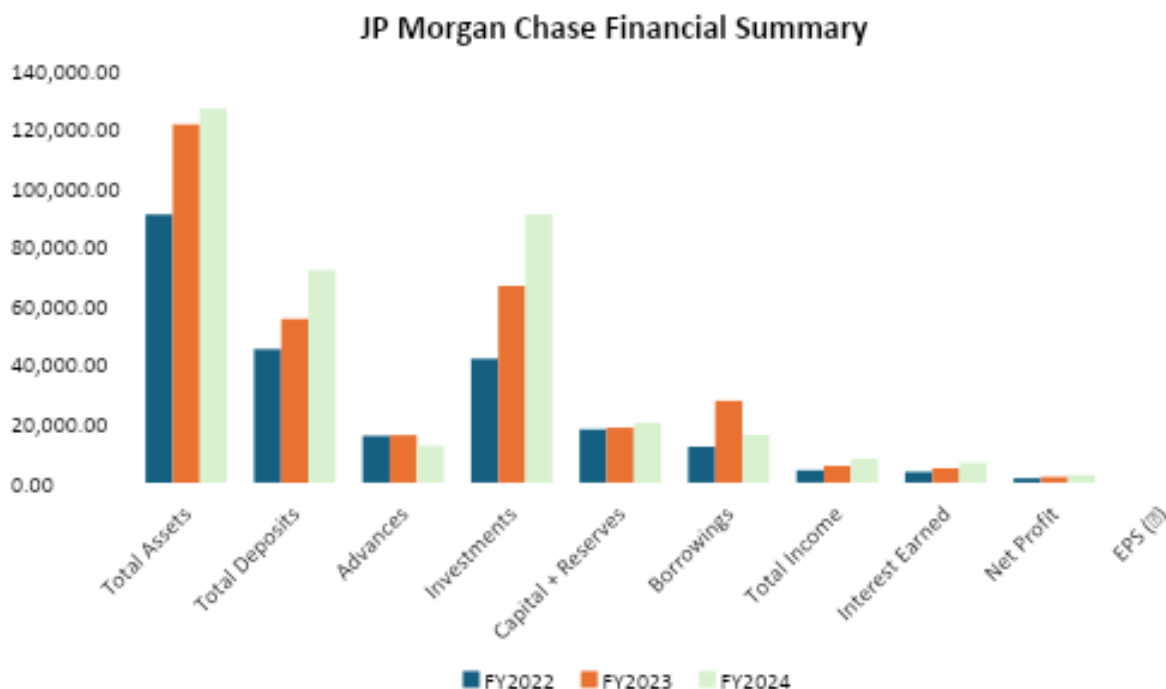
Although there is a decline in certain aspects of the balance sheet for FY2023, capital and reserves show a steady increase of 7.04% and 8.86% in FY2023 and FY2024, respectively, indicating a good capitalization for the bank during the period. The borrowings have also fallen significantly by 40.32% in FY2023, indicating lesser reliance on external funding sources, after which they have increased by 30.19% in FY2024 to support business expansion.

The income and profitability of the bank showed steady growth over the three-year period. There is an increase in total income of 7.30% in FY2023 and an acceleration to 24.91% in FY2024, and the interest earned increased by 24.61% and 14.15%, respectively. Although net profit and EPS showed a marginal decline of 0.47% and 0.57%, respectively, in FY2023, there was sharp growth in FY2024 of 34.76% and 34.48%, respectively.

The change from negative growth in FY2023 to positive growth in FY2024 could be because of the combination of changes in the balance sheet, improved macroeconomic environment, portfolio management, and base effect. As there is a decline in certain financial measures in FY2023, the low base resulted in higher percentage growth in FY2024.

4.1.2 J P Morgan Chase – Financial Summary

Metric (₹ Crores)	FY2022	FY2023	FY2024	FY23 YOY (%)	FY 24 YOY (%)
Total Assets	90,873.77	1,21,602.24	1,26,875.52	33.81%	4.34%
Total Deposits	45,265.81	55,596.82	72,033.93	22.82%	29.56%
Advances	15,876.29	16,097.43	12,494.74	1.39%	-22.38%
Investments	42,022.01	66,758.15	91,025.35	58.86%	36.35%
Capital + Reserves	18,077.92	18,650.18	20,264.64	3.17%	8.66%
Borrowings	12,197.39	27,761.19	16,272.33	127.60%	-41.38%
Total Income	4,190.58	5,704.88	8,096.89	36.14%	41.93%
Interest Earned	3,651.94	4,827.74	6,739.16	32.20%	39.59%
Net Profit	1,480.31	1,932.35	2,563.73	30.54%	32.67%
EPS (₹)	2.25	2.94	3.9	30.67%	32.65%



Financial and operational performance of JP Morgan Chase was quite good during the three-year period under review. Total assets of the company rose from ₹90,873.77 crore in FY2022 to ₹1,26,875.52 crore in FY2024, thus demonstrating consistent growth of the firm. Deposits made by the customers grew too: there was a growth by 22.82% in FY2023 and 29.56% in FY2024.

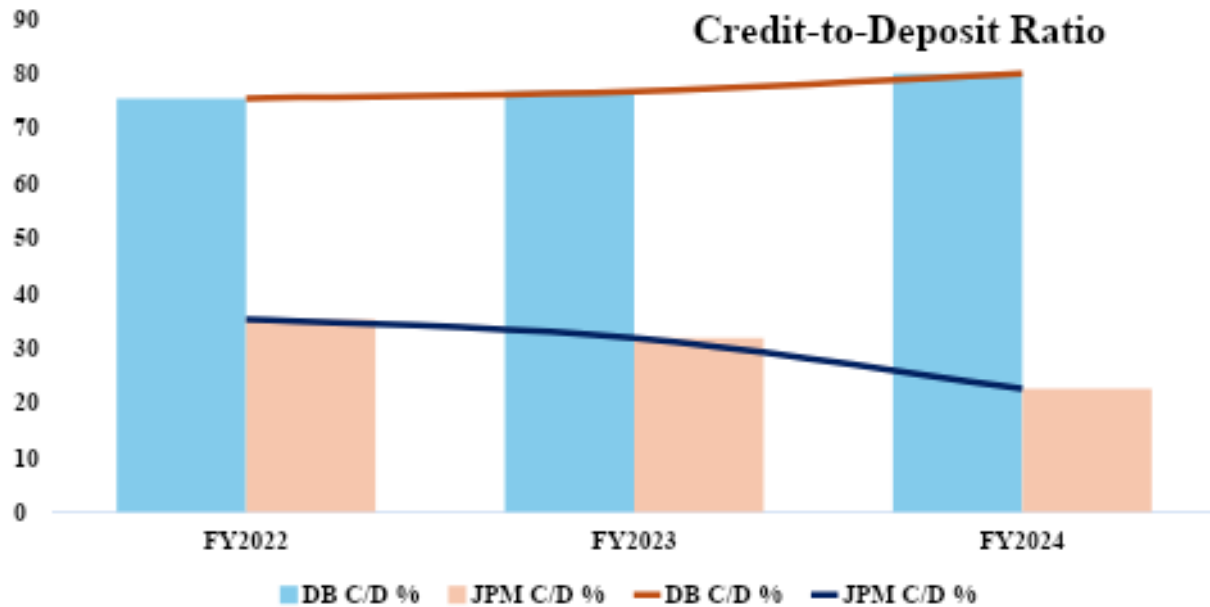
It should be noted that investments made by the bank also experienced significant growth (by 58.86% in FY2023 and 36.35% in FY2024). Thus, it is possible to assume that the bank has paid a lot of attention to its investment operations. Income of the company and interest earned showed consistent growth: there was a rise by 36.14% in FY2023 and 41.93% in FY2024 in case The firm's profitability increased significantly since the net profit went up by 30.54% for FY2023 and further by 32.67% for FY2024, coupled with an increase in EPS from ₹2.25 to ₹3.90. The firm also recorded stable increases in the capital and reserves, which indicated that there was a healthy capital structure. Nevertheless, the advances fell by 22.38% for FY2024, showing a more prudent borrowing stance of the company or re-balancing of the portfolio. Moreover, the borrowings fell by 41.38% for FY2024, following a significant increase in FY2023, which implied less borrowings.

Overall, the performance of JP Morgan Chase was characterized by good asset growth, deposits, investment, income, and profitability.

4.2 Capital Allocation

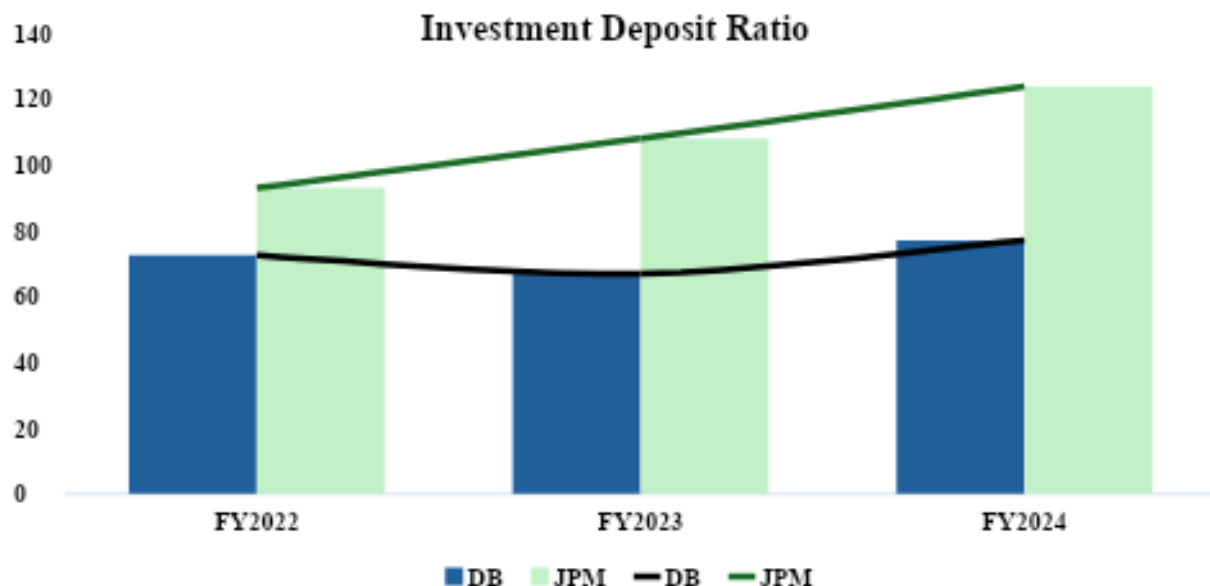
4.2.1 C/D Ratio

The Credit–Deposit (C/D) ratio shows the extent to which deposits are transformed into loans. It is also used to assess the structure of capital and the function of finance. Deutsche Bank India's C/D ratio (75.33% to 79.85%) shows the bank's aggressive deployment of local credit and the relatively decentralized structure of finance. This means that regional units have more freedom to make credit decisions. On the other hand, JPMorgan Chase India's C/D ratio (35.07% to 22.40%) shows the relatively centralized structure of finance, meaning centralized management of treasury function and global capital. What is evident from the data given is that decentralization provides flexibility to lending, and centralization offers a better liquidity position and control over risks, as well as more strategically placed capital.



4.2.2 Investment to Deposit Ratio

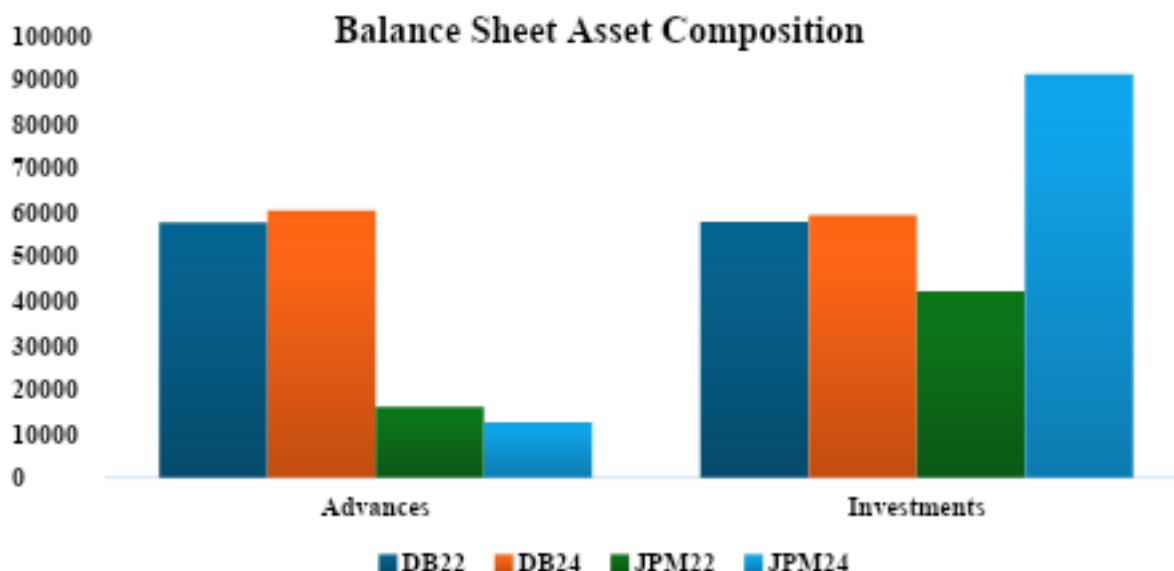
This ratio shows the extent to which deposits are placed into investment portfolios as opposed to lending. JPMorgan Chase India's Investment-to-Deposit ratio shows the bank's centralized treasury function and finance structure, and placement of global funds and a diversified capital and investment approach (the ratio exceeded 100% from FY 2023). On the other hand, Deutsche Bank India's ratio remained between 66% and 77% showing a relatively stable (balanced) placement of funds in lending and investments. This data indicates that centralization provides control over liquidity and the capital and investment placement structure, while decentralization provides greater lending to customers and financial intermediation.



4.2.3 Asset Composition on Balance Sheet

The analysis of asset composition shows two varying methods of capital deployment within the two banks. Deutsche Bank India demonstrated a stable portfolio complemented with a moderate increase in both advances and

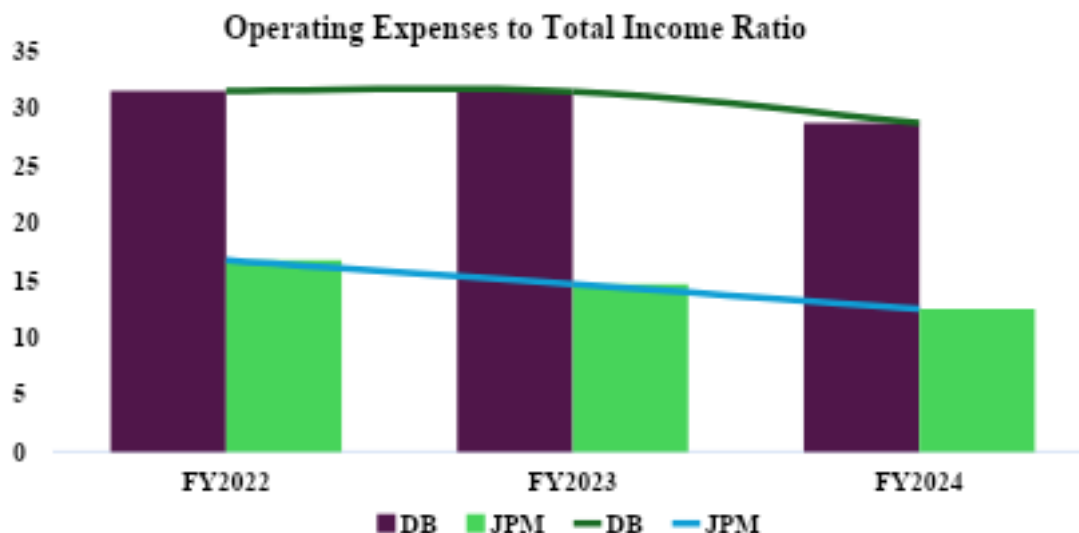
investments, indicating a somewhat decentralized finance function with a focus on local lending and client financing. In comparison, JPMorgan Chase India reported a marked increase in investments coupled with a decrease in advances. By FY2024, investments made up more than 70% of total assets. This demonstrates a finance function design of a centralized treasury, with the preference for investments over the expansion of local credit. The evidence shows the finance function design shapes the availability and accessibility of capital in the long run.



4.3 Cost Efficiency

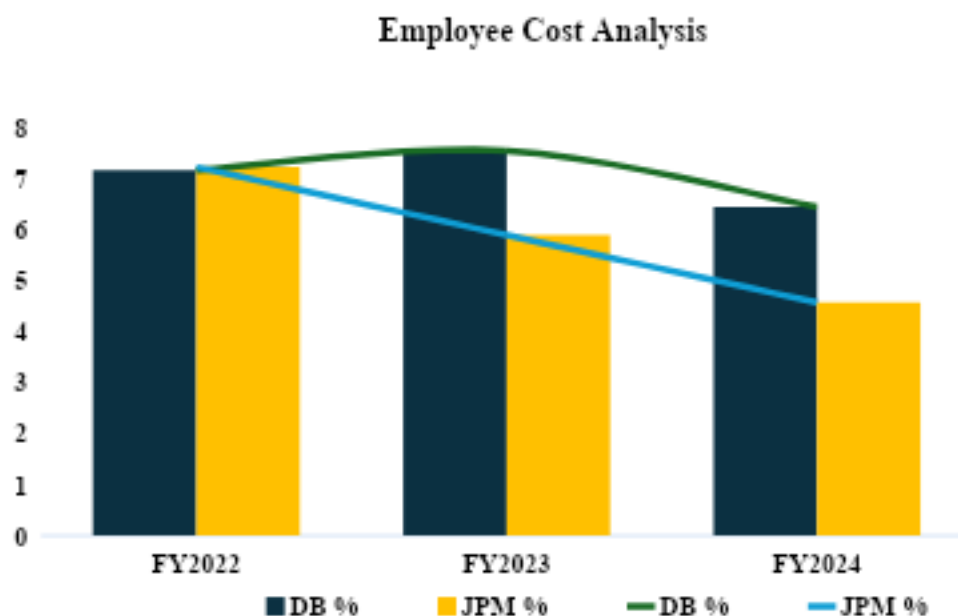
4.3.1 Operating Expenses to Total Income Ratio

This ratio shows how much of an organization's income is spent on operating expenses. JPMorgan Chase India achieved this efficiency target consistently and comparatively lower than Deutsche Bank India. Deutsche Bank India's Operating Expenses to Total Income Ratio for the period 2018 to 2022 is noted between 16.65% in 2018, and 12.42% in 2022. It also shows Deutsche Bank India's capability to manage their operating costs, and standardize some of the banking processes, and achieve cost optimizations along with improved economies of scale with the service of the centralized Finance function. Deutsche Bank India's Operating Expenses Ratio also registered marginal improvement from 31.41% to 28.60%. However, Deutsche Bank India's operating costs were significantly higher. This is in-line with Deutsche Bank India's approach of managing their operations in a decentralized manner and sustaining their local administration offices. The observations also indicate the benefits of operational efficiency and cost rationalization with the aid of digitalization and integrated centralized Financial Management.



4.3.2 Employee Cost Analysis

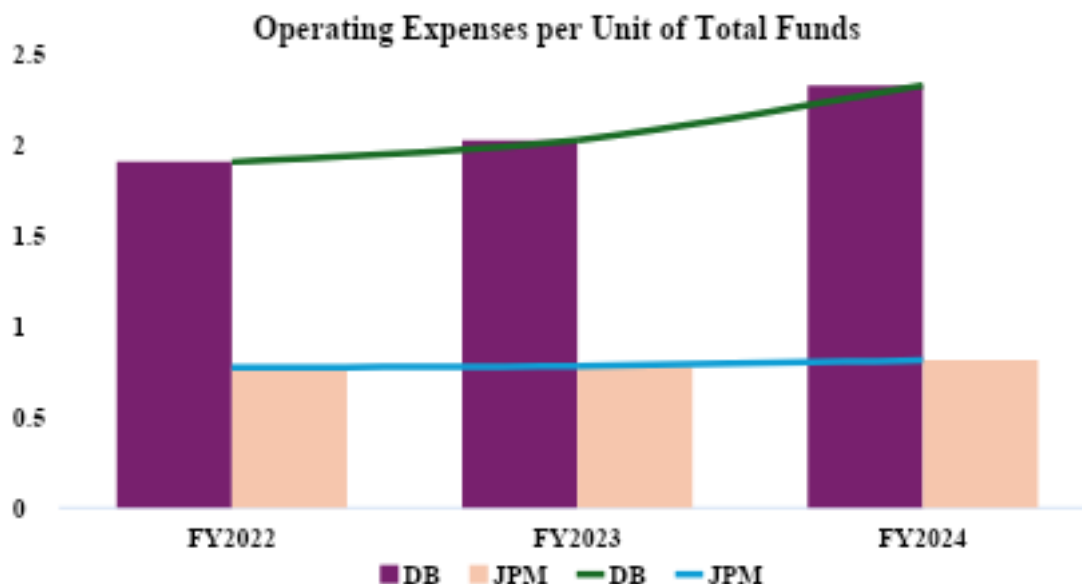
The rationalization of costs in the central finance function and improved employee productivity is apparent in the employee cost analysis. Deutsche Bank India's decentralized finance function, which makes operating units maintain dedicated personnel and local management, leads to higher employee costs than the operating income. Employee costs (as a % of income) improved for JPMorgan Chase India from 7.21% to 4.56%. The observations also indicate the benefits of operational efficiency and cost rationalization with the aid of digitalization and integrated centralized Financial Management



4.3.3 Operating Expenses per Unit of Total Funds

Operating Expenses per unit of Total Funds shows up the operational cost per unit of financial resource utilized by banks. JPMorgan Chase India continued to enjoy single digit or low digits at around 0.8%, which demonstrates prudent cost control measures under central finance function. In contrast, Deutsche Bank India experienced increasing operational cost intensity from 1.90 per cent to 2.32 per cent due to higher administration and upkeep cost

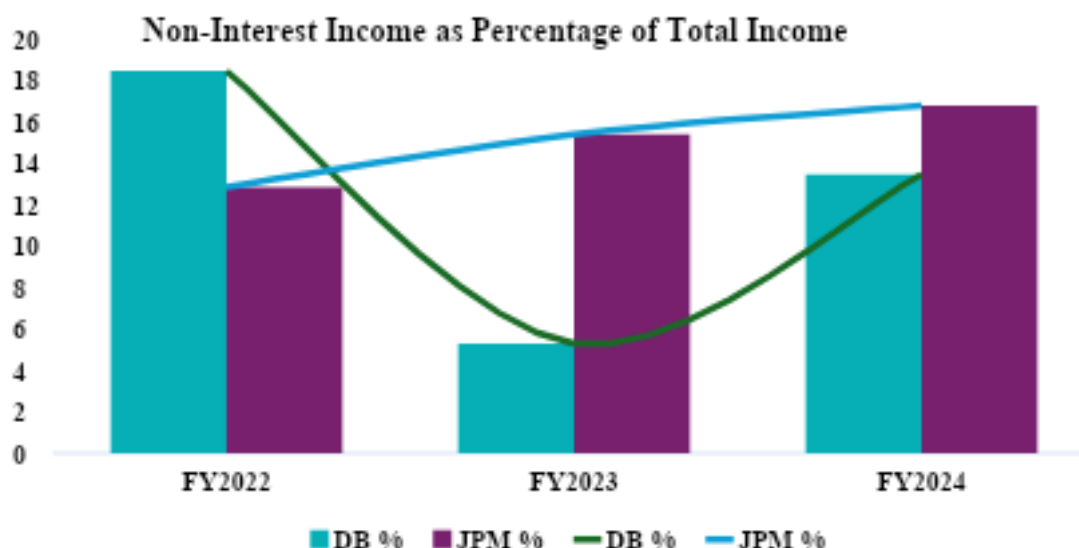
due to decentralized set up. Divergence shows that centralized finance supported by digital technology could have better operational leverage, resource efficiency and also sustain long-term cost efficiency.



4.4 Revenue and Financial Performance

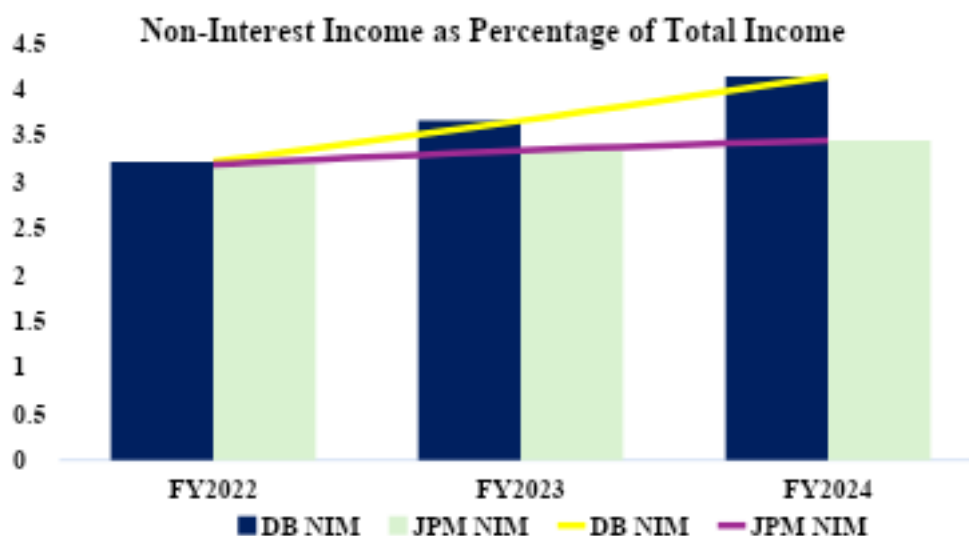
4.4.1 Non-Interest Income as Percentage of Total Income

Percentage contribution of non-interest income-This is indicative of how well the revenues are diversified apart from interest earnings on its core lending business. JPMorgan Chase India exhibited a constantly growing share of contribution by non-interest income at 16.77% FY2024 comprising income derived from investment Banking treasury functions as well as various fee-based activities. On the contrary, Deutsche Bank India was more volatile and has a more traditional banking outlook depending on interests through core lending as analysed by the experts. The conclusion drawn, therefore is that, with a well-structured Finance Function at the core facilitated by digital transformation and integrated treasury structure, banks will also able to generate diversified revenue stream, which significantly bring down their dependence on the traditional lending related interest income.



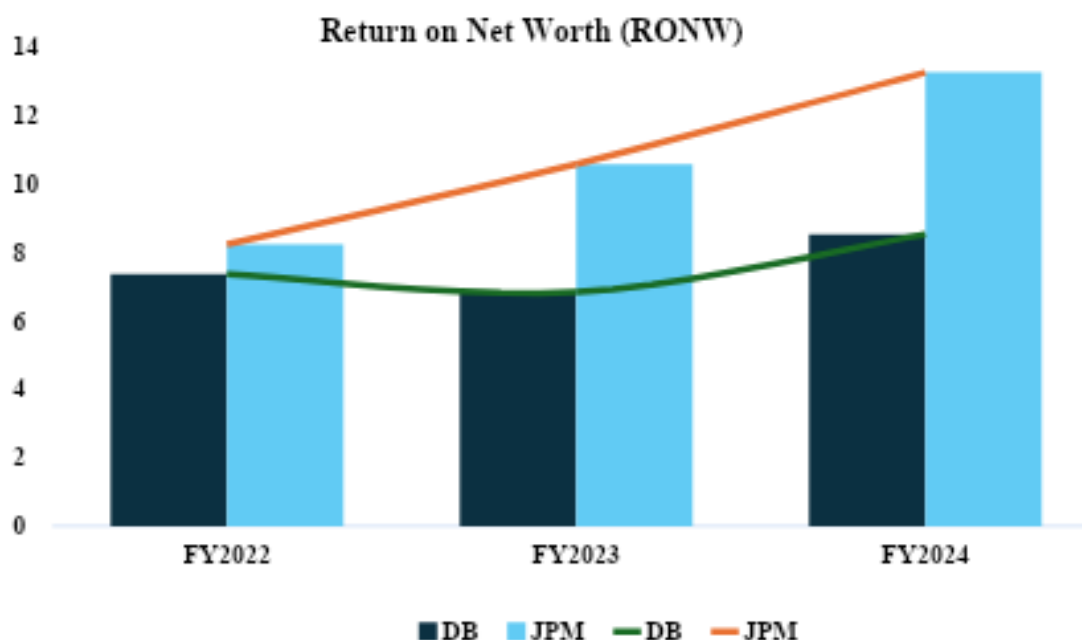
4.4.2 Net Interest Margin (NIM)

The Net Interest Margin (NIM), an indicator of bank's efficiency in earning from their lending and investments, has been steady upward trend of 3.21% to 4.13% in case of Deutsche Bank India showing their localized credit deployment effectively with de centralize way of lending. The case for J.P. Morgan Chase, its margin has been comparatively on steady note on de centralizing mode where its financial centralization helps in de-emphasis of lending growth by favouring with Treasury function of Bank to focus on investment and other activities and risk-free business to get the risk weighted returns from that.



4.4.3 Return on Net Worth (RONW)

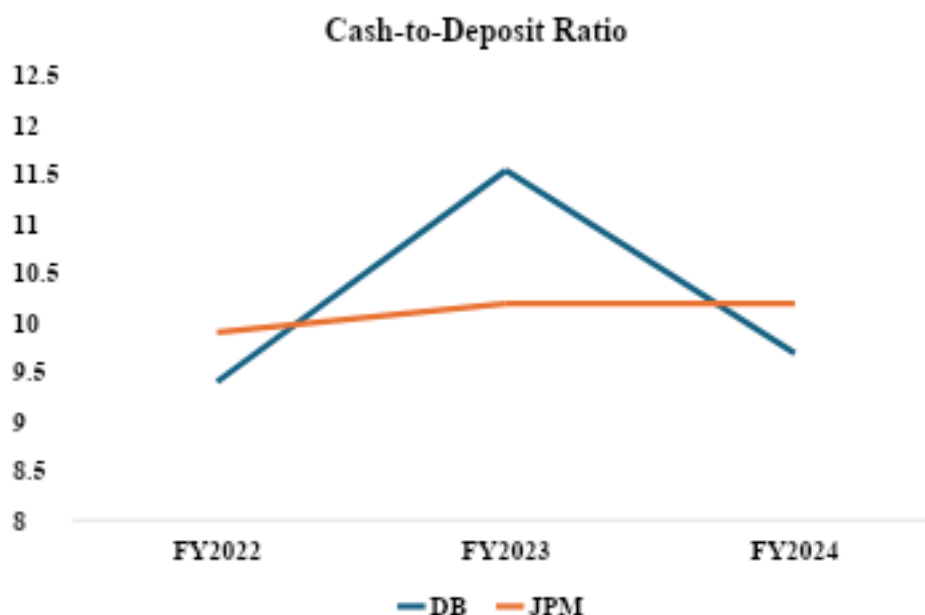
JPMorgan India outperformed Deutsche India with RO NW of 8.19 to 13.18%. In terms of capital allocation, it delivered superior returns and managed costs more efficiently due to centralised finance function. Despite an increase of RO NW to 8.48% in FY2024 Deutsche Bank continues to lag due to operational expenses and higher proportion of loans being granted. Centralised Finance function enabled digital adoption creating shareholder value.



4.5 Liquidity Management

4.5.1 Cash-to-Deposit Ratio

The Cash to Deposit ratio is an indicator of the banking firm's capacity to meet their short-term commitments for liquidity at the best interest rate. JPMorgan Chase India's ratio remained stable, close to the vicinity of 10% for the entire duration under survey thereby showing the control provided by the organized treasury for centralized liquidity regulation; where Deutsche Bank India had high variability which is expected with decentralisation since the financial management being localised for managing liquid resources based on local needs. ⁸ This implies that the firm centralised liquidity manages well with no negative effect over its operational feasibility with regulatory compliance, stable finances and efficient utilisation of liquidity, ⁹⁸ Deutsche Bank India was considered worse from both points of view.



5. Findings

As can be seen in our comparative analysis, a relatively centralized finance function within the organisation at JPMorgan Chase India appears to be a superior strategy compared to Deutsche Bank India's relatively decentralized approach on a wide range of financial and operational metrics in FY2022-FY2024. The confluence of these centralisation efforts along with Digital Standardisation has resulted in JPMorgan Chase India reporting better cost efficiency, efficient capital allocation, efficient liquidity and enhanced Return on Net Worth (RONW). Our observation of improving investment-to-deposit and consistent low operating cost ratio reveals the digital impact to the centralized finance function where good resource allocation capabilities, enhanced use of Automation, and tight fiscal management lead better decision making through a central channel. In the case of Deutsche Bank India, our comparison suggests higher local deployment, as measured by the higher CD ratio where local operational agility and efficiency provide faster localized decisions in a more localized manner.

Although decentralisation helps in faster, localized, and customer friendly credit disbursal which can make the local management quicker, it does create cost redundancies and financial volatility in the organization. Our comparative study reiterates that digital can also provide the right level of automation and operational efficiency for any of the finance functions. Technologies like ERP, Automation, Analytics, centralization, and an ERP system can also enable a de-centralised approach of finance function and can improve on efficiency, financial reporting and the overall strategic governance of a financial institution; however, the centralized finance has shown better results on returns and operational efficiency parameters. Our research shows an implication that centralization offers organizational

agility and fiscal efficiency whereas de-centralization offers efficiency in the local operations and the speed in decision making; organization must adopt the right balance of Centralization and De- centralization based on the digital capabilities.

6. Recommendations

Based on the results obtained, it can be argued that financial institutions need to move towards a finance function which will be digitally integrated and incorporate the strengths of both the centralized and decentralized finance functions. Centralized functions like treasury operations, financial reporting, compliance, risk management, and capital allocation should continue to benefit from AI, ERPs, predictive analytics, and automation. Simultaneously, the banks should preserve decentralized control of customer loans, regional credit analysis, and decision making to gain more responsiveness and better service.

In terms of sustainability, banks should promote digital banking initiatives which will ensure effective resource usage, elimination of paper processes in finance, real-time reporting and analytics, and decision-making to achieve operational efficiency and sustainability of their operations in the long run. Investments in digital infrastructure, cyber-security, development of digital competencies of the employees, and AI governance would bring even greater organizational resilience and compliance with the regulations. Hybrid models of governance which combine centralized strategic management and decentralized execution supported with integrated digital platforms are another step banks could take to improve their financial performance.

7. Scope for Future Study

This research paper makes use of the comparison of finance functions of JPMorgan Chase India and Deutsche Bank India through secondary financial data. Future research could benefit from extending the scope of the research to cover a more extensive number of commercial banks around the globe with varying banking sectors. Researchers could further explore how the development of technologies such as Artificial Intelligence (AI), Machine Learning (ML), blockchain, cloud computing, and predictive analytics affects centralized and decentralized finance functions.

Primary data can be incorporated for future studies to gather information on organizational practice and digital transformation from finance functioners and banking executives. Moreover, future research could explore the connection between finance functions transformation through digitalization and Environmental, Social, and Governance (ESG) initiatives, sustainable banking practices, and financial performance.

8. Limitations of the Study

There exist certain limitations of the study. Firstly, the analysis is conducted with the focus on two commercial banks functioning in India, which makes the generalizability of the results to the banking sector impossible. Secondly, the study is purely focused on the use of secondary financial data, collected through Capitaline AWS database and does not involve any primary data collected from bank employees and managers. Thirdly, the analysis is carried out for only three fiscal years, namely FY2022, FY2023 and FY2024, which makes it impossible to analyse the long-term tendencies related to the digital transformation and organizational performance. Fourthly, the distinction between the relative centralization and decentralization of the finance functions is made by comparing their financial and organizational parameters. Lastly, external factors like macroeconomic situation, technological advancements and others may affect financial performance, yet they are not considered in this study.

9. Conclusion

In the present study, the impact of centralized versus decentralized finance functions on organizational performance in the digital banking environment is explored through the comparative analysis of JPMorgan Chase India and Deutsche Bank India. The study found that while JPMorgan Chase India had more centralized finance function, it

proved to perform better in terms of cost, capital management, liquidity management and financial performance, thanks to digital integration of its treasury systems and automation of financial operations.

However, Deutsche Bank India with its more decentralized finance function was able to make better use of credit locally and showed greater flexibility to changing market conditions, albeit at the price of comparatively high operating costs. Therefore, the study demonstrates that digital transformation substantially improves performance of finance functions because of enhanced financial control, efficiency, transparency and governance. Instead of advocating for any particular type of organizational structure, the study highlights the need for finding a proper balance between centralized strategic control and decentralized flexibility in the rapidly changing digital banking environment.

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Data Source

Capitaline database: <https://awsone.capitaline.com/>

Digital Public Infrastructure and Financial Self-Reliance: Reimagining India's Banking and Payments Ecosystem under Atmanirbhar Bharat

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Information of Article	ABSTRACT
Article history: Received: 01 July 2026 Presented: 22 August 2026 (INSPIRE-2026, GIBS Bengaluru) Keywords: Digital Public Infrastructure UPI Financial Inclusion Atmanirbhar Bharat DBT Digital Payments Banking Ecosystem Financial Resilience NPCI India Stack	Digital Public Infrastructure (DPI) — publicly governed, interoperable, and built to work at population scale — has become central to how India approaches financial inclusion, welfare delivery, economic resilience, and institutional modernisation. This paper examines the role of DPI in advancing the developmental vision of Atmanirbhar Bharat, analysing its contribution across five dimensions: financial inclusion, transaction efficiency, MSME credit expansion, fiscal governance, and payment sovereignty within India's banking and payments ecosystem. The study adopts a descriptive, analytical, and policy-oriented design, combining qualitative policy analysis with quantitative trend interpretation of secondary data for 2015–2025, organised through a three-pillar framework of infrastructure expansion, inclusion and resilience outcomes, and governance and sustainability. UPI transaction volumes grew from 1,079 crore in 2019 to over 20,849 crore in 2024, while cumulative DBT transfers crossed ₹30 lakh crore and eliminated an estimated ₹4 lakh crore in leakages. The Account Aggregator framework, together with UPI transaction histories, expands MSME formal credit penetration by reducing information asymmetry. The evidence supports all four hypotheses: DPI improves financial inclusion, digital payments strengthen MSME credit access, DPI reinforces financial resilience and payment sovereignty, and its effectiveness depends on regulatory governance and cybersecurity preparedness. Financial self-reliance in the digital age is built through infrastructure, not isolation.

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1. Background

Few digital governance transitions anywhere in the world compare in scale to what has happened inside India's financial system over the last ten years. A combination of interoperable platforms, biometric identity, real-time payment rails, and consent-based data-sharing has produced one of the largest public digital ecosystems ever built. Digital Public Infrastructure (DPI) — publicly governed, interoperable, and built to work at population scale — sits at the centre of this shift, and it has become central to how India now thinks about financial inclusion, welfare delivery, economic resilience, and institutional modernisation.

What sets DPI apart from earlier waves of digitisation is that it is not another set of siloed applications. It is foundational plumbing — infrastructure that governments, banks, fintechs, and everyday businesses can build on top of, rather than around. Aadhaar, UPI, DBT, DigiLocker, e-KYC, and the Account Aggregator framework together make up what is widely known as the 'India Stack,' and each of these components does a distinct job within a shared architecture.

It is worth being precise about what Atmanirbhar Bharat actually asks for, because the phrase is often misread as a call for economic isolation. It is not. The vision is about strengthening domestic institutional capacity, building financial resilience, encouraging innovation-led growth, and reducing unnecessary dependence on external systems — while remaining fully engaged with the global economy. Financial infrastructure sits close to the core of that

ambition, since the efficiency of a country's financial system shapes its ability to mobilise savings, allocate capital where it is needed, and deliver public welfare without leakage.

It is easy to forget how recently India's banking system looked very different. Before this transformation, roughly half of India's adult population had no meaningful access to formal banking. Opening an account could take the better part of a week, KYC compliance cost banks somewhere between ₹150 and ₹200 per customer, and welfare subsidies leaked away at a rate of 20 to 40 per cent. Cash, informal middlemen, and unregulated credit filled the gap, especially in rural India.

The turning point came with what is now called the JAM Trinity — Jan Dhan, Aadhaar, and Mobile. Aadhaar gave people a reliable digital identity; Jan Dhan opened bank accounts for those who had never had one; and mobile connectivity carried financial services into places bank branches never reached.

Together, these three pieces built the foundation on which everything else — UPI, DBT, Account Aggregator — was subsequently constructed.

This article works through five lenses to assess what DPI has actually delivered for the Atmanirbhar Bharat agenda: (i) the expansion of financial inclusion; (ii) improvements in state capacity and fiscal governance; (iii) reductions in transaction cost; (iv) better credit access for MSMEs; and (v) gains in payment sovereignty and economic resilience. It also takes a hard look at the governance challenges that rapid digitalisation has brought with it, drawing on evidence from the RBI, NPCI, the World Bank, the IMF, UNDP, and PwC over the period 2015–2025.

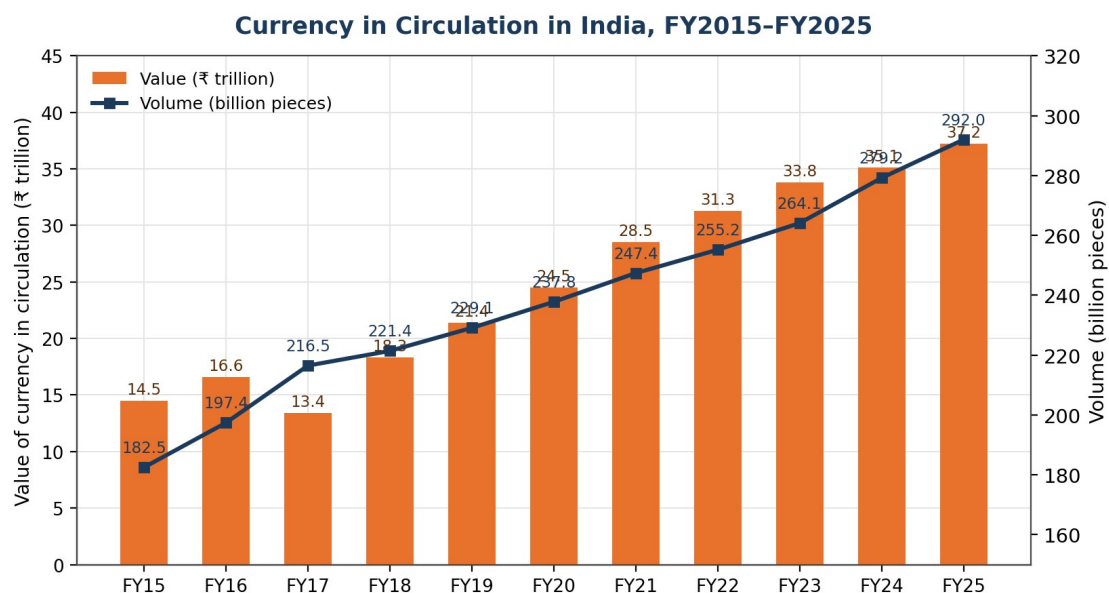


Figure 1: Currency in Circulation in India, FY2015–FY2025 (Source: RBI)

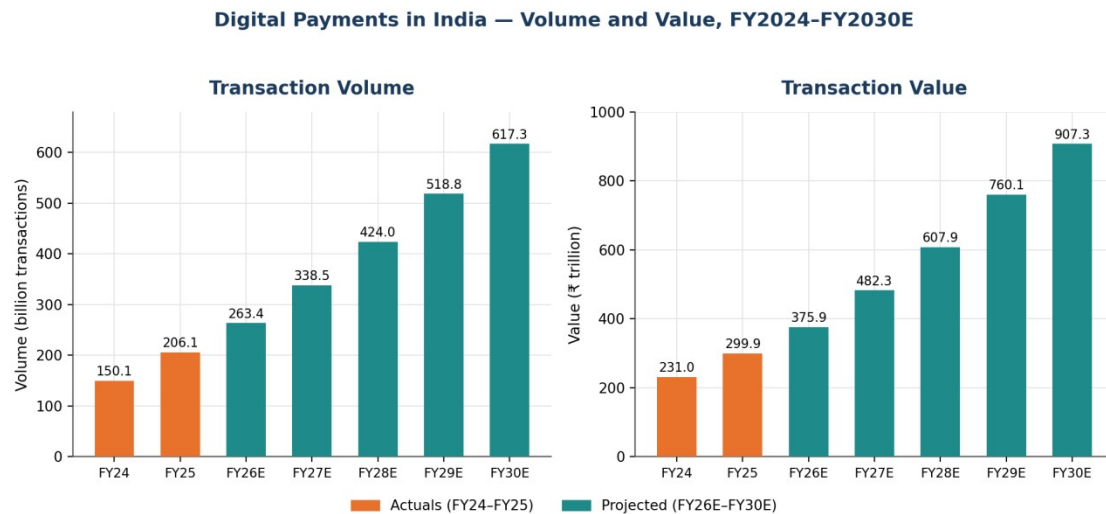


Figure 2: Digital Payments Transactions — Volume and Value, FY2024–FY2030E (Source: PwC Analysis)

A useful way to read Figures 1 and 2 together is that cash in circulation has kept rising in absolute terms — India is still a large, growing economy — but the growth curve for digital transactions is far steeper. Digital payments are on course to more than triple in volume and nearly quadruple in value between FY2024 and FY2030, a trajectory that would have been difficult to imagine a decade ago.

2. Review of Related Literature

A growing body of institutional and academic work has examined how digital financial infrastructure intersects with economic development. The strands most relevant to this study are summarised below.

- Desai et al. (2023) treat DPI as a reusable, horizontal foundation that prevents ecosystems from fragmenting into incompatible silos, pointing to Aadhaar and UPI as well-executed examples. Their central claim is that well-governed DPI creates room for innovation, competition, and productivity gains at the application layer, across many sectors at once.
- The Global Partnership for Financial Inclusion (2023) singles out India's JAM Trinity as a benchmark, arguing that open, interoperable DPI generates network externalities that lower transaction costs and widen economic participation.
- The World Bank (2023) describes India as having built the world's largest and most technically sophisticated DPI for financial inclusion, with particular emphasis on scalability, cost-efficiency, and the quality of its governance arrangements.
- RBI's Payments Vision 2025 lays out five strategic goalposts — Integrity, Inclusion, Innovation, Institutionalization, and Internationalization — that continue to shape India's digital payments trajectory.
- The IMF's Growing Retail Digital Payments report documents that UPI now accounts for roughly 49 per cent of global real-time payment transactions, a figure that alone signals India's position in this space.
- The UNDP DPI Playbook (developed with the G20) frames DPI as a social good — publicly governed, interoperable, and open-access — and positions it as foundational to achieving the Sustainable Development Goals.
- PwC's Indian Payments Handbook 2025–2030 examines the sustainability of the zero-MDR (Merchant Discount Rate) policy, the evolving use cases for UPI, and the trajectory of digital lending.
- Documentation from the Government of India's DBT Mission traces cumulative Direct Benefit Transfers exceeding ₹30 lakh crore, spread across hundreds of schemes and reaching millions of beneficiaries.

- Mahadevan and Srinivasan (IIM Bangalore, 2025) show that India built a national payments backbone at one of the lowest per-transaction costs anywhere in the world, treating NPCI's institutional model as a case study in frugal, transparent infrastructure design.
- IBEF's UPI reporting documents UPI's share of digital payments rising from roughly 34 per cent in 2019 to 83 per cent in 2024 — a compound annual growth rate of around 74 per cent.
- The World Bank Financial Access Survey and IMF data (2024) provide the cross-country panel data on mobile banking, SME credit penetration, and branch density used throughout this study, spanning 2017–2024.
- The Payment and Settlement Systems Act, 2007 (as updated in 2025) establishes the legal basis for oversight of India's payment systems, with the RBI as the designated supervisory authority and clear rules on netting and settlement finality.
- UNDP's G20 Compendium, Accelerating the SDGs through Digital Public Infrastructure, examines how DPI can advance sustainable development across health, education, agriculture, and financial inclusion, treating India's model as a template that other countries might adapt.

3. Objective

The paper dwells in detail on the role of Digital Public Infrastructure in promoting the developmental vision of Atmanirbhar Bharat, analysing its contribution across five core dimensions — financial inclusion, transaction efficiency, MSME credit expansion, fiscal governance, and payment sovereignty — within India's banking and payments ecosystem. The study is organised around five specific objectives:

- Tracing the evolution of DPI within India's banking and payments ecosystem.
- Examining DPI's contribution to financial inclusion.
- Assessing how UPI, DBT, and interoperable payment systems have advanced Atmanirbhar Bharat.
- Evaluating digital payments' effect on MSME credit access.
- Identifying the governance, cybersecurity, and regulatory challenges that remain.

Four hypotheses guide the analysis:

- H1: Digital Public Infrastructure significantly improves financial inclusion in India.
- H2: Growth in digital payments positively influences MSME formal credit penetration.
- H3: DPI strengthens India's financial resilience and payment sovereignty.
- H4: The effectiveness of DPI depends on strong regulatory governance and cybersecurity preparedness.

4. Methods

The study encompasses a descriptive, analytical, and policy-oriented research design, combining qualitative policy analysis with quantitative trend interpretation over the period 2015–2025. This study takes a descriptive, analytical, and policy-oriented approach, pairing qualitative policy analysis with quantitative trend interpretation to assess how digital financial infrastructure affects financial inclusion, governance efficiency, payment sovereignty, and economic resilience. Because DPI is still a relatively young and fast-moving field within financial governance and digital economics, the design remains deliberately exploratory.

4.1 Nature and Sources of Data

The study relies entirely on secondary data drawn from credible institutional reports, policy documents, and international databases. Principal sources include RBI Annual Reports and Payments Vision 2025, NPCI transaction statistics, the World Bank Financial Access Survey and IMF Data Portal, the IMF's Growing Retail Digital Payments report, the UNDP DPI Playbook, DBT Mission documents from the Government of India, PwC's Indian Payments

Handbook 2025–2030, and the IIM Bangalore institutional analysis of NPCI. The study window runs from 2015 to 2025, covering the core period of India's digital financial transformation.

4.2 A Three-Pillar Framework

To keep the analysis organised, the study uses a three-pillar framework for judging DPI's effectiveness. The three pillars interact continuously, and it is their combined effect — not any one pillar alone — that determines how much DPI contributes to financial self-reliance and economic resilience under Atmanirbhar Bharat.

Pillar I — Infrastructure Expansion	Pillar II — Inclusion & Resilience Outcomes	Pillar III — Governance & Sustainability
UPI transaction growth	Financial inclusion metrics	Regulatory reforms
Mobile banking transactions	DBT coverage	Cybersecurity preparedness
QR-code deployment	MSME credit expansion	Fraud trends & prevention
Digital payment penetration	Transaction cost reduction	Data privacy concerns
Banking access indicators	Household financial resilience	Institutional safeguards

Figure 3: Three-Pillar Analytical Framework for Evaluating DPI Effectiveness — the interaction of these pillars drives the outcome of financial self-reliance and economic resilience under Atmanirbhar Bharat (Source: Authors)

4.3 Tools and Techniques of Analysis

Trend analysis is used to track UPI transaction growth, the expansion of digital banking, and MSME credit trends over time. Comparative analysis sets traditional, branch-based banking against the digital ecosystem, and contrasts pre-DPI and post-DPI financial inclusion indicators. Policy analysis works through RBI's Payments Vision 2025, the architecture of DBT, the Payment and Settlement Systems Act 2007, and the various India Stack initiatives. Finally, conceptual analysis is used to explore the relationships between digital transaction intensity and MSME credit access, between financial inclusion and economic resilience, and between digital infrastructure and payment sovereignty.

5. Findings

UPI transaction volumes have grown from 1,079 crore in 2019 to over 20,849 crore in 2024, while cumulative DBT transfers crossed ₹30 lakh crore and eliminated an estimated ₹4 lakh crore in leakages through Aadhaar-seeded beneficiary verification. The Account Aggregator framework, in combination with UPI transaction histories, is shown to meaningfully expand MSME formal credit penetration by reducing information asymmetry and lowering appraisal costs. The detailed findings, organised by theme, are set out below.

5.1 Conceptual Framework of Digital Public Infrastructure

DPI can be thought of as an intermediate digital layer that lets governments, businesses, and citizens interact seamlessly. Where conventional digitisation tends to produce fragmented, one-off solutions, DPI is deliberately built around open standards, interoperability, scalability, and public governance. UNDP's framing captures this well: DPI is a publicly governed, interoperable, open-access digital architecture that enables both public and private innovation, while reducing transaction costs, increasing transparency, and producing more inclusive outcomes. Its core building blocks typically include digital identity systems, real-time payment rails, data-sharing frameworks, authentication layers, and public registries.

India Stack — Components and Functional Roles

India's version of DPI is among the most developed in the world. Nandan Nilekani's often-quoted line captures its ambition well: India Stack is 'to the digital economy what the railways were to industrial India' — foundational infrastructure that makes broader economic transformation possible. Table 1 sets out the main components and what each one does.

Table 1: India Stack — Components and Functional Roles (Source: RBI, NPCI, World Bank)

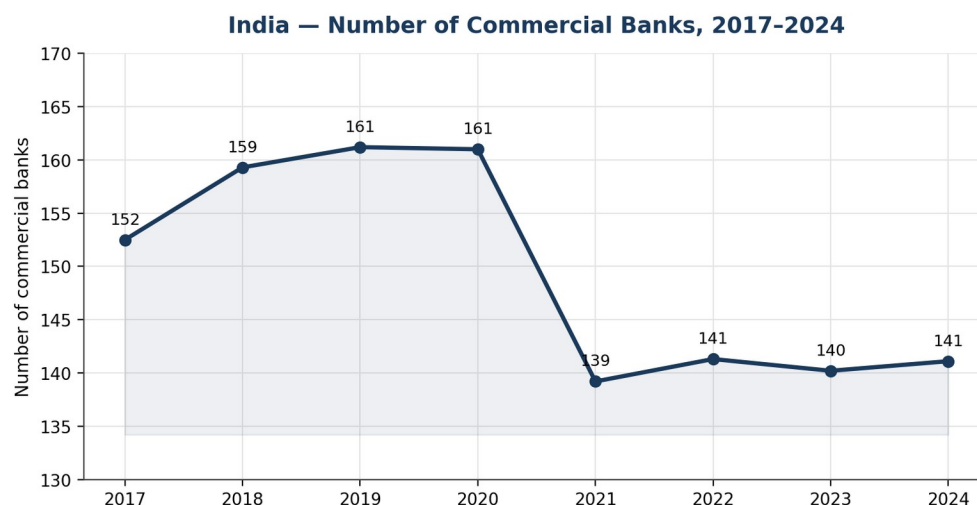
Component	Functional Role
Aadhaar	Biometric digital identity for over 1.4 billion residents
Jan Dhan	Financial inclusion — mass bank account opening across India
Mobile Connectivity	Digital access and financial reach to remote populations
DigiLocker	Trusted digital document storage and verification
e-KYC	Digital verification and streamlined customer onboarding
UPI	Real-time interoperable payments infrastructure at population scale
Account Aggregator	Consent-based financial data sharing enabling credit access

The COVID-19 pandemic ended up being an unplanned stress test for DPI, and it passed convincingly. Countries that already had digital identity and payment systems in place could get social protection benefits to people faster and more transparently than those that did not. In India, DBT rails carried welfare payments straight into beneficiaries' bank accounts even as the economy was disrupted. That episode is a useful reminder that DPI is not merely a technological layer — it functions as institutional infrastructure, one that improves governance efficiency, transparency, and economic participation all at once.

5.2 Financial Inclusion and the Digital Transformation of Banking

Financial inclusion has long been recognised as one of the more reliable predictors of economic development. Access to formal financial services — active accounts, affordable digital payments, credit, and basic consumer protection — builds household resilience, mobilises savings, supports investment, and reduces reliance on informal credit markets. Before DPI, India's banking system carried high KYC compliance costs (₹150–200 per customer), thin rural branch coverage, heavy cash dependence, slow account opening, and welfare leakages of 20–40 per cent. The JAM Trinity changed that picture by enabling digital onboarding at population scale.

The number of commercial banks in India tells an interesting, if secondary, part of this story. Bank numbers rose from roughly 152 in 2017 to a peak of about 161 in 2019, before falling to around 139 by 2021 — largely the result of government-driven consolidation among public sector banks. Since then, the count has stabilised near 141, suggesting a sector that has become leaner and more consolidated even as digital reach has expanded.

**Figure 4:** India — Number of Commercial Banks, Annual, 2017–2024 (Source: World Bank Financial Access Survey / IMF)

What is notable is that this consolidation happened without a corresponding contraction in access. Physical branch density held broadly steady, at roughly 14.3–14.6 branches per 100,000 adults, while mobile and internet banking

transactions grew from around ₹20–30 trillion in 2020 to an extraordinary ₹130 trillion by 2024. In other words, the banking system shifted from being branch-centric to mobile-centric, delivering efficiency gains that did not require a matching build-out of physical infrastructure.

Expansion of Digital Payments

The most visible sign of India's shift to digital finance is the sheer growth of UPI. By the first half of 2025, digital payments accounted for close to 99.8 per cent of all payment volume and 97.7 per cent of total transaction value. UPI's own share of India's digital payments climbed from around 34 per cent in 2019 to 83 per cent in 2024 — a compound annual growth rate of roughly 74 per cent. India now processes close to 49 per cent of the world's real-time payment transactions through UPI alone (IMF; IBEF).

A few statistics illustrate the scale of this shift:

- UPI transaction volumes crossed 20,849 crore annually in 2024, up from 1,079 crore in 2019 (NPCI).
- Transaction value reached ₹2,830 lakh crore in 2024, up from ₹18.4 lakh crore in 2019.
- Monthly UPI transactions crossed 19 billion in 2025, worth more than ₹24.5 lakh crore (The Economic Times).
- More than 688 banks now participate in the UPI ecosystem, serving 491 million individuals and 65 million merchants (NPCI, August 2025).
- The Payments Infrastructure Development Fund (PIDF) has enabled 5.45 crore digital touch points and more than 56 crore QR codes across roughly 6.5 crore merchant entities.

UPI Transactions — Volume and Value, FY2024-FY2030E

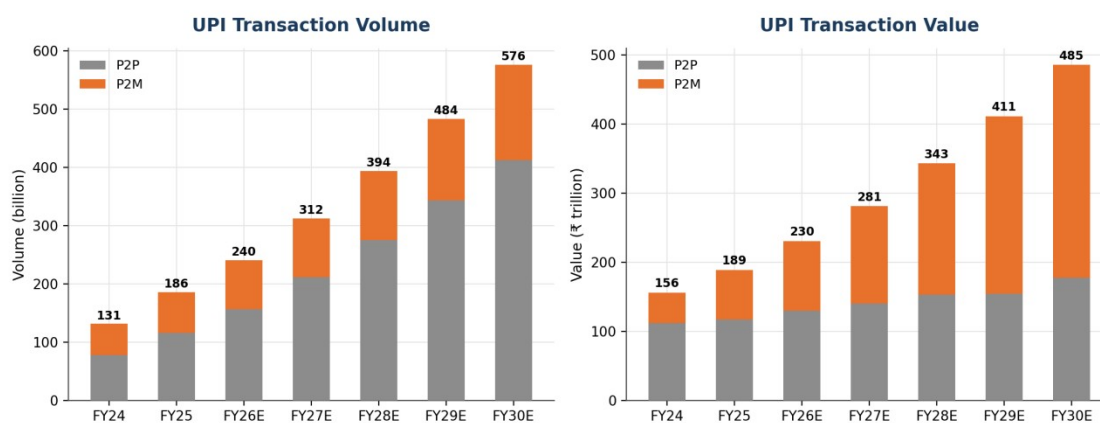


Figure 5: UPI Transactions — Volume and Value (P2P and P2M split), FY2024–FY2030E (Source: RBI; NPCI; PwC Analysis)

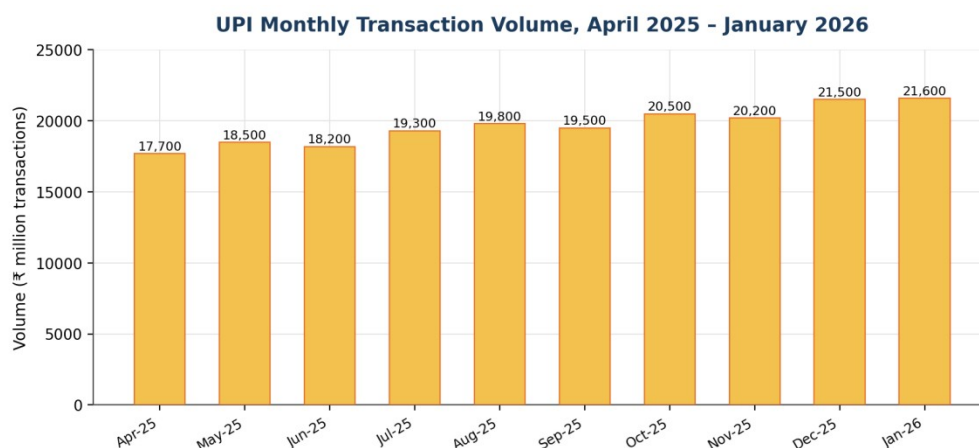
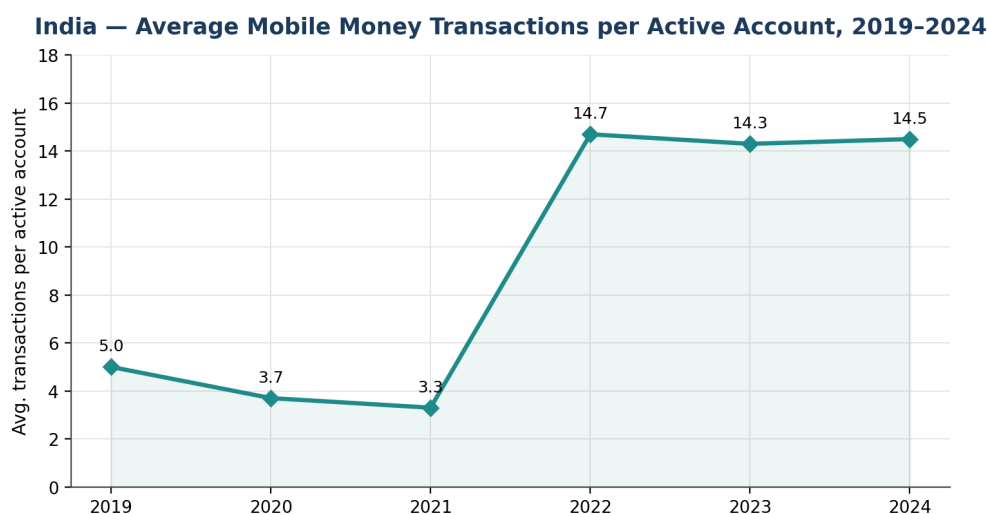


Figure 6: UPI Monthly Transaction Volume, April 2025 – January 2026 (Source: NPCI)**Commercial Banking Transformation**

The shift from physical to digital delivery channels shows up clearly in the numbers. Assets held by credit unions and cooperatives grew steadily from around ₹8 million in 2017, accelerating after 2020 and reaching close to ₹13 million by 2024 — evidence that cooperative institutions have been deepening their reach into semi-urban and rural credit markets alongside the larger digital push. Meanwhile, the value of mobile and internet banking transactions rose from negligible levels in 2017–18 to well above ₹1,300,000 million by 2024, which points not just to more transactions but to progressively higher-value payments moving through digital channels.

Financial Inclusion Outcomes

DPI's contribution to financial inclusion shows up across several dimensions at once: more bank accounts, more transaction activity, lower transaction costs, better welfare access, and greater participation by small merchants. Between 2021 and 2022–23, average mobile money transactions per active account nearly quadrupled, reaching about 15 transactions annually. Mobile money transaction counts rose from roughly 1 billion in 2017 to nearly 6.3 billion by 2024 — almost a sixfold increase. Registered mobile money accounts grew dramatically as well, from about 200 million in 2017 to close to 2 billion by 2021, tracking the parallel explosion in UPI-linked and digital wallet accounts. On average, every adult in India now conducts roughly six mobile money transactions a year — a fair indicator of how mainstream digital payments have become across demographic groups.

**Figure 7: India — Average Mobile Money Transactions per Active Account, Annual, 2019–2024 (Source: World Bank Financial Access Survey / IMF)****5.3 DPI, DBT, and Fiscal Governance**

Direct Benefit Transfer (DBT), introduced on 1 January 2013, changed how India delivers welfare — moving it toward efficient, transparent, and targeted disbursal. It began in just 43 districts and expanded nationwide from 12 December 2014. The JAM Trinity underpins the entire DBT system: more than 22 crore Jan Dhan accounts, 100 crore Aadhaar enrolments, and roughly 100 crore mobile connections together give India an implementation capacity for welfare delivery that few other countries can match.

As of January 2026, the Pradhan Mantri Jan-Dhan Yojana (PMJDY) has enrolled 57.37 crore beneficiaries across public sector banks, regional rural banks, private sector banks, and rural cooperative banks. Deposits held in these accounts stood at over ₹2,83,201 crore — a fair measure of just how deep financial inclusion has gone under the Jan Dhan programme. The scheme has also issued 39.63 crore RuPay debit cards, pulling beneficiaries further into the digital payments ecosystem.

The governance dividends from this architecture are substantial:

- Cumulative savings of roughly ₹4 lakh crore between 2014 and 2024, achieved by eliminating duplicate and 'ghost' beneficiaries.
- Aadhaar seeding has removed duplicate beneficiaries, ensuring welfare reaches only verified individuals.
- During COVID-19, digital transfers delivered fiscal support to targeted beneficiaries quickly and without any need for physical contact.
- Real-time monitoring of fund flows across schemes has meaningfully improved transparency and accountability.
- Cumulative DBT transfers have now crossed ₹30 lakh crore across hundreds of schemes and millions of beneficiaries.

Table 2 below draws on the DBT Performance Ranking of States/UTs, which scores India's federal units on parameters such as State Aadhaar Act adherence, Aadhaar saturation, CSS identification, portal compliance, data reporting, and savings/expenditure ratios. Haryana, Uttar Pradesh, and Tripura lead the overall rankings — a result that underlines how much institutional capacity and inter-governmental coordination matter for effective DBT implementation, quite apart from the underlying technology.

Table 2 (summary): DBT Performance Ranking of States/UTs — top and bottom performers (Source: DBT Mission, Government of India)

Rank	State/UT	Overall Score
1	Haryana	88.8
2	Uttar Pradesh	85.2
3	Tripura	80.2
4	Gujarat	77.3
5	Uttarakhand	74.3
...	...	...
34	Telangana	29.6
35	Assam	26.4
36	West Bengal	13.2

5.4 Digital Public Infrastructure and MSME Credit Expansion

MSMEs occupy an outsized place in India's economy relative to their size, contributing heavily to employment, exports, and GDP. Yet they have historically struggled to access formal credit, hampered by weak collateral, information asymmetry, thin financial documentation, and the simple fact that small-ticket lending is expensive to underwrite. DPI has the potential to change this picture by attacking the information problem directly, rather than working around it.

Digital payment systems generate a running transaction history that functions as an alternative measure of creditworthiness. Combined with the Account Aggregator framework, which allows consent-based sharing of financial data between borrowers and lenders, this creates a data-rich environment for credit assessment — one that depends much less on physical collateral or a conventional credit history, both of which have historically shut small enterprises out.

The implications for MSME financing run in several directions at once:

- Digital footprints reduce information asymmetry, lowering credit appraisal costs and enabling faster underwriting.
- Real-time transaction data speeds up credit appraisal, compressing lending cycles from weeks down to days.

- Lower transaction costs for lenders make smaller-ticket lending commercially viable in a way it previously was not.
- Formal credit is reaching segments that were previously underserved, reducing reliance on informal, high-cost credit.
- Combining GST data, UPI transaction histories, and Account Aggregator-sourced financial statements allows for a more holistic view of creditworthiness.

SME lending by commercial banks has followed a remarkably steady upward path. Outstanding loan assets grew from roughly ₹10,000,000 million in 2017, continued expanding through the pandemic years, and accelerated sharply after 2021. By 2024, outstanding SME loans had reached approximately ₹21,500,000 million — more than double the 2017 figure — a trend that reflects both stronger institutional appetite for SME lending and the effectiveness of MSME credit guarantee schemes.

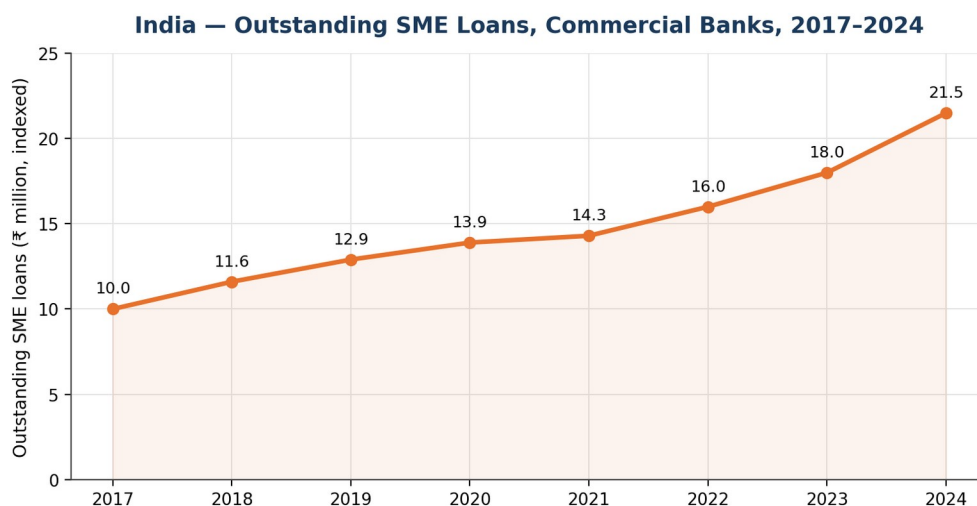


Figure 8: India — Outstanding SME Loans, Commercial Banks, Annual, 2017–2024 (Source: World Bank Financial Access Survey / IMF)

State-level panel data reinforces this pattern: a one per cent increase in digital transaction intensity is associated with a statistically significant rise in MSME formal credit penetration, and states with higher UPI adoption consistently show lower reliance on informal credit. This is precisely the relationship Hypothesis H2 predicts, and it carries real policy weight for anyone thinking about digital infrastructure as a lever for strengthening credit access among small enterprises.

5.5 Payment Sovereignty and Financial Self-Reliance

Financial self-reliance, in a globalized economy, does not mean cutting ties with international financial systems. It means something more specific: the capacity to mobilize domestic savings effectively, run resilient payment systems, deliver public transfers transparently, and avoid unnecessary dependence on foreign-controlled financial infrastructure. India's digital payment ecosystem has done a great deal to strengthen this kind of sovereignty, largely by building domestic, interoperable payment rails at national scale.

The National Payments Corporation of India (NPCI) — a not-for-profit institution established under the Payment and Settlement Systems Act 2007 — is the institutional anchor of India's payment sovereignty. NPCI operates UPI, RuPay, IMPS, NACH, AePS, FASTag, NFS, and CTS, which together form the backbone of the country's financial transactions. Mahadevan and Srinivasan (IIM Bangalore, 2025) document how NPCI has combined frugality with operational discipline to build a national payments backbone at one of the lowest per-transaction costs in the world. India now accounts for close to half of global real-time payment transactions.

RBI's Payments Vision 2025 reinforces this direction through its '4Es' theme — E-Payments for Everyone, Everywhere, Every time — aimed at making every e-payment option safe, secure, fast, convenient, accessible, and affordable. This is organized around five anchor goalposts: Integrity, Inclusion, Innovation, Institutionalization, and Internationalization.

UPI Pricing and Sustainability

The government's zero Merchant Discount Rate (MDR) policy has clearly accelerated UPI adoption, but it has also raised a legitimate question about long-run financial sustainability. UPI transactions currently generate no direct revenue, with the associated costs absorbed through government subsidy. Industry participants have flagged, consistently, that a zero-MDR framework leaves a structural funding gap for payment infrastructure. Balancing affordability against financial viability is likely to be one of the central policy challenges of the next phase, and it may eventually call for new revenue models or some re-calibration of the MDR framework — one that keeps the inclusion gains intact while putting infrastructure financing on a more sustainable footing.

Global Leadership and Strategic Positioning

India's DPI model is increasingly being looked at by other emerging economies as a possible template. India has entered UPI linkage agreements with Singapore, the UAE, France, Nepal, Bhutan, and Sri Lanka, and continues to push the internationalization of RuPay. These collaborations reinforce India's standing in global digital governance while keeping domestic autonomy intact — a genuine example of self-reliance operating alongside, rather than against, international engagement. The G20 India Presidency's Framework for Systems of Digital Public Infrastructure has further cemented India's leadership role in promoting DPI as a development tool worldwide.

5.6 Contributions

The paper offers a three-pillar framework for evaluating DPI effectiveness and identifies governance risks — cybersecurity fraud, data privacy, and the digital divide — that must be addressed to sustain these gains. It can be argued that financial self-reliance under Atmanirbhar Bharat is achieved through infrastructure-led inclusion rather than isolationist policy, and that the country's NPCI-anchored model of payment sovereignty offers a globally replicable template for other emerging economies.

5.7 Governance Challenges and Emerging Risks

For all its success, India's DPI ecosystem still faces real governance and institutional challenges. Data-driven governance gives the administration a powerful ability to design, implement, and monitor financial programmes — but that same capability brings a wide set of risks that need to be addressed proactively rather than after the fact.

Cybersecurity Risks

Digital payments have grown fast, and fraud has grown alongside them. Fraud transactions rose from 2.0 million in FY24 to 2.4 million in FY25. UPI fraud losses reached ₹5,730 million in 2022–23 (0.4 per cent of total UPI value), climbing to ₹11 billion in 2023–24 (0.5 per cent). By September 2024, 632,000 UPI fraud cases had been reported, with a total fraud value of ₹4,850 million.

The most common patterns behind this fraud fall into three categories: refund fraud, where scammers exploit the ease of P2P transfers by falsely claiming a mistaken payment and pressuring victims to 'return' funds; AI-driven impersonation, where deep-fake voice or video is used to pose as bank officials and extract OTPs or authorization for payments; and mule account fraud, where individuals are recruited — often through fake job offers — to move stolen funds through their own bank accounts, obscuring the money trail. Despite existing safeguards such as device binding, two-factor authentication, daily transaction limits, and use-case restrictions, fraud incidence keeps climbing. Centralized fraud databases and AI-based detection systems, including the MuleHunter AI initiative, are under active development and represent one of the more important frontiers in payment security right now.

Data Privacy and Governance

As digital identity and transaction data become more centralized, concerns naturally arise around privacy, data ownership, surveillance risk, and algorithmic discrimination. Getting the governance architecture right means balancing continued innovation against rights-based safeguards, in step with India's evolving data protection legislation. Transparent grievance redressal, meaningful consent mechanisms, and genuine algorithmic accountability are not optional extras here — they are what sustains public trust in DPI systems over time.

Digital Divide

Gaps in digital literacy, internet connectivity, smartphone access, and regional infrastructure persist, and they are sharpest in remote and tribal areas. Without deliberate, targeted intervention, digital transformation risks reinforcing exclusion among the very populations it is meant to help — undermining the inclusive development goals that Atmanirbhar Bharat is built around. Gender gaps in digital access deserve particular policy attention if DPI's benefits are to be shared equitably.

Sustainability of Free Payment Models

The zero-MDR policy has clearly done its job in accelerating adoption, but it leaves open a longer-run question about how payment infrastructure gets financed. Getting this balance right — affordability on one side, financial sustainability on the other — will likely require new revenue models or a rethink of the MDR framework.

Legacy Systems and Implementation Challenges

Rolling DPI out successfully means overcoming institutional inertia and integrating it with legacy systems still in use across banking, insurance, and government services. That, in turn, calls for building in data protection and security from the design stage rather than bolting it on afterward, adopting a genuinely human-centred approach to service delivery, investing in capacity building at both the institutional and individual level, and fostering collaboration across government, the private sector, civil society, and other stakeholders.

5.8 Policy Implications and Future Roadmap

India's experience with Digital Public Infrastructure carries lessons that extend well beyond its own borders. Sustaining and deepening the gains already made will likely depend on the following set of policy interventions.

Strengthening Regulatory Architecture

- Establish a unified Digital Financial Consumer Protection framework to safeguard user interests consistently across platforms.
- Mandate AI audit trails within digital credit algorithms, to keep decisions transparent and guard against discriminatory outcomes.
- Expand regulatory sandbox mechanisms to allow controlled experimentation in digital finance.
- Strengthen interoperability standards across payment systems to prevent the ecosystem from re-fragmenting.

Cybersecurity and Resilience

- Set up a National Digital Financial Resilience Fund to finance infrastructure upgrades and incident response.
- Require periodic stress testing of payment infrastructure to surface vulnerabilities before they are exploited.
- Deepen public-private cybersecurity coordination through structured information sharing and joint response protocols.
- Build out centralised fraud-monitoring systems and AI-based fraud detection, including initiatives like MuleHunter AI.

Expanding MSME Financial Inclusion

- Integrate UPI transaction data into formal credit scoring frameworks to widen credit access.
- Expand credit guarantee schemes for digitally verified MSMEs, reducing risk on the lender side.

- Strengthen Account Aggregator adoption in rural enterprises to enable consent-based credit assessment.

Bridging the Digital Divide

- Expand digital literacy missions and multilingual digital interfaces to reach non-English-speaking populations.
- Use subsidy frameworks to incentivise QR infrastructure deployment in low-income geographies.
- Direct targeted investment toward digital infrastructure in underserved regions.

Internationalization of India's DPI Model

India's DPI ecosystem is well placed to serve as a replicable model for other emerging economies. Strategic collaboration around digital payments and financial infrastructure can strengthen India's standing in global digital governance while preserving domestic autonomy. The next phase will likely focus on extending infrastructure into underserved areas, improving fraud prevention, exploring agentic AI, creating new UPI use cases, supporting innovation in lending and embedded finance, and further strengthening regulatory frameworks (PwC — The Indian Payments Handbook 2025–2030). India's bilateral UPI linkages and the G20 DPI Framework offer useful multilateral platforms for carrying this agenda forward.

6. Conclusion

Digital Public Infrastructure has, in a fairly short span of time, reshaped India's banking and payments ecosystem into something scalable, interoperable, and genuinely inclusive. The combination of Aadhaar, Jan Dhan, mobile connectivity, UPI, DBT, and the Account Aggregator framework has strengthened financial inclusion, brought transaction costs down, improved fiscal governance, widened MSME credit access, and enhanced payment sovereignty all at once. India now accounts for close to half of global real-time payment transactions, which is itself a striking demonstration that national-scale financial infrastructure can be built and run with real efficiency, and at low cost.

The broader lesson here is that financial self-reliance in the digital age is built through infrastructure, not through isolation. India's experience shows that publicly governed, interoperable platforms can support innovation, inclusion, and institutional resilience all at the same time, rather than forcing a trade-off between them. The evidence gathered in this study supports all four of the hypotheses set out at the start: DPI has meaningfully improved financial inclusion (H1); growth in digital payments has positively influenced MSME formal credit penetration (H2); DPI has strengthened India's financial resilience and payment sovereignty (H3); and DPI's effectiveness continues to depend on strong regulatory governance and cybersecurity preparedness (H4).

None of this progress is self-sustaining, however. Keeping it on track will require continued investment in cybersecurity architecture, data protection frameworks, AI governance mechanisms, institutional capacity, and digital literacy. Closer attention to system harmonisation, local capacity building, regulatory innovation, and genuine stakeholder collaboration would help DPI continue serving as a backbone for both government services and business development, without losing sight of citizen safety along the way. The DBT architecture's demonstrated ability to eliminate roughly ₹4 lakh crore in leakages, the Jan Dhan programme's enrolment of more than 57 crore beneficiaries, and UPI's emergence as the world's leading real-time payment platform together make a fairly compelling case for what well-designed digital public infrastructure can achieve.

The next phase of India's digital financial evolution has to move past pure expansion and toward resilience, trust, and governance maturity. Digital Public Infrastructure has become something more than a technological innovation — it now functions as the financial backbone of Atmanirbhar Bharat. Whether that continues to hold will depend on India's ability to balance scale with security, innovation with regulation, and digital efficiency with inclusive development — a balance that, if maintained, offers a genuinely replicable model for inclusive digital development elsewhere.

6.1 Research Significance

The findings have direct relevance for regulators, financial institutions, and policymakers seeking to strengthen inclusive fintech governance, cybersecurity preparedness, and MSME credit ecosystems. The study also documents the growing international interest — augmented by India's bilateral UPI linkages and the G20 DPI Framework — in adapting India's DPI model to advance financial inclusion and resilience goals across other developing economies. India has entered UPI linkage agreements with Singapore, the UAE, France, Nepal, Bhutan, and Sri Lanka, and the G20 India Presidency's Framework for Systems of Digital Public Infrastructure has cemented India's leadership role in promoting DPI as a development tool worldwide, positioning the country's NPCI-anchored model as a template that other emerging economies are actively studying.

6.2 Scope for Future Research

This study offers a fairly comprehensive assessment of DPI's contribution to Atmanirbhar Bharat through India's banking and payments ecosystem, but several avenues remain open for deeper scholarly inquiry.

Future research could usefully examine:

- Long-term causal relationships between DPI adoption and household financial resilience, using longitudinal primary surveys rather than secondary aggregates.
- The growing role of AI and machine learning in credit underwriting and fraud detection within the DPI ecosystem.
- Cross-country comparative work on how India's DPI model might translate — or fail to translate — to Sub-Saharan Africa, Southeast Asia, and Latin America.
- The gender dimensions of DPI adoption, and how effectively it is closing (or not closing) financial access gaps between men and women.
- The convergence of CBDCs, Account Aggregator frameworks, and open banking architectures as they mature alongside one another.
- The interplay between digital financial systems and cybersecurity governance as India's data protection legislation continues to evolve.

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Role of Digital Payments in Promoting a Sustainable Economy: A Conceptual Study with Reference to India

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ABSTRACT

Digital payments have become a common part of everyday life in India. People can now pay for goods and services, transfer money, pay bills and receive payments through mobile phones and other digital methods. UPI, QR codes, mobile banking, internet banking, debit cards and digital wallets have made payments easier and faster.

The importance of digital payments is not limited to convenience. They can also support economic and social development. Digital payments can help small businesses receive payments, maintain transaction records and participate in the formal financial system. They can also help people access financial services and receive government benefits directly. From an environmental point of view, digital payments may reduce some paper-based activities and the need for certain physical cash-handling activities.

This paper examines how digital payments can contribute to a sustainable economy in India. The study is conceptual and descriptive and is based on secondary information from sources such as the Reserve Bank of India, the Government of India, NPCI and other reliable publications. The study looks at three main areas: economic sustainability, social sustainability and environmental sustainability.

The study finds that digital payments can support small businesses, financial inclusion, transparency and efficient transactions. However, problems such as cyber fraud, lack of digital knowledge, poor internet connectivity, privacy concerns and lack of trust can reduce their benefits. The paper concludes that digital payments can contribute to sustainable development only when they are secure, affordable, accessible and easy for people to use.

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1. Introduction

Technology has changed many parts of our daily life. One important change can be seen in the way people make payments.

Earlier, most people depended on cash for buying products, paying bills and transferring money. Today, a person can make a payment within a few seconds using a mobile phone. A customer can scan a QR code at a shop and make payment directly from a bank account.

Digital payment means making or receiving a payment electronically without physically exchanging cash.

Some common digital payment methods in India are:

- UPI
- QR-code payments
- Mobile banking
- Internet banking

- Debit cards
- Credit cards
- Digital wallets
- NEFT
- RTGS
- IMPS
- Aadhaar Enabled Payment System

The growth of digital payments in India has been very rapid. Government initiatives, banking facilities, smartphones, internet services and payment technology have all contributed to this growth.

UPI has become particularly important. According to the Government of India, retail digital- payment transactions increased from 7,176.90 crore in FY 2021–22 to 22,167.90 crore in FY 2024–25. UPI accounted for 81% of retail digital-payment transactions in FY 2024–25.

The growth of digital payments is important not only because payments become faster. It can also influence businesses, financial inclusion, transparency and resource use.

This makes digital payments relevant to the idea of a **sustainable economy**.

A sustainable economy is an economy that tries to achieve long-term development while also considering people's welfare and responsible use of resources.

Therefore, this paper studies how digital payments can support economic, social and environmental sustainability in India.

2. Objectives of the Study

The study has the following objectives:

1. To understand the meaning of digital payments.
2. To examine the role of digital payments in promoting a sustainable economy.
3. To study the economic benefits of digital payments.
4. To understand how digital payments can support financial inclusion.
5. To examine the possible social and environmental benefits of digital payments.
6. To identify the major challenges of digital payment adoption.
7. To suggest measures for making digital payments safer and more inclusive.

3. Research Methodology

This study is **conceptual and descriptive** in nature.

The study is based on **secondary data**. No questionnaire, interview or primary survey has been conducted.

Information has been referred to from reliable sources such as:

- Reserve Bank of India
- Government of India
- Ministry of Finance
- National Payments Corporation of India
- World Bank

- Research publications and other relevant sources The information has been studied and explained under three main areas: **Economic Sustainability** → **Social Sustainability** → **Environmental Sustainability** The purpose is to understand how digital payments can contribute to sustainable economic development in India.

4. Digital Payments in India

India has experienced a major change in its payment system.

Today, digital payments are used not only in large shopping centres but also by small shops, vegetable sellers, street vendors, restaurants and home-based businesses.

UPI has played a major role in this change.

The NPCI's official statistics show the continued growth of UPI. For example, UPI recorded more than **23.2 billion transactions in May 2026**, with a transaction value of about **₹29.90 lakh crore** for that month.

The Government of India reported that UPI had **55.49 crore users by June 2026**, showing how widely the system has been adopted.

RBI has also continued to focus on financial inclusion and expansion of the digital-payment ecosystem. Its 2024–25 Annual Report notes the expansion of the programme for deepening the digital-payment ecosystem and **continued** efforts to improve financial inclusion.

These developments show that digital payments have become an important part of India's financial system.

5. Meaning of Sustainable Economy

A sustainable economy **can** continue to grow and provide opportunities over a long period without creating serious economic, social or environmental problems.

For this paper, sustainability is understood through three areas.

5.1 Economic Sustainability

It means supporting businesses, employment, income and economic activities for the long term.

5.2 Social Sustainability

It means making economic and financial opportunities available to different sections of society.

5.3 Environmental Sustainability

It means using resources carefully and reducing unnecessary pressure on the environment. Digital payments can potentially contribute to all three areas.

6. Role of Digital Payments in Promoting a Sustainable Economy

6.1 Support for Small Businesses

Digital payments can be very useful for small businesses.

A small shopkeeper does not always need expensive payment equipment. A QR code can allow customers to make payments directly from their mobile phones.

For example, a small grocery shop can accept payment through UPI. A street food seller can also receive payment digitally.

This gives small businesses an additional way to receive money.

Digital transactions also create records. These records may help business owners understand their sales and manage their money better.

Therefore, digital payments can support small businesses and entrepreneurship.

6.2 Lower Cash Handling

Cash needs to be counted, stored, transported and protected.

Businesses and banks spend time and resources handling physical money.

Digital payments reduce the need to physically handle cash for every transaction.

This can make payment collection easier and save time for businesses and customers. However, digital payments also require technology and infrastructure. Therefore, they do not completely remove costs; they change the way payment-related resources are used.

6.3 Financial Inclusion

Financial inclusion means giving people access to useful financial services.

Digital payments can help people become more connected with the formal financial system. A person with a bank account and access to digital payment facilities can transfer money, pay bills and receive payments without visiting a bank branch for every transaction.

Government payments are another important example.

Benefits such as pensions, scholarships and other government payments can be transferred directly into eligible beneficiaries' bank accounts.

RBI continues to focus on financial inclusion and has reported improvement in its Financial Inclusion Index. The index increased to 64.2 in March 2024 from 60.1 in March 2023.

Digital payments can therefore support financial inclusion when people also have access to bank accounts, smartphones, connectivity and digital knowledge.

6.4 Transparency

Digital payments create electronic records.

For example, when a customer pays a shopkeeper through UPI, both parties normally receive a digital record of the transaction.

Such records can help people keep track of their payments.

Businesses can also use transaction records for accounting and financial management. Digital records may support greater transparency, although digital payments alone cannot eliminate corruption or tax evasion.

Good governance, proper accounting and effective enforcement are also required.

6.5 Support for Digital Entrepreneurship

Digital payments have also created opportunities for small online businesses.

A person selling clothes, handmade products, food or other items through social media or online platforms can receive payments digitally.

This means a small business does not always need a physical shop to receive payments. Digital payments can therefore support new forms of entrepreneurship and online business activity.

7.SOCIAL BENEFITS OF DIGITAL PAYMENTS Digital payments can make daily financial activities easier.

People can pay:

- electricity bills;
- telephone bills;
- school and college fees;
- insurance premiums;
- hospital bills;
- shopping expenses; and
- transport-related charges.

This saves time and reduces the need to carry cash.

Digital payments can also support women and small entrepreneurs by giving them greater access to formal financial services.

However, these benefits are possible only when people have access to smartphones, bank accounts, internet services and digital knowledge.

Therefore, digital inclusion is necessary along with financial inclusion.

7. Environmental Benefits

Digital payments may also have some environmental benefits.

Physical currency requires paper, printing, transportation, storage and replacement.

Digital transactions can reduce the need for some physical cash-related activities.

Similarly, digital receipts can reduce the need for printed receipts.

Online payment of bills can also reduce some journeys to banks or payment centres. However, digital payments are **not completely free from environmental impact**.

Mobile phones, computers, servers and data centres require electricity and other resources. Therefore, it would be incorrect to say that every digital payment is completely environmentally friendly.

A better conclusion is that digital payments can reduce some physical and paper-based activities, while the digital infrastructure itself should also become more energy efficient.

8. Transparency and Formal Economy

Another important benefit of digital payments is the creation of transaction records.

Cash transactions may sometimes take place without formal records.

Digital payments normally create an electronic trail.

This can help:

- businesses maintain records;
- customers prove payments;
- institutions monitor transactions; and
- governments improve financial transparency.

For small businesses, regular digital transactions may also help create a better financial history. However, digital payment records should be protected carefully because they contain financial information.

9. Challenges of Digital Payments

Although digital payments provide many benefits, there are also important challenges.

9.1 Cyber Fraud

Cyber fraud is one of the biggest concerns.

Fraudsters may use fake calls, messages, links or websites to cheat people.

Users must therefore be careful while sharing financial information.

9.2 Lack of Digital Knowledge

Some people do not know how to use digital payment applications safely. Older people and first-time users may need additional support and training.

9.3 Internet Problems

Digital payment systems depend on connectivity.

Poor internet service can make digital payments difficult, especially in rural and remote areas.

9.4 Privacy

Digital payments create financial data.

People need to know that their personal and financial information is being protected.

9.5 Lack of Trust

If people experience failed transactions, fraud or delays in receiving refunds, they may lose confidence in digital payments.

Therefore, quick complaint handling is important.

9.6 Digital Divide

Not everyone has the same access to smartphones, internet services or banking facilities. If these differences are not addressed, some people may remain outside the digital economy.

10. Findings of the Study

Based on the conceptual study, the following findings are made:

1. Digital payments have become an important part of India's financial system.
2. UPI has made small-value payments easier and faster.
3. Digital payments can support small businesses.
4. Digital payment records can improve financial record-keeping.
5. Digital payments can support financial inclusion.
6. Government payments can be transferred more directly through digital banking systems.
7. Digital payments can reduce some cash-handling and paper-based activities.
8. Digital payments may support social and economic participation.
9. Cyber fraud and privacy concerns remain important challenges.
10. Digital literacy and internet connectivity are necessary for successful adoption.
11. Digital payments can support sustainability, but they should be combined with secure and responsible digital infrastructure.

11. Suggestions

The following suggestions are made:

11.1 Increase Digital Awareness

Simple training programmes should be conducted for people who are new to digital payments.

11.2 Teach Fraud Prevention

People should be taught never to share OTPs, passwords, PINs or confidential banking information.

11.3 Improve Rural Connectivity

Internet and digital infrastructure should be improved in rural and remote areas.

11.4 Help Small Businesses

Small shopkeepers and street vendors should be given training on digital payments and cybersecurity.

11.5 Improve Complaint Services

Banks and payment providers should provide simple and quick systems for reporting failed or fraudulent transactions.

11.6 Protect Personal Information

Strong security measures should be used to protect customers' financial information.

11.7 Make Applications Simple

Digital payment applications should be easy to understand and use, especially for elderly and first-time users.

11.8 Promote Energy-Efficient Technology

Digital infrastructure should increasingly use energy-efficient systems so that the environmental benefits of digitalisation are improved.

12. Limitations of the Study

The study has some limitations.

First, it is based only on secondary information. No survey or interview was conducted. Second, the study is conceptual and does not use statistical testing.

Third, the study does not calculate the exact environmental impact of digital payments. Future researchers can conduct surveys among consumers, shopkeepers and small businesses to understand their actual experiences with digital payments.

13. Future Research

Future researchers can study:

- digital-payment adoption in rural areas;
- digital payments and women entrepreneurs;
- digital payments and MSME growth;
- digital-payment awareness among senior citizens;
- cyber fraud and consumer behaviour;
- digital payments and financial inclusion; and

- environmental impact of digital versus cash payments.

A future study can also use primary data and statistical techniques.

14. Conclusion

Digital payments have changed the way people in India make and receive money.

They are no longer limited to large businesses or cities. Small shops, street vendors, students, workers and ordinary consumers also use digital payment methods.

The study shows that digital payments can contribute to a sustainable economy in different ways.

From an **economic point of view**, they can support small businesses, make transactions easier and encourage digital entrepreneurship.

From a **social point of view**, they can support financial inclusion and make access to financial services easier.

From an **environmental point of view**, they may reduce some paper-based activities and certain physical cash-handling activities.

However, digital payments also have challenges. Cyber fraud, lack of digital knowledge, poor connectivity, privacy concerns and lack of trust can reduce their benefits.

Therefore, the goal should not simply be to increase the number of digital transactions. The focus should be on making digital payments **safe, simple, affordable, reliable and accessible to everyone**.

With better digital education, stronger cybersecurity, improved infrastructure and effective consumer protection, digital payments can become an important tool for building a more inclusive and sustainable economy in India.

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Dynamics between Intellectual Capital and Corporate Governance: A Study of Indian Listed Firms in Construction, Energy and Information Technology Sector

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ABSTRACT

Purpose – This study examines the influence of Corporate Governance over Intellectual Capital disclosure among BSE500 listed construction, energy and information technology sector firms in India.

Design/methodology/approach – This study analyses data from 70 listed Indian construction, energy and information technology companies using Panel-Corrected Standard Error regression analysis over the year 2014-2021.

Findings – The empirical findings reveal that corporate governance in the Indian publicly listed construction, energy and information technology firms did not exhibit a significant influence on the intellectual capital of the selected firms during the study period.

Originality/Value: This study represents the first comprehensive examination of the relationship between corporate governance and intellectual capital in listed construction, energy and information technology firms. It is also pioneering in its application of Panel Corrected Standard Error regression analysis, alongside VAIC and MVAIC models, to analyse the relationship between corporate governance and intellectual capital.

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1. Introduction

The impact of Corporate Governance (CG) on Intellectual Capital (IC) is crucial in business studies, especially for construction, energy and information technology sector companies. Effective governance, which involves rules and practices for directing and controlling a firm, is essential. The term "governance" originated from the Egyptian word "gubernet," meaning "to govern or steer." CG refers to directing an organization towards desired goals (Bijalwan, 2012). Makki and Lodhi (2014) describe CG as a mechanism for achieving efficiency and ensuring productivity, sustainability, and profitability. Effective CG, characterized by a sound board structure, transparency, defined procedures, and investor rights protection, is crucial for organizational success (Bijalwan, 2020). Firms with robust CG, through strong boards and ownership structures, tend to perform better and make decisions that enhance shareholder wealth (Weimer and Pape, 1999; Keenan and Aggestam, 2001). CG plays a crucial role in effectively managing companies in India. It encompasses a set of principles and practices that ensure accountability, transparency, and ethical decision-making in how a company is directed and controlled (Wondem & Batra, 2019). Strong CG is key to a company's long-term success and helps build trust among all the key stakeholders (Srivastava et. al., 2019). A well-structured governance framework relies on qualified board members who uphold core values

such as discipline, fairness, responsibility, transparency, shareholder rights, independence and social responsibility (Farag et. al., 2018; Alsagr et. al., 2018).

With the rise of knowledge-based companies, productivity and value creation have shifted from tangible assets (capital, plant, and machinery) to intangible inputs, known as IC (Teece, 2000; Delios & Beamish, 2001; McGaughey, 2002; Goh & Lim, 2004). IC is now a critical factor for competitiveness across all industries (Makki & Lodhi, 2014). Johnson and Kaplan (1987) emphasize that IC can significantly influence company performance. Alipour (2012) defines IC as knowledge-based assets owned or controlled by an organization, essential for creating value for key stakeholders. CG includes human capital, brand name, corporate reputation, intellectual property, customer relations, organizational processes, patents, and innovation. Pulic (2000, 2004) defined it as the sum of human, structural, and physical capital efficiencies. Bontis (1998) added relational capital. Relational capital encompasses costs associated with managing relationships with clients, shareholders, suppliers and government.

CG encompasses intangible assets like knowledge, skills, and innovation. Empirical studies show that CG significantly influences the development of CG within organizations. Additionally, previous research (Safieddine et. al., 2009) highlights the importance of recognizing and understanding CG's role in maintaining and effectively utilizing CG. According to Adesina (2019), IC consists of Human Capital Efficiency (HCE), Physical Capital Efficiency (PCE), and Structural Capital Efficiency (SCE). Vishnu and Gupta (2015) and Sharabati et. al. (2010) identifies IC components as Human Capital (HC), Structural Capital (SC), and Relational Capital (RC). Makki (2014) emphasizes that HC is the most significant asset, enhancing operational effectiveness and generating intangible assets. Many studies have independently examined CG and IC (Abeysekera and Guthrie, 2005), but fewer have explored their interplay. In this research, CG refers to the structures, systems, and processes that ensure organizational direction, control, and accountability (Chambers and Cornforth, 2010).

The current study aims to study the association among CG and IC, building on previous research. Hypotheses are developed regarding the associations between different CG mechanisms (such as Board Size, Board Independence, Board Gender Diversity, and Board Meetings) and IC components (HCE, CEE, SCE, and RCE). Panel corrected standard error regression analysis is employed using data from 70 firms listed under BSE 500 index and working under the Construction, Energy and Information Technology firm during the year 2014-2021, extracted from the selected firm's annual reports. Numerous previous studies have explored the topics of CG and IC (Abeysekera and Guthrie, 2005). However, Keenan and Aggestam (2001) highlighted that limited attention has been paid to the relationship between IC and CG, as prior research predominantly emphasized the dependencies of CG on financial and physical capital. Previous empirical studies demonstrate how CG affects the way IC develops inside an organisation. Additionally, several recent studies (Safieddine et. al., 2009; La Rocca et. al., 2008) underscore the necessity to recognise and comprehend the function of CG in preserving, effectively deploying, and keeping IC in business organisations. The study's findings will greatly benefit senior management in Indian construction, energy and information technology sector companies, aiding them in enhancing governance to attain a competitive edge. Additionally, it offers insights into the broader CG landscape in India among the three selected sector firms. CG mechanisms are shaped by factors such as the prevailing legal and regulatory framework, capital strength, business culture, and the socio-political environment of each country.

Construction sector was chosen for the study as in India still a large number of unskilled labours work in this sector and thus good CG in this sector can uplift the lives of poor and needy. Again, Energy sector was chosen for the current study as this sector is an asset heavy sector, wherein a lot of capital is used and thus proper governance among these companies becomes imperative. Similarly, Information Technology sector was chosen for the study as this sector currently accounts for 7-8% of Indian GDP, and thus proper governance among these companies is very necessary. Thus, we see that all the selected sectors play a big role in boosting the Indian Economy.

The current study contributes significantly to existing literature in various ways. First, the study seeks to add to the body of literature of IC by investigating further regarding the dynamics between IC and CG. Second, this is a preliminary study to assess the correlation between IC and CG efficiency among Indian companies working in

construction, energy and information technology sector. Third, we have incorporated the modified VAIC - MVAIC model by adding Relational Capital (RC) to the existing ones. It is argued that the MVAIC model is significantly better than the VAIC model to compute the IC (Tiwari *et. al.*, 2023; Xu & Li, 2020; Ge & Xu, 2020; Vidyarthi, 2019). Fourth, the application of panel-corrected standard error regression analysis generates more reliable results by accounting for cross-sectional dependency, heteroskedasticity, and serial correlation, inherent in multi-sectoral panel data. Fifth, prior research underscores the country-specific nature of CG and its varied impact on decisions related to IC (Vafeas and Theodorou, 1998; Weimer and Pape, 1999; Keenan and Aggestam, 2001). Therefore, it is crucial to analyze different governance measures and their effects on IC individually for each country. This study presents a novel examination of the dynamics between CG and IC within the Indian context.

The study is structured as follows: Section 2 reviews key prior studies to contextualize the current research. Section 3 outlines the methodology, including sample data, time frame, variable descriptions, and analytical approaches. Section 4 presents the study's results, along with discussions on theoretical, managerial, and academic implications. Section 5 presents the study's concluding remarks, discusses its limitations, and identifies potential directions for future research.

2. Literature Review

2.1 Theoretical framework

The current study explores the intricate relationship among IC and CG, recognizing IC as a critical requirement for sustained competitive advantage in the contemporary knowledge-based economy. While exploring IC and CG, several key theories are commonly referenced, and these perspectives collectively offer meaningful insights into the various components of IC and CG.

2.1.1 Agency Theory

Agency Theory explores the potential conflicts between shareholders (principals) and managers (agents) arising from differing interests. In certain circumstances, managers may prioritize their personal interests over the maximization of shareholders' wealth, thereby giving rise to agency costs. Effective CG, including independent board oversight, performance-based executive compensation, and enhanced transparency, mitigates these issues by keeping in line managerial actions with shareholder interests (Meckling & Jensen, 1976; Fama & Jensen, 1983; Healy & Palepu, 2001).

2.1.2 Resource Dependence Theory

Resource Dependence Theory explains that companies depend on external resources to sustain operations and gain a competitive edge. CG plays a crucial role in reducing this dependency by strategically structuring boards with members who have valuable external connections. This approach ensures access to critical resources and enhances firm performance by minimizing environmental uncertainty (Hillman *et. al.*, 2000).

2.1.3 Stakeholder Theory

Stakeholder Theory implies that for a firm to achieve sustained success, it must generate value not only for its shareholders but also for a broader network of stakeholders, including employees, customers, suppliers, and the community. By addressing the interests of all stakeholders, organizations can foster trust, enhance corporate reputation, and build a more resilient and sustainable business model (Carroll & Shabana, 2010). Together, these theories offer an integrated framework for understanding the different dimensions of CG and its relationship with CG.

A detailed review of the previous literature demonstrates that the importance of knowledge-based assets such as human capital, customer relationships, brand value, organisational procedures, corporate partnerships, patents, innovation, and so on is gradually increasing in developing or growing economies like India. CG provides us with several ways in which company stakeholders control management decisions in a way that serves their interests (John & Senbet, 1998). Countries having good CG mechanism have experienced growth in their corporate sector and thus

have always attracted more capital and investment. *Bonn et. al., 2004* emphasized that the most important element in maintaining shareholder confidence in CG is the role of the board structure, which can ultimately result in the highest level of financial performance and market growth. Various researchers reported a positive influence of various CG practices on IC in developing/emerging economies (*Ciftci et. al., 2019; Mardnly et. al., 2018; Paniagua et. al., 2018; Darko et. al., 2016*).

IC and CG are associated with each other due to their significant role to attain the objective of the organization, and it assures survival and growth (*Saeed et. al., 2015*). The board of directors in firms is liable to constitute strategies to use human and structural resources efficiently to improve banking performance (*Nawaz & Haniffa, 2017*). Thus, the combination of IC and CG has become a keystone for companies to generate good profit and sustainable growth (*Nawaz, 2019*). In India, the principles of CG are similar to those in other countries but with a few unique characteristics due to the country's regulatory environment and business culture. These principles include:

a. Transparency: Firms are expected to maintain transparency in their business operations, financial disclosures, and decision-making processes by providing stakeholders with accurate, reliable, and timely information. Transparency helps to build trust and confidence in the company and its management (*Bijalwan, 2020*).

b. Accountability: Companies are expected to ensure responsibility for their actions and decisions. This implies that they must be accountable for their actions and be answerable to stakeholders. Accountability helps to ensure that companies act in the best interests of their stakeholders and that they are held responsible for any misconduct (*Srivastava et. al., 2019*).

c. Board of Directors: The board of directors plays a pivotal role in supervising the company's management, formulating its strategic objectives, and ensuring that corporate strategies align with stakeholders' interests. It is also responsible for monitoring managerial performance, promoting effective organizational governance, and ensuring that potential risks are identified, assessed, and managed appropriately. In India, the board of directors is required to have at least one-woman director and an independent director, depending on the size and nature of the company (*Bijalwan, 2020*).

d. Ethics and Values: Companies must operate with a strong sense of ethics and values. This means that they must act with integrity, honesty, and fairness in all their operations. Companies are required to operate in accordance with all relevant legal provisions and regulatory requirements, and must not engage in any unethical or illegal activities. In India, companies must also adhere to the principles of corporate social responsibility (CSR) and report their CSR activities to stakeholders (*Srivastava et. al., 2019*).

e. Risk Management: Companies must adhere to effective risk management systems. This means that they must identify and manage risks effectively to ensure that the firm's exposure to unnecessary risks is minimized. Effective risk management helps to protect the company and its stakeholders from potential losses. In India, companies must also comply with the regulations and guidelines issued by the Securities and Exchange Board of India (SEBI) on risk management (**Wondem & Batra, 2019).

To apply the principles of CG in India, companies must develop regulations and practices that are aligned with the CG principles. For example, companies must ensure that they have an effective way for financial reporting, risk management, and ethics & values. They must also ensure that their board of directors is independent, diverse, and possess skills and expertise necessary to effectively oversee the management of the company. In India, companies must also comply with the regulations and guidelines issued by SEBI on CG (*Srivastava et. al., 2019*). Good CG parameters as suggested by *Bijalwan, (2020)*: A good CG in an organisation can be characterized by transparency inside the organisation, a sound board structure, well defined board procedures, investor's rights protection and a good CG strategy.

Safieddine et. al., (2009) examined the correlation between IC and CG in academic institutions. They tested the ideas of all the faculties at the American university of Beirut. And the results suggested that there is a connection between IC and CG, and faculty members believe that CG attracts IC. Also, *Halder et. al., (2016)* examined how two

knowledge-based industries' levels of international competitiveness and CG flexibility relate to one another, i.e. I.T and Pharma in India during the period from 2006 to 2014. The researchers found that flexibility in CG significantly affects IC. *Keenan and Aggestam (2001)* also concludes that “the responsibility for the prudent investment of IC resides with CG”. *Bijalwan, (2012)* concludes that an efficient CG, reduces risks on the organisation, improves performance of employees, improves access of firms to various capital markets, enhances the visibility of goods and services of the firm, improves leadership in the organisation, demonstrates transparency inside the organisation and improves social influence and accountability.

Not many recent studies have focused on both the topics together and have also examined the influence of different CG mechanisms on the disclosure of CG (*Cerbioni & Parbonetti, 2007*). A broad review of literature shows that the researchers are yet to reach any unanimity and certain research found that, IC has a major impact on CG. (*Gemmill & Thomas, 2004; Alves & Mendes, 2002 and Drobetz et. al., 2004*) while others demonstrate almost no association between IC and CG (*Sueyoshi et. al., 2010; Aboagye & Otieku, 2010; and Bauer et. al., 2010*).

Table 1: Literature review:

Sl. No.	Author & Year	Findings	Research Gap
1	Smriti N. and Das N., (2021)	The present study found that the firm's CG is significantly enhanced by presence of diverse gender on board.	This research is focused only on the Indian listed firms.
2	Dalwai T. & Mohammadi S. S., (2020)	The findings indicate that board size and number of audit committee meetings have a significant association with the IC efficiency. CG of banks effectively engages in utilizing the potential of IC efficiency.	The sample size is small as the study is limited to the listed financial sector of Oman.
3	Kumar Singla, H. (2019),	According to the study, IC is a critical asset for Infrastructure firms looking to enhance their corporate performance.	The research is done only on Quantitative VAIC Model, further Qualitative Models can also be used.
4	Kamath B. (2019),	According to the study, only large-cap enterprises' IC performance is significantly influenced by the board's features. The board's size and independence have a significant detrimental and positive impact, respectively. Industry type and company age also have an impact on IC performance.	The paper has limitations like: some aspects of CG, such as duality, diversity, and de-classified ownership patterns and board structure, could not be incorporated into the model.
5	Nadeem, M., Farooq, M. B., & Ahmed, A. (2019),	The results reveal a significant positive relationship among representation of female on boards and IC efficiency.	The study was based on top 500 listed firms in the UK, and the findings may be difficult to apply in other firms.
6	Hamdan et. al., (2017),	The relationship among IC and firm performance was found to be positively impacted by CG, which was shown to be significant.	Only 2-year data of firms listed on Saudi Stock Exchange were considered for the study.
7	Haldar, A., Rao, S. V. D., & Momaya, K. S., (2016).	Flexibility in CG has a big impact on IC.	The non-financial components of firm performance such as enterprise and stakeholders were not considered.
8	Appuhami, R. and Bhuyan, M., 2015.	Researchers found out that CEO duality, board composition and remuneration committee composition have significant impact on IC.	Further research is required in the area of measurement of IC to measure IC in firms both in quantitative and qualitative manner.
9	Mubaraq S. & Haji A. A., (2014)	The results imply that CG plays an important role in amplifying IC information.	Current study only considers the Nigerian listed banks.
10	Safieddine, A., Jamali, D. and Nouredine, S., 2009.	The findings imply that CG and IC are really related, and the faculties consider CG to be a key attractiveness element for IC.	Further research is required to gain a more comprehensive understanding of the nature and dynamics of the relationship between IC and CG across a broader range of knowledge-intensive firms.

The above studies indicate that the relationship between these two variables may be complex and potentially influenced by sector-specific factors. In summary, while there is evidence to suggest that IC can have an impact on CG, the nature of this relationship appears to be multifaceted and may vary across different sectors and contexts. The studies reviewed do not provide a consensus, with results ranging from positive to negligible impacts. For a research paper focused on Indian listed companies in the energy sector, it would be essential to consider these diverse findings and explore whether the patterns observed in other markets and sectors hold true in the Indian context. Further empirical research would be required to establish a clearer understanding of this relationship within the specific

framework of the Indian construction, energy and information technology sector. The results obtained from several studies also reveal that IC and CG are an important field for researchers and studies, nevertheless, that number has substantially reduced. It might be attributed to the struggles in obtaining relevant data and also a lack of uniformity and consistency persists among all the proposed analysis methods.

3. Methodology

3.1 Sample and data collection

In line with past studies, the researchers have studied the trends and composition of IC in the listed energy sector companies in India. Secondary data for IC was extracted from CMIIE – ProwessIQ database, whereas CG data was extracted from the annual reports of each selected company. The study uses the data of 8 years, 2014-2021 of 70 companies working in the construction, energy and information technology sector in India, listed under BSE 500. The researchers have used the data of listed companies due to data reliability and availability. Also, factors of IC, Human Capital Efficiency, Structural Capital Efficiency, Capital Employed Efficiency, and Relational Capital Efficiency have been studied. Leverage, Size and Age are used as Control variables. VAIC and MVAIC methods have been used to calculate the IC component of the companies considered for study. The researchers have done a preliminary study using descriptive statistics like: Mean, Median, Range and Standard Deviation of the Variables. Further, correlation matrix along with Panel corrected standard error regression analysis is also used to study the IC and CG dynamics.

Table 2: Variables Used Description:

Sl. No.	Variables Used	Description	Reference	
1	Value-added intellectual coefficient (VAIC)	$VAIC = HCE + SCE + CEE$	Kamath, 2019; Appuhami & Bhuyan, 2015	
2	Modified Value-added intellectual coefficient (M-VAIC)	$M-VAIC = HCE + SCE + CEE + RCE$	Tran et. al., 2020;	
3	Human capital efficiency (HCE)	$HCE = VA / HC$. Human capital efficiency coefficient for the firm (HCE); VA, value added; HC, total salary and wage costs for the firm.	Tran et. al., 2020; Nadeem et. al., 2019; Kamath, 2019;	
4	Capital employed efficiency (CEE)	$CEE = VA / CE$, Capital employed efficiency coefficient for firm (CEE); VA, value added for the firm; CE, book value of the net assets for firm.	Tran et. al., 2020; Nadeem et. al., 2019; Kamath, 2019;	
5	Structural capital efficiency (SCE)	$SCE = SC / VA$, $SC = VA - HC$, Structural capital efficiency for the firm (SCE); VA, Value added for the firm; HC, total salary and wage costs for the firm.	Tran et. al., 2020; Nadeem et. al., 2019; Kamath, 2019;	
6	Relational Capital Efficiency (RCE)	$RCE = RC / VA$, $RC = \text{Marketing, Selling or Advertising expenses}$; VA, Value added.	Tran et. al., 2020;	Smriti & Das, 2018, 2021; Vidyarthi, 2019; Alipour, 2012; Xu & Li, 2020.
7	Board size (BSIZE)	Number of members on the board of the firm.	Tran et. al., 2020; Nadeem et. al., 2019; Appuhami & Bhuyan, 2015; Mubaraq & Haji, 2014.	
8	Board Independence (BIND)	Number of Independent Directors divided by total number of directors on the board.	Tran et. al., 2020; Nadeem et. al., 2019; Appuhami & Bhuyan, 2015.	
9	Board Gender Diversity (BGEND)	Percentage of Female Directors to total number of directors on the board.	Nadeem et. al., 2019;	
10	Frequency of Board meetings (BMET)	Number of board meetings held for the financial year.	Nadeem et. al., 2019; Mubaraq & Haji, 2014	
11	Leverage (LEV)	$LEV = \text{Total Debt} / \text{Total Equity}$	Tran et. al., 2020; Nadeem et. al., 2019.	
12	SIZE	Log of total assets	Tran et. al., 2020.; Nadeem et. al., 2019;	
13	AGE	Natural logarithm of number of years since the firm's inception.	Dalwai & Mohammadi, 2020; Zaid et. al., 2020; Mohapatra et. al., 2019.	

3.2 Conceptual Framework

The diagrammatic representation of the research conceptual model is as given below:

model is as given below:

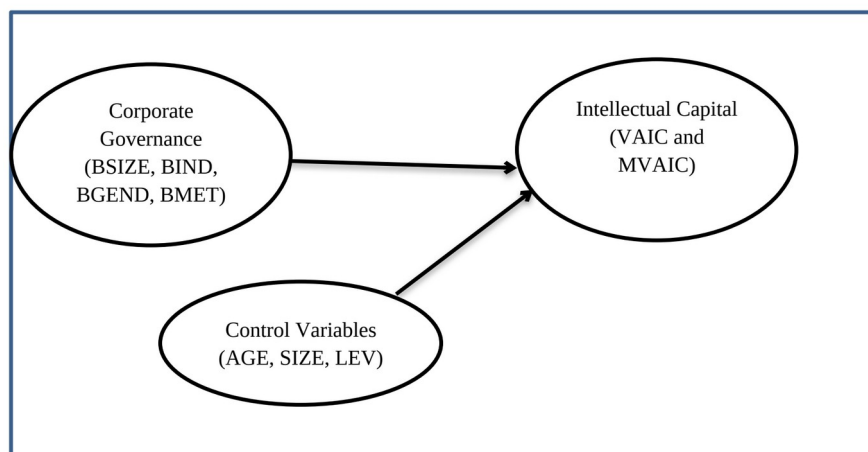


Fig 1: Impact of CG on IC using Age, Size and Leverage as Control variables.

3.3 Regression Models

$$1. VAIC_{it} = \beta_1 + \beta_2 BSIZE_{it} + \beta_3 BCOM_{it} + \beta_4 BIND_{it} + \beta_5 BGEND_{it} + \beta_6 BMET_{it} + \beta_7 AGE_{it} + \beta_8 SIZE_{it} + \beta_9 LEV_{it} + \epsilon_{it}$$

$$2. MVAIC_{it} = \beta_1 + \beta_2 BSIZE_{it} + \beta_3 BCOM_{it} + \beta_4 BIND_{it} + \beta_5 BGEND_{it} + \beta_6 BMET_{it} + \beta_7 AGE_{it} + \beta_8 SIZE_{it} + \beta_9 LEV_{it} + \epsilon_{it}$$

Where, VAIC, MVAIC, BSIZE, BIND, BGEND, BMET, LEV, SIZE and AGE, represents Value Added Intellectual Capital Coefficient, Modified - Value Added Intellectual Capital Coefficient, Board Size, Board independence, Board Gender Diversity, Board Meeting, leverage, Size and Age respectively. Also, β_1 is the constant term, " ϵ_{it} " denotes the error term for firm i at time t .

4. Empirical Results

4.1 Descriptive Statistics

Table 3 presents the summary statistics, giving a brief overview of the data. The researchers observed that the mean of VAIC and MVAIC are 6.926 and 6.99, respectively, which implies that on an average, the selected companies created between 6.926 and 6.99 INR for every INR 1.00 spent, and the mean for HCE is 5.423, which is significantly greater than other factors of VAIC and MVAIC, such as SCE (0.641), CEE (0.862), and RCE (0.063). This comparison indicates that the selected company's focus on HCE is greater than the remaining components of CG. It also illustrates that the selected companies generate the majority of their money from their Human Capital Efficiency.

Table 3: Summary Statistics of the selected sample

Variable	Obs	Mean	Std. Dev.	Min	Max
ROA	546	.0756	.0875	-.4723	.35
ROE	546	.0148	2.8063	-65.3146	1.0069
ATO	546	.6685	.4968	0	3.1781
VAIC	546	6.9268	8.2164	-5.4589	123.4513
MVAIC	546	6.9902	8.2035	-5.0023	123.4992
HCE	546	5.4231	6.3871	-6.0735	44.2791
SCE	546	.6415	.5523	-5.6087	6.0163
CEE	546	.8622	5.0592	-8.4782	116.9231
RCE	546	.0634	.2321	-3.0552	1.2845
LEV	546	.1033	.1335	0	.7939
SIZE	546	8.7164	1.7964	-2.8134	13.7872
AGE	546	3.176	.7259	0	4.7185

Mean of ATO (0.668) highlights that the selected companies are not efficiently using their assets to gain revenue. The aggregate of mean values of HCE, SCE and RCE (6.127) is greater than the mean of CEE (0.862), suggesting that the selected firms generate more value by employing CG rather than their physical and financial capital, which corresponds to prior research findings (*Smriti & Das, 2018; Xu & Li, 2020; Ge & Xu, 2020*). Also, the control variables LEV, SIZE and AGE have a mean value of 0.103, 8.716 and 3.176 respectively.

4.2 Correlation Matrix

Table 4: Matrix of correlations of the selected sample

Variables	ROA	ROE	ATO	VAIC	MVAIC	HCE	SCE	CEE	RCE	LEV	SIZE	AGE
ROA	1.000											
ROE	0.261	1.000										
ATO	0.407	0.062	1.000									
VAIC	0.094	0.035	0.111	1.000								
MVAIC	0.092	0.031	0.112	0.999	1.000							
HCE	-0.014	0.024	0.012	0.786	0.786	1.000						
SCE	-0.105	0.021	-0.146	0.267	0.250	0.269	1.000					
CEE	0.182	0.024	0.182	0.603	0.603	-0.015	-0.015	1.000				
RCE	-0.071	-0.140	0.036	-0.070	-0.042	-0.035	-0.602	-0.003	1.000			
LEV	-0.426	-0.135	-0.283	0.136	0.135	0.216	0.157	-0.069	-0.067	1.000		
SIZE	-0.092	-0.027	-0.252	0.037	0.036	0.136	0.152	-0.127	-0.060	0.332	1.000	
AGE	0.117	0.013	-0.131	-0.022	-0.021	0.001	0.011	-0.038	0.023	-0.226	0.330	1.000

Table 4 demonstrates how the factors are correlated among each other. Here the researchers observed that the two coefficients of CG, VAIC and MVAIC are perfectly correlated with each other. Also, we see that out of all the measures of CG, HCE is highly linked with VAIC and MVAIC, followed by CEE and the remaining variables of CG, viz. SCE and RCE have a very weak correlation with the CG coefficients, i.e. VAIC and MVAIC, however RCE is having a negative correlation with both VAIC and MVAIC.

CEE is positively correlated with all the firm's financial performance indicators, i.e. ROA, ROE and ATO which implies that CEE of the selected companies contribute more to the firm's productivity and market value and that the physical and financial capital is still a major component in a firm's financial performance. Also, HCE is found to

have a beneficial relationship with ATO, which demonstrates that Human Capital can enhance the value of the available assets. No independent variable has a substantial coefficient of correlation greater than 0.90, implying that there is no multi-collinearity (Smriti & Das, 2018). Annual VAIC and MVAIC of selected Companies and Average Annual VAIC and MVAIC of the selected companies indicate significant variability in the values of Average, minimum and maximum values across. The minimum and maximum values for VAIC are (-5.459, 123.451) and MVAIC (-5.002, 123.499).

4.3 Corporate Governance and Intellectual Capital Dynamics

Evaluating the impact of CG on CG, VAIC and MVAIC are taken as the Dependent variables, whereas BSIZE, BIND, BGEND and BMET are taken as independent variables and LEV, SIZE and AGE are considered as control variables. The results show that VAIC and MVAIC have an insignificant impact over the CG measures – BSIZE, BIND, BGEND and BMET.

Table 5: Result of panel corrected standard error regression analysis.

	VAIC	MVAIC
BSIZE	-0.029	0.0001
BIND	-1.887	-2.521
BGEND	-0.721	-0.590
BMET	-0.047	-0.042
LEV	4.270***	4.395***
SIZE	-1.071***	-1.118***
AGE	0.284	0.292
_cons	17.486***	17.953***
Observations	546	546
R-squared	0.196	0.201

The term “ ϵ_{it} ” denotes the error term for firm i at time t .

Among the control variables, LEV is found to have a positive and significant impact over both VAIC and MVAIC, whereas SIZE is found to have a significant but negative impact over both VAIC and MVAIC at 1% confidence level. And, AGE has an insignificant impact over VAIC and MVAIC.

4.4 Robustness Check

VAIC is employed as a measure of IC in the current study, and to double check with the robustness of the results, the researchers have additionally employed the MVAIC model using the additional RCE (Relational Capital efficiency). The sample was additionally examined for multi-collinearity using the Variance Inflation Factor (VIF), which was less than 2. As a result, multi-collinearity is not a major issue in the selected sample. Control variables comprise of LEV (Leverage), SIZE, and AGE.

5. Conclusion

For the current study, 70 companies working in the construction, energy and information technology sector and listed under the BSE500 index during the financial year 2014–2021 were used to examine the effects of CG on CG. VAIC and MVAIC were used as measures of IC and Board Size, Board Independence, Board gender diversity and Board meetings are used as measures of CG and Leverage, Size and Age are used as control variables.

Average of VAIC and MVAIC are 6.94 and 7.003 respectively. And the main contributor to these is the HCE, which is followed by CEE, SCE and RCE respectively. The results clearly support and advocates for fuller and comprehensive use of Human Capital and Financial Capital to cope up with the ever changing and advancing industrial requirements. Human Capital can be further improved by adopting Industrial best practices to enhance the

capabilities of employees, by continuously up-skilling and re-skilling the employees in order to remain abreast with the latest market trends. The researchers also observed that the firms on an average generate between 6.94 and 7.003 INR for every INR 1.00 Invested. Results of the current study shows CG to have almost no impact over CG, which may be since many of the relevant changes took place after the Companies Act, 2013, such as presence of one female board member was made mandatory. At least 50% of the board members should be independent directors and others. Most of these companies have slowly but successfully adopted these changes, whereas there are still few companies, which are yet to oblige with these regulations.

Implications: This study has various implications such as, for managers – it was found that firms need to focus more on better and transparent CG by having greater number of independent directors and female directors, which will ultimately provide the firms a competitive advantage. Also, for the policymakers, the focus on CG should be increased, as it directly impacts the country's GDP and livelihood of poor and needy.

Research limitations – In India, little research has been done in the emerging area of CG and IC. As a result, there haven't been many studies devoted to comprehending CG and IC dynamics in the Indian construction, energy and information technology sector firms.

Future Scope of Study: The relationship between CG and company performance, capital structure, corporate value, and social responsibility can be assessed through further research. Future research should broaden the sample and/or compare variations across industries or nations.

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Technological Innovation, External Debt, and Sustainable Economic Growth: Evidence from India

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ABSTRACT

The paper aims to analyse the dynamics of technological innovation, sustainable economic growth, FDI, external debt, inflation, and trade in India spanning 1990 to 2024. The ARDL technique is taken because all the variables namely GDP, inflation, external debt, technological innovation, FDI and trade openness are determined to be mixed integration order by the tests of unit root. In this empirical analysis, the short and long run response functions are evaluated with the help of ECM. Empirical results show, in the analyses of long run, the selected variables are cointegrated. In the growth model, external debt, technological innovation and trade are significantly and positively related with sustainable expansion in the long run while consumer price and FDI exert a adverse but not significant relationship with the sustainable growth. The external debt model suggests that FDI is a major factor in lowering external debt, whereas inflation and technological innovation are important long-run factors. Some of the conclusions derived from the results indicate that the technological innovation needs to be enhanced, productive utilization of external borrowing has to be encouraged and trade integration and macroeconomic stability are vital for long-term economic progress in India. The study outlines the bidirectional connection between economic development and overseas debt using a single framework of ARDL, and provides the practical policy suggestions for external debt management and innovation-based economic growth.

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1. Introduction

Technology innovation is now a crucial component of macroeconomic stability and prosperity in both developed and emerging nations. The World Bank (2024) reports that, GDP increased by around 3.2% globally in 2023, and nations with higher levels of productivity and technical advancement demonstrated greater resilience to external economic shocks. Concurrently, foreign debt is crucial for funding industrial growth, infrastructure, and structural change, especially in developing nations when domestic savings is insufficient. The Report of World Bank (2024) projects, the foreign debt stock of low- and middle-income nations will exceed US\$8.8 trillion in 2023 due to this rise (Huang & Wang, 2026). However, the loan's economic return will rely on how well it is used and directed toward initiatives that promote economic growth. Furthermore, it is currently projected that 63% of the GDP of world is open to trade; this growth in trade opening has led to market integration, technological diffusion, and export competitiveness. Simultaneously, inflows in foreign direct investment (FDI) have increased to a projected US\$1.5 trillion in 2023 (UNCTAD, 2024), facilitating the transfer of technological and the development of capital and productivity enhances in the host countries. Stable inflation also encourages more investment, which lowers macroeconomic uncertainty and helps to properly channel resources. In the context of its effects on long-term economic growth and external financial stability, the connections between technological innovation and external debt, between economic growth and openness, between FDI and inflation, and between the two are becoming a major area of interest in current macroeconomic policy.

The Endogenous (Romer, 1990) postulates, technological advancement promotes productivity growth, capital accumulation, and long-term economic growth, provides the basis for our investigation. Debt Overhang Theory (Krugman, 1988) states that growth can benefit from foreign borrowing as long as it is not excessive; if it is, investment and economic performance would be constrained. According to the Trade-Led Growth hypothesis (Grossman & Helpman, 1991), trade openness increases the likelihood of technology transfer and export competitiveness. The Eclectic (OLI) Theory (Dunning, 1988) can explain the rise and relaxation of financial limitations and FDI as well as the transfer of capital and technology. Additionally, the Phillips curve illustrates the association between macroeconomic stability, investment, and inflation, all of which affect economic growth and external borrowing.

For both sustained economic growth and macroeconomic stability, India's economic development policy has placed an increasing emphasis on technological innovation. Since economic liberalisation in 1991, India has become more actively integrated in worldwide networks since increasing technology transfer and productivity enhancement through enhanced trade liberalism and liberalised FDI standards. India's real GDP increased by 8.2% in FY2023–2024, making it one of the world's most rapidly developing largest economies (NSO, First Revised Estimates, 2025) and is expected to expand by around 7.0% in FY2024–2025 (World Bank, India Development Update, 2025). At the same time, FDI inflows, projected at US\$81 billion in FY2024–2025 (FDI Fact Sheet, 2025, DPIIT), continued to be robust and investor confidence has remained high worldwide. Similarly, increased trade openness and FDI inflows have improved competitiveness and facilitated knowledge transfer (Grossman & Helpman, 1991; Borensztein et al., 1998). As of December 2024, India's foreign debt was estimated to be approximately \$718 billion, with foreign debt to GDP ratio of about 18.7% (RBI, India's foreign Debt Report, 2025). This indicates an acceptable level of external vulnerability on a global scale. The macroeconomic climate for investment and capital formation has improved as inflation has been steadily approaching the Reserve Bank of India's target range over the past few years, with the Consumer Price Index (CPI) averaging 4.6% for the fiscal year 2024–2025 (RBI, Annual Report 2024–2025). Despite these successes, India is still far from advancement in technology, foreign investment, trade liberalisation, and capital inflow to boost productivity and lessen reliance on borrowing from outside sources. In this contemporary policy environment, it is crucial to explore the connections among technological innovation and external debt, economic development, trade openness, inflation, and fdi within a single empirical policy framework.

In India, the role of innovation, ICT adoption, R&D, and digital transformation in growth is often overlooked in favour of macro-economic interactions. (Maheshwari & Loke, 2024; Erumban & Das, 2016; Rooj & Kaushik, 2024). The existing body of work on the impact of external debt on economic growth has focused on the direct effects of external debt on the economy, and largely ignored the relationship between technology innovation, foreign direct investment, trade openness and inflation in a more comprehensive empirical analysis. While much work has been done on the impact of external debt on growth, this research has typically focused on the direct link without taking other important relationships into account. Additionally, the majority of earlier research has concentrated on the unidirectional relationship in which foreign debt is viewed as a dependent variable; modelling external debt as an independent variable and its effect on economic development have received very less attention. Furthermore, only a small number of studies have examined the other side of the equation, modelling the external debt as the dependent variable and the impact of external debt on economic growth as the independent variable. The majority of studies have been carried out from a forward-looking perspective, that is, by defining the dependent variable as economic growth. The purpose of this study is to examine the impact of technological innovation on India's economic growth and its external debt from the year 1990 up to 2024. The study also applies the ARDL bounds testing approach to analyze both the short-term and long-term connections among trade openness, inflation, foreign direct investment, economic growth, foreign debt, and technological innovation.

2. Review of literature

It has been suggested in the literature that sustainable economic growth is a result of combined effects of innovation, external financing, foreign capital, and openness on India's economy, not any single macroeconomic factor (Ahmed

et al., 2026; Halim & Moudud-Ul-Huq, 2024; Maheshwari & Loke, 2024). Endogenous growth theory is the primary explanation of positive role of innovation as technology change, human capital and accumulation of knowledge lead to continuing productivity gains and enhance the LT growth potential (Ahmed et al., 2026; Qamruzzaman & Jianguo, 2018; Qayyum et al., 2025). Over this, open-economy growth theory suggests that the extent of trade openness and international integration can expand market size, enhance efficiency and promote the diffusion of new technologies (Chien et al., 2022; Halim & Moudud-Ul-Huq, 2024).

In this context, the majority of studies in India have shown that innovation is a positive contributor to sustainable growth. Technological innovation directly contributes to long-run growth in India, particularly with the backing of quality education, skills, R&D investments and institutions (Ahmed et al., 2026). Green innovation and green finance also have a positive impact on sustainability-adjusted growth, indicating that the quality and direction of innovation is as important as the quantity (Manigandan et al., 2024; Nenavath & Mishra, 2023). But the evidence is not always encouraging: In India and China, financial innovation has had positive short-run impacts, but has had weak negative longer-term relationships with sustainable growth, suggesting that financial innovation can have a negative relationship or association with efficient resource allocation, especially when it is capital intensive and not conducive to sustainable growth (Qayyum et al., 2025).

Whereas the debt literature is more contentious and can be best understood with the lens of debt overhang theory. At the macro level, this theory suggests that high external debt lowers the motivation to invest as future returns are expected to be used to pay off the debt, and crowding-out theory focuses on a reduction in fiscal space and less productive expenditure (Dawood et al., 2024). This concern is backed up by many studies related to India which have indicated that external debt has a negative impact on growth in the long run, short-run or both (Barik & Sahu, 2022; Kaushik & Lamba, 2026; Roy, 2023). But not all relationships are bad. Several studies do not show any significant long-term impact of debt in India (Kaushik & Lamba, 2026; Ponceno & Indumati, 2023; Gupta & Singh, 2025). This conditional view is further reinforced by cross-country analysis, which identifies the debt thresholds and demonstrates that institutions and savings, along with the efficiency of investment help in mediating the relationship between debt and growth (Biswal & Patra, 2026; Mohsin et al., 2021).

The role of FDI is intermediated and highly conditional in this system. Ideally, FDI should bring technology, capital and managerial expertise, thereby augmenting domestic innovation and minimizing the need for borrowing (Chien et al., 2022; Maheshwari & Loke, 2024). But it is mixed evidence in India. Others, however, have reported negative spillover effects of FDI for innovation growth in the long run (Maitra & Shil, 2024; Ponceno & Indumati, 2023) and weak spillover effects (Maheshwari & Loke, 2024). In contrast, in South Asia, cross-country evidence reveals that FDI can be a booster to growth or a debt reducing force depending upon the effective absorptive capacity and regulatory framework (Kaushik & Lamba, 2026; Ponceno & Indumati, 2023).

The variable that is consistently found to be most supportive of growth in external sector in this literature is trade openness. The literature on BRICS, CIVETS, South Asia and India shows that openness is related to growth in the exports, market size effects and technology access (Halim & Moudud-Ul-Huq, 2024; Kaushik & Lamba, 2026; Mohsin et al., 2021). Meanwhile, there are some cautions about being open, as it may lead to vulnerability, import dependency, or a combination of both if domestic capabilities are low (Chien et al., 2022; Maitra & Shil, 2024).

The literature as a whole suggests that innovation, debt, FDI and openness have a conditionally joint impact on sustainable growth. The most powerful growth-enhancing factor is innovation; trade openness is typically reinforcing; and FDI is enhancing growth when it is used to finance investment that creates productive, innovation-enhancing, and export-augmenting investment processes; and external debt is enhancing growth when it funds investment that is productive, innovation-enhancing, and export-generating, rather than recurrent imbalances or debt-servicing pressures (Ahmed et al., 2026; Dawood et al., 2024; Ponceno & Indumati, 2023; Singh & Kumar, 2024). The overall message for India is that an innovation-led, trade-integrated and wisely managed debt policy will produce the best growth outcomes, with FDI as a complementary and not an automatic driver of growth.

3. Nature of data and methodology

3.1 Data

India's time-series data is used in the present research which is available on an annual basis from 1990 to 2024. Analysis is based on the data on Foreign Direct Investment, net inflows, % of GDP; Inflation, consumer prices, annual %; External debt stocks, % of GNI; Trade % of GDP; and GDP per capita, constant 2015 US\$; Technology innovation. Per capita of GDP is an indicator of economic growth and Patent application, resident is proxy for technology innovation as technology advancement indicator. The datasets are collected from the WDI. Before, empirical investigation the variables are taken in natural logarithm, except FDI.

3.2 Methodology

The primary goal of the research paper is to explore the effect of technology advancement on economic growth and external debt. The study also explores the connection between technology advancement, external debt, inflation, trade openness, economic growth, and FDI inflows. The following equations are used in our study to accomplish these goals:

Model 1: Economic Growth Model

$$\ln \text{GDPPC}_t = \beta_0 + \beta_1 \ln \text{TI}_t + \beta_2 \ln \text{EXDBT}_t + \beta_3 \ln \text{INF}_t + \beta_4 \ln \text{TRADE}_t + \beta_5 \text{FDI}_t + e_t \text{-----}(1)$$

Model 2: External Debt Model

$$\ln \text{EXDBT}_t = \alpha_0 + \alpha_1 \ln \text{TI}_t + \alpha_2 \ln \text{GDPPC}_t + \alpha_3 \ln \text{INF}_t + \alpha_4 \ln \text{TRADE}_t + \alpha_5 \text{FDI}_t + u_t \text{-----}(2)$$

where GDPPC, TI, EXDBT, INF, TRADE, and FDI represents per capita GDP, Technology innovation, external debt, inflation, trade, and net inflows of FDI, respectively. The subscript t, ln, et, and ut represent for the time period, natural logarithm and error terms, respectively, which are considered to be distributed normally and white noise terms. The logarithm conversion was used primarily to modify all of the variables seasonally and to account for the variables' magnitude changes. Additionally, it aided us in interpreting the elasticity term data.

The characteristics of all variables must be analyzed before applying the econometric technique in order to not get wrong results. The Autoregressive Distributed Lag (ARDL) technique verifies the integration characteristics of the variables selected to perform this technique, as the variables should not be an I(2) process, which is problematic and unsuitable for this approach. Phillips-Perron (PP) and The Augmented Dickey-Fuller (ADF) tests are used to check the sequence of variables integration.

To investigate the long-term and short-term relationship between technological innovation, foreign debt and macroeconomic variables in India, we use the ARDL bounds testing technique to integration proposed by Pesaran and Shin (1995) and Pesaran et al (2001). For the following reasons, this strategy is better than other conventional methods of Johansen and Juselius (1990) and Johansen (1991) cointegration. First of all, it is among the most widely used and adaptable techniques. It may be used regardless of the integration order or a combination of both, and it does not impose any restrictions on any type of data. Secondly, compared to other long-run estimations, particularly when the sample size is small, ARDL estimators provide the actual parameters and coefficients, as stated by Pesaran and Shin (1995). Thirdly, it also aids in eliminating the endogeneity issue that arises in the model. Lastly, it can even concurrently collect estimates for the short and long terms. Below are a representation of the unrestricted error correction models (UECM) of the ARDL model for model 1 and 2:

$$\begin{aligned} \Delta \ln \text{GDPPC}_t = & \alpha_I + \alpha_G \ln \text{GDPPC}_{t-1} + \alpha_E \ln \text{EXDBT}_{t-1} + \alpha_T \ln \text{TI}_{t-1} + \alpha_{TR} \ln \text{TRADE}_{t-1} + \alpha_I \ln \\ & \text{INF}_{t-1} + \alpha_F \text{FDI}_{t-1} + \sum_{h=1}^{m_1} \beta_h \Delta \ln \text{GDPPC}_{t-h} + \sum_{i=0}^{n_1} \beta_i \Delta \ln \text{EXDBT}_{t-i} + \sum_{j=0}^{o_1} \beta_j \Delta \ln \text{TI}_{t-j} \\ & + \sum_{k=0}^{p_1} \beta_k \Delta \ln \text{TRADE}_{t-k} + \sum_{l=0}^{q_1} \beta_l \Delta \ln \text{INF}_{t-l} + \sum_{m=0}^{r_1} \beta_m \Delta \text{FDI}_{t-m} + \varepsilon_{1t} \text{-----}(3) \end{aligned}$$

$$\begin{aligned} \Delta \ln EXDBT_t = & \alpha_2 + \alpha_E \ln EXDBT_{t-1} + \alpha_G \ln GDPPC_{t-1} + \alpha_T \ln TI_{t-1} + \alpha_{TR} \ln TRADE_{t-1} + \alpha_I \ln \\ & INF_{t-1} + \alpha_F FDI_{t-1} + \sum_{h=1}^{m_2} \beta_h \Delta \ln EXDBT_{t-h} + \sum_{i=0}^{n_2} \beta_i \Delta \ln GDPPC_{t-i} + \sum_{j=0}^{o_2} \beta_j \Delta \ln TI_{t-j} \\ & + \sum_{k=0}^{p_2} \beta_k \Delta \ln TRADE_{t-k} + \sum_{l=0}^{q_2} \beta_l \Delta \ln INF_{t-l} + \sum_{m=0}^{r_2} \beta_m \Delta FDI_{t-m} + \varepsilon_{2t} \text{-----} (4) \end{aligned}$$

where α_1 and α_2 are the constants; $\beta_h, \beta_i, \beta_j, \beta_k, \beta_l$ and β_m are the short-run coefficients; $\alpha_G, \alpha_E, \alpha_T, \alpha_{TR}, \alpha_I$ and α_F are the long-run coefficients; and ε_t is the error term.

The Akaike Information Criteria (AIC) had been employed to find the most optimum lag. The first stage in developing the ARDL model is to estimate equations 3 and 4 using OLS. The Wald or F test is used to determine the long-run relationship of the variables' lagged values. After determining the long-run connection between the variables, we will utilise the error correction model to study the variables' short-run adjustment speed and dynamics (Samal 2018).

4. Results and discussion

4.1 Tests for Unit root

The integration qualities of variables were tested by the use of the unit root tests of PP and ADF, to ensure that none of the variables had spurious regressions from the non-stationary data. The length of the lag for these tests was again identified through the use of the AIC criterion. The table 1 findings demonstrate inflation (INF) is stationary at level i.e, I (0), while other variables are stationary at first differences i.e, I (1). These results imply that the variables are integrated in a mixed order, I (0) and I (1). As a consequence, we employ the ARDL bounds testing approach to look into the long-term relationship between the variables.

Table 1: Results of Unit Root Test

Variables	ADF (level) t-statistic	Prob.	ADF (first difference) t-statistic	Prob.	PP (level) t-statistic	Prob.	PP (first difference) t-statistic	Prob.
GDPPC	0.960	0.9951	-5.702***	0.0000	1.317	0.9982	-6.541***	0.0000
EXDBT	-1.399	0.5711	-5.987***	0.0000	-1.476	0.5333	-5.986***	0.0000
FDI	-2.206	0.2076	-6.733***	0.0000	-2.191	0.2127	-6.884***	0.0000
INF	-3.439***	0.0173	-7.529***	0.0000	-2.376	1.555	-7.510***	0.0000
TI	1.492	0.9989	-6.178***	0.0000	1.492	0.9989	-6.170***	0.0000
TRADE	-2.189	0.2134	-5.103***	0.0002	-2.189	0.2134	-5.100***	0.0002

Note: *, **, and *** denote the 0.1, 0.05, and 0.01 levels of significance rejection of null. Source: Authors' estimations.

4.2 Cointegration test using ARDL

Table 2: Results of Bound Testing – Bound Testing Approach to Cointegration

Estimated Model	Optimal lag length	F-statistics
$GDPPC = f(EXDBT, FDI, INF, TI, TRADE)$	(1, 3, 3, 0, 1, 3)	4.758
$EXDBT = f(FDI, GDPPC, INF, TI, TRADE)$	(1, 2, 0, 3, 3, 0)	4.532

Critical values: significance level	Lower bound I(0)	Upper bound I(1)
10%	2.508	3.763
5%	3.037	4.443
1%	4.257	6.04

Source: Authors' estimations.

The unit root test indicates that none of the variables are integrated of order 2, and instead they exhibit a mix of zero and one integration. The ARDL bounds test approach is employed to examine long-term relationships in India for the time period from 1990 to 2024. In this context, AIC is employed to identify the most suitable lag length for both models. Table 2 shows that the calculated F-statistic of 4.758 is higher than the upper bound critical values of 3.763 and 4.443 at the 10percent and 5percent significance levels, respectively, when GDPPC is treated as the dependent variable. This indicates that there is a long-run relationship or cointegration among the variables. Similarly, the calculated F-statistic of 4.532 exceeds the upper bound critical values of 3.763 and 4.443 at the 0.1 and 0.05 significance levels, respectively, when EXDBT is used as the dependent variable, suggesting there is a long-run relationship among the variables. This finding suggests that over time, these macroeconomic variables tend to reach a long-term balance and are connected in their development, even though they experience short-term fluctuations. The cointegration relationship aligns with the theoretical framework proposed by Pesaran et al. (2001) and is supported by the estimation of the error correction model and long-run coefficients as discussed in Dey and Tareque (2020).

4.3 Analyses of Long-run and short- run

Table 3: Model 1 Results (Dependent variable: GDPPC)

Variables	Coefficient	t-statistics	p-value
Long-run results			
EXDBT	0.028	2.148**	0.049
FDI	-0.074	-0.823	0.423
INF	-0.148	-1.966*	0.069
TI	0.318	11.864***	0.000
TRADE	0.720	2.639**	0.019
R- squared	0.773		
Short-run results (ECM)			
Constant	0.371	7.018***	0.000
Δ EXDBT	-0.000	-0.449	0.660
Δ EXDBT (-1)	-0.003	-1.631	0.123
Δ EXDBT (-2)	-0.006	-2.882**	0.011
Δ FDI	-0.024	-3.969***	0.001
Δ FDI (-1)	0.008	1.007	0.330
Δ FDI (-2)	0.027	3.414***	0.003
Δ TI	0.001	0.051	0.960
Δ TRADE	0.091	2.242**	0.040
Δ TRADE (-1)	0.016	0.366	0.720
Δ TRADE (-2)	-0.111	-2.980***	0.009
ECT (-1)	-0.230	-6.169***	0.000
Diagnostic tests			
	p-value	F-statistics	
BP test	0.183	1.760	
LM test	0.073	2.431	
Ramsey RESET	0.539	0.398	
Durbin- Waston	1.984		
CUSUM	Stable		
CUSUMSQ	Stable		

Note: *, ** and *** denote the 0.1, 0.05 and 0.01 levels of significance. Source: Authors' estimations.

The substantial correlation between the variables was demonstrated by the ARDL bounds testing method. Nevertheless, the cause-and-effect connections between per capita of GDP, TI, INF, TRADE, FDI, and EXDBT was not revealed by the cointegration test results. Therefore, after examining the long-term association among the variables, we investigate the long-term elasticities of the ARDL bounds testing technique. Table 3 in panel - I show the findings from the long-term study regarding GDPPC, which serves as the dependent variable. In Table 3, an analysis of long-term shows that EXDBT is statistically significantly and positively affected by GDPPC. This implies that a one percent accelerate in EXDBT leads to a corresponding increase in GDPPC by 2.8%, keeping other variables constant. This means that the external borrowing has enabled India to develop its economy by enabling productive investments and by meeting the domestic resource constraints. This positive role, however, relies upon the efficient use and sustainability of borrowed funds; if the debt servicing obligations are too high, it can lower growth at some point (Pattillo et al., 2002). Similarly, TRADE and TI are positively affecting GDPPC at 10%, 5% and 1% significant levels. The findings show that a one percentage rise in TI leads to a 31.8% increase in GDPPC, supporting the endogenous growth theory. This theory emphasizes the role of innovation and the accumulation of knowledge as key drivers of long-term productivity and income growth. Recent empirical evidence also points towards India, which shows that technological advances can have a significant contribution towards improving long-term productivity and economic performance (Ghosh & Parab, 2021). Also, one increase in TRADE induces GDPPC by 72%, *ceteris paribus*, highlighting the importance of the integration with the global markets for growth through technology diffusion, competitiveness and efficient resource allocation, as has been shown in empirical studies of the trade-growth relationship (Irwin & Tervio, 2000). While, INF is negatively affecting GDPPC at 10% significant level, implies one percent increase in INF will reduce GDPPC by 7.4%, keeping variables constant. Whereas, FDI in long-run, is statistically insignificant.

In order to estimate the short-run parameter with speed of adjustment, the ARDL model's last step is error correction. In Table 3, panel-II displays the error correction model's findings. The presence of long-run equilibrium is further supported by the ECM. According to the economic growth model, the EC coefficient shows that about 23% of short-term imbalances are adjusted within one period, and this coefficient is negative and statistically very significant. This shows how quickly adjustments can be made following temporary economic shocks. In an analysis of the short-run results, FDI exerts strong negative and statistically significantly ($\beta = -0.024$, $p = 0.001$) affecting GDPPC, whereas, FDI (-2) becomes positive and significantly ($\beta = -0.027$, $p = 0.003$) impacting GDPPC, reflecting a time lag of FDI's benefits, which will appear in the future, namely through technology transfer and spillovers. Similarly, EXDBT (-2), that is second lag of EXDBT has a adversarial and statistically significant relationship with GDPPC, with a regression coefficient of -0.006 and a p-value of 0.011. Likewise, TRADE is impacting

GDPPC positively and significantly ($\beta = 0.091$, $p = 0.040$), whereas, but its lag of two is significant and negative with coefficient of -0.111 and p value of 0.009. This indicates that there are short-term adjustment challenges associated with trade liberalization, which may hinder the realization of long-term benefits. Technology innovation is included in the selected ARDL model without any short-run lags, meaning its effect is primarily observed through the long-term equilibrium rather than through short-term economic adjustments.

Table 4: Model 2 Results (Dependent variable: EXDBT)

Variables	Coefficient	t-statistics	p-value
Long-run results			
GDPPC	-17.738	-1.128	0.276
FDI	-5.483	-2.670**	0.017
INF	4.189	2.040*	0.058
TI	11.971	1.713*	0.104
TRADE	-1.399	-0.350	0.730
R- squared	0.703		
Short-run results (ECM)			
Constant	25.680	5.947***	0.000
Δ FDI	0.096	0.239	0.814
Δ FDI (-1)	1.108	2.810**	0.012
Δ INF	1.627	2.084*	0.052
Δ INF (-1)	0.913	1.208	0.243
Δ INF (-2)	2.519	3.586***	0.002
Δ TI	-5.984	-2.842**	0.011
Δ TI (-1)	-14.362	-5.052***	0.000
Δ TI (-2)	-14.780	-4.610***	0.000
ECT (-1)	-0.470	-5.932***	0.000
Diagnostic tests		p-value	F-statistics
BP test	0.378		1.072
LM test	0.1149		2.509
Ramsey RESET	0.121		2.678
Durbin- Waston	2.007		
CUSUM	Stable		
CUSUMSQ	Stable		

Note: *, ** and *** denote the 0.1, 0.05 and 0.01 levels of significance. Source: Authors' estimations.

The above table exhibits the findings of the short-run as well as long-run analysis for model 2, where EXDBT is considered as a dependent variable. Panel 1 shows the long-run results, indicating ceteris paribus, one percentage rise in FDI decreases EXDBT by 5.483%. That is FDI is negatively and significantly affecting EXDBT. This conclusion is consistent with earlier studies demonstrating that foreign direct investment works alongside local investments and decreases the reliance on borrowing to fund development efforts (Kumari & Sharma, 2017). Whereas, INF exhibits positive and statistically significant relationship with EXDBT, suggesting one percent increase in INF induces EXDBT by 4.189%. This suggests that prolonged inflation may boost external borrowing through larger fiscal deficits and macroeconomic imbalances. Further, TI shows statistically significant and positively at 0.1 level and TRADE is statistically insignificant in an analysis of long-run.

The ECM explains the dynamics of the short run, where the ECM is statistically significant and negative, implying that roughly 47% of the short-term imbalance is adjusted in a year, showing a quick movement towards long-run equilibrium. The findings also exhibits that lag period in one of FDI shows positive and significantly affecting EXDBT ($\beta = 1.108$, $p = 0.012$) and INF also reveals positive and significantly impacting EXDBT ($\beta = 1.627$, $p = 0.052$) in short-run. Technology innovation (TI) has negative and statistically affecting external debt (EXDBT) in the all lags, that is Δ TI ($\beta = -5.984$, $p = 0.011$), Δ TI (-1) ($\beta = -14.362$, $p = 0.000$), and Δ TI (-2) ($\beta = -14.780$, $p = 0.000$),

showing that advancements in technology boost productivity and strengthen fiscal ability, which in turn reduces the need for borrowing from foreign sources. These results back up the idea that innovation helps a country make better use of its own resources and lowers the need for foreign funding (Romer, 1990).

Tables 3 and 4 demonstrate the diagnostics test results for cointegration using the long-run testing technique. The models do not exhibit non-normality, heteroscedasticity, autocorrelation, or misspecification errors, according to the diagnostic test. Lastly, in order to assess the stability of the models, we ran the CUSUM and CUSUMSQ tests. Figures 1 and 2 exhibit the test results for the same. It means that any model remains stable throughout time.

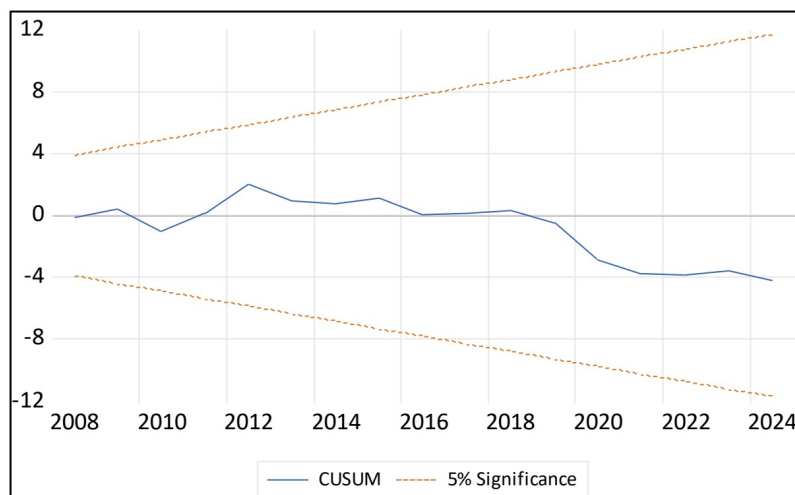


Figure 1: CUSUM test

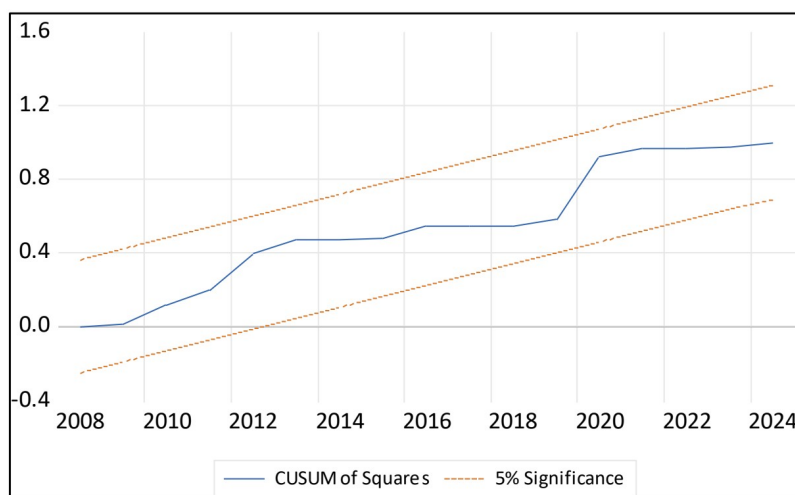


Figure 2: CUSUM SQ test

5. Conclusion and policy implications

The paper investigated the relationship between TI, EXBDT, INF, GDPPC and FDI in India from 1990 to 2024. We have used the ARDL bounds model test in this paper to take into account both the short-run and the long-run study of variables. The ARDL findings demonstrate a long-term association between TI, GDPPC, and EXBDT. The long-run analysis reveals that EXBDT, TRADE and TI have positive and significantly impacting per capita GDP, whereas INF has negative influence on GDPPC and FDI is insignificant in the long-run. While, FDI inflows has negative and significantly affecting EXBDT and INF impacting positively on EXBDT.

Whereas, TI is positive towards EXDBT but significant at 10% level. However, in short-run TI has negative influence on EXDBT in all lag periods.

Empirical results indicate that India's policy must not only be directed towards augmenting the number of external debts taken but also on their productive use. It is important to note that in the long run, external debt has a favourable effect on GDPPC but borrowing should not be considered as a solution to the problem of low GDPPC. Instead, external funding should be channeled into investments that boost productivity, such as investments in climate-resilient initiatives, infrastructure, technological innovation, and human capital development, while continuing to manage the debt in a prudent manner and conducting regular debt sustainability reviews. The role of FDI in lowering external debt is negligible to the long-run economic growth, suggesting larger INFDI may not be enough. Therefore, should be enhanced by increasing skilled human capital, increasing institutional quality and increasing technology spillovers through closer contact between foreign companies and domestic industries. Moreover, the substantial role of technology innovation in the economy emphasises the necessity for continued investment in research and development, digital infrastructure and the protection of intellectual property for the future productivity of the economy. Lastly, the benefits of openness trade argue for export diversification, global value chain participation and improving competitiveness at home, while limiting exposure to external disturbances through diversified export markets and good macroeconomic policy.

Nonetheless, the results have limitations that must be considered. The research relies on yearly data on macroeconomic, and which may influence the relationship between growth and debt, structural changes, institutions and their quality, fiscal governance, and the mix of debt (public versus private debt) are not included. In order to get more comprehensive information, these elements might be included in future projects using either a panel econometric model or a nonlinear econometric model.

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The Evolution of FinTech for Sustainable Finance: A Bibliometric Analysis

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ABSTRACT

The emergence of financial technology (FinTech) has transformed the entire industry by providing fast, convenient, and transparent financial transactions. At the same time, the increased attention paid to ESG principles and sustainable development worldwide has increased the role of sustainable finance in general. All these factors have resulted in an increased need for the exploration of digital financial innovations for promoting sustainable finance. Therefore, the purpose of this study is to analyze the evolution of the scientific literature concerning the FinTech applications for sustainable finance using the bibliometric approach with the focus on Scopus-indexed papers published during 2015-2025. Thus, this study will consider such aspects of bibliometric analysis as publication dynamics, influential authors, major journals, country contribution, collaboration, citation metrics, and keywords\ co-occurrence for revealing the intellectual development of the studied scientific field. At the same time, the paper will explore the major topics and promising research directions within FinTech applications for sustainable finance.

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1. Introduction

FinTech has revolutionized the financial sector due to its technological developments that have increased the accessibility, effectiveness, and transparency of financial actions. Technologies such as artificial intelligence, blockchain technology, big data analytics, mobile payment, and digital banking have made changes in the way financial services can be accessed, managed, and provided. With the continuous developments of technologies, FinTech has gone past the aspect of improving financial operations towards helping to solve broader socio-economic problems in order to become an increasingly relevant subject of study (Desalegn & Tangl, 2022).

While all these changes occur, sustainable finance has become a priority at the global level. The inclusion of ESG considerations in the financial policy is gaining popularity among governments, financial institutions, and investors. Initiatives like the Paris Agreement and the UN Sustainable Development Goals have put pressure on the promotion of the low-carbon sustainable economy. On the same vein, the Sustainable Stock Exchanges (SSE) initiative has pushed for improved ESG disclosures from the listed firms. Due to the need to achieve carbon neutrality goals and other changed stakeholder perceptions, there is an increasing trend for organizations to incorporate sustainability in their business and investment strategies (Chen et al., 2023). All these changes have promoted responsible finance in that firms are seeking economic growth while taking care of environmental protection and the social component (Cornell & Shapiro, 2021; George et al., 2021; Crawford & Leslie, 2023; Rivera et al., 2022).

The emergence of FinTech combined with sustainable finance has brought up possibilities to develop green investment, financial inclusion, disclosure, and the proper allocation of financial resources. Digital technologies become more significant for promoting sustainable finance through ESG disclosure, data transparency, funding of renewable energy projects, and the creation of new financial instruments like green bonds and digital investment

platforms. FinTech companies, including well-established firms and startups, contribute to climate finance, carbon accounting, and responsible investments using technology-based solutions in finance (Ashta, 2023). On the other hand, governments and regulators encourage the formation of sustainable digital financial ecosystems through relevant policies and technology-related initiatives (Bayram et al., 2022).

Given the growing interest in the inter-disciplinary subject area, the body of academic work on FinTech and sustainable finance has grown significantly over the last ten years. While previous studies in this area have been conducted on a broad spectrum of issues such as blockchain, artificial intelligence, ESG investment, green finance, digital banking, and financial inclusion, there has been little synthesis of this literature to date. As a result, there is little knowledge regarding the progression of the research within this field, especially in terms of publications, contributors, networks of cooperation, and emerging trends. The use of bibliometric analysis would help fill this gap, offering an overview of the intellectual history of FinTech research for sustainable finance and suggesting new avenues for further research.

Thus, this study utilizes a bibliometric method to analyze the development of research on FinTech for sustainable finance through the use of articles published in Scopus from 2015 to 2025. The aspects that will be analyzed within this study include publication pattern, notable authors, significant journals, contribution of different countries, institutional collaboration, citation, and keyword co-occurrence to gain an extensive perspective on the intellectual development of the field of study. Through these aspects, it is expected that major research themes will be revealed and emerging themes will be highlighted in order to provide useful information to various stakeholders.

To achieve these objectives, the study addresses the following research questions:

RQ1: How has research on FinTech for sustainable finance evolved between 2015 and 2025 in terms of publication trends, influential contributors, and global research collaboration?

RQ2: What are the major research themes and emerging directions in the literature on FinTech for sustainable finance?

2. Literature Review

2.1 Evolution of FinTech

FinTech has transformed the financial services sector due to the use of innovations which have led to faster, easier, and more efficient financial transactions. The technologies such as blockchain, artificial intelligence (AI), big data analytics, cloud computing, and mobile payments have influenced the way financial organizations provide services and interact with customers. Innovations have made it possible for organizations to provide personalized financial products, improve the level of operational efficiency, increase transparency, and expand the provision of financial services to underdeveloped regions. As a result, FinTech has evolved from being a technological innovation to becoming a key component of the modern financial system (Desalegn & Tangl, 2022).

Widespread adoption of digital technologies has prompted organizations to reconsider their business models and improve their operational competencies. Digital transformation has positively affected organizational performance through better governance practices, internal processes, and decision-making based on data analysis (Peng & Tao, 2022; Hu et al., 2024). Furthermore, digital technologies have contributed to innovation by making organizations more responsive to changes in the market environment and customer preferences (Nambisan et al., 2019; Yang et al., 2024). These developments highlight that the influence of FinTech now extends well beyond financial services, contributing to wider economic development and supporting the transition toward more sustainable and resilient financial systems.

2.2 Sustainable Finance and ESG

The increasing awareness of climate change, environmental degradation, and sustainable resource use has made sustainable finance a very important topic in the global policy and investment agenda. Sustainable finance refers to

the process whereby investments take into consideration ESG (Environmental, Social, and Governance) as well as financial considerations, thus allowing firms to create economic value while solving wider social and environmental issues. It has led to the inclusion of sustainability within financial planning and investment strategies by governments, banks, and investors.

The Paris Agreement and national pledges of carbon neutrality are just some of the international programs that have led to the acceleration of the move towards more sustainable finance. In the same manner, the SSE initiative has made efforts to push listed companies to enhance ESG reporting and disclosure. In response to the above changes, firms have become more inclined to integrate sustainability in their business decisions and allocate their financial assets to renewable energy and other green initiatives (Chen et al., 2023; Cornell & Shapiro, 2021; George et al., 2021; Crawford & Leslie, 2023; Rivera et al., 2022).

Despite many studies on sustainable finance in academic circles, the link between the practices of ESG and financial performance is still being debated. There are some scholars who found that the incorporation of sustainability in the strategy of business contributes to better performance, but there are some scholars who have found inconsistent results based on the market conditions, regulatory framework, industry, and stakeholder pressure (Huang, 2022a, 2022b; Nirino et al., 2021; Shaikh, 2022; Sharma et al., 2019; Thomas et al., 2021; Zhang & Lucey, 2022).

2.3 FinTech and Sustainable Finance

Combining FinTech and sustainable finance has been seen as a rapidly rising area of research, due to the increasing importance of the use of technology in sustainable economic development. Innovations like blockchain, artificial intelligence, and big data have been used by financial firms to increase transparency, enhance ESG disclosures, evaluate climate risks, and take more informed decisions regarding investments. In addition, these innovations facilitate the development of novel financial solutions that encourage responsible investments.

Moreover, the emergence of digital financial innovations has enabled new opportunities for green finance via the provision of online investment platforms, carbon accounting systems, and the financing of renewable energy sources. This is evident according to Ashta (2023), where the author points out that both traditional financial entities and innovative FinTech companies are involved in the adoption of environmentally friendly financial practices through technological innovations. In addition, Bayram et al. (2022) indicate that enabling policies and regulations will ensure faster development of digital financial environments for sustainable finance. However, the success of such initiatives will depend on sound regulation, strong digital infrastructure, and coordination between various parties.

2.4 Research Gap

The current literature points towards the rising convergence between FinTech and sustainable finance in terms of an increased emphasis on innovation in technology, ESG integration, green finance, financial inclusion, and technology-based investment solutions. Even though these studies have made considerable contributions to the existing knowledge of the subject, a majority of these studies have been done on the basis of particular technologies or financial applications in specific countries.

Despite the availability of many literature reviews that address some dimensions of FinTech or sustainable finance, no substantial bibliometric study has been carried out to shed light on the intellectual growth of the field. In fact, there has been little effort made towards the analysis of publication patterns, influential authors, prominent journals, collaboration patterns, citation patterns, and the changing nature of research themes in FinTech or sustainable finance over time.

In order to fill this gap, this research paper performs a bibliometric analysis of the articles indexed in Scopus, which were written from 2015 until 2025. Using the analysis of research productivity, scientific impact, collaboration patterns, citation networks, and keywords, the study presents an intellectual evolution of FinTech in the context of sustainable finance.

Table 1. Compilation of Literature on FinTech and Sustainable Finance

Authors	Focus of the Study	Key Findings	Research Gap
Mention (2019)	Evolution of FinTech	FinTech disrupted traditional financial services through innovative digital products and business models.	Limited discussion on the role of FinTech in achieving sustainability objectives.
Jarvis and Han (2021)	Technological innovations in FinTech	Blockchain, AI, and P2P lending accelerated the global growth of FinTech.	Focused primarily on technological advancement rather than sustainable finance.
Suryono et al. (2020)	Digital financial technologies	FinTech improved payment systems, lending, and asset management through digital technologies.	Environmental and sustainability outcomes were not examined.
Desalegn and Tangl (2022)	FinTech services	FinTech expanded financial accessibility and customized financial solutions.	Limited attention to sustainable financial ecosystems.
Ashta (2023)	FinTech and sustainability	FinTech firms support carbon accounting, renewable energy finance, and environmental sustainability.	Based mainly on secondary evidence; empirical validation remains limited.
Bayram et al. (2022)	Sustainable finance policies	Government policies encourage FinTech adoption for climate risk analysis and green finance.	Implementation challenges remain due to regulatory and technological barriers.
Almansour (2023)	AI in FinTech	AI enhanced customer experience through personalized financial services and digital marketing.	Sustainability applications were not the primary focus.
Mogaji and Nguyen (2022)	AI-enabled FinTech	AI improved fraud detection, customer service, and operational efficiency.	Limited discussion on sustainable financial development.
Orij et al. (2023)	FinTech adoption challenges	Regulatory complexity, technological limitations, and consumer concerns hinder adoption.	Sustainable finance implications require further exploration.
Atadoga et al. (2024)	Barriers to FinTech adoption	Trust, privacy, perceived risk, and legal compliance significantly influence FinTech adoption.	More research is needed on balancing innovation with sustainability goals.
Kamuangu (2024)	Risk management in FinTech	Effective risk management and technology integration are essential for long-term FinTech success.	Future studies should examine sustainability-oriented risk management frameworks.
Adeoye et al. (2024)	Future of FinTech	Highlights opportunities and challenges associated with the future development of FinTech.	Calls for comprehensive reviews that map research trends and future directions.

3. Research Design

This study makes use of the secondary research methodology, which is built on analyzing the scientific literature related to FinTech and sustainable finance. In light of the significant growth of scientific articles related to the interdisciplinary area, this study focuses on the articles indexed in the Scopus database from 2015 to 2025. The research context of this study will be determined by summarizing the literature related to FinTech, sustainable finance, ESG, green finance, blockchain, artificial intelligence, and digital finance innovation in Table 1 below. The table provides information about the goals, major findings, and contributions of the research. It can help define recent trends, new areas of research, and knowledge gaps in this area.

4. Findings and Discussion

This study examined the intellectual development of research on FinTech for sustainable finance through a bibliometric analysis of publications indexed in the Scopus database between 2015 and 2025. The findings are presented according to the two research questions formulated in the study.

4.1 RQ1: How has research on FinTech for sustainable finance evolved between 2015 and 2025 in terms of publication trends, influential contributors, and global research collaboration?

According to the bibliometric analysis, there has been a considerable increase in research about FinTech used in sustainable finance. This is evidenced by an increasing number of published articles, which signifies the growing interest in this topic in the scientific community. There has been a rising importance of ESG investing, climate finance, financial inclusion, and digital transformation, which has led to contributions of researchers from various disciplines.

The analysis also reveals that the development of the literature has been influenced by works of multiple authors and institutions from various countries. It is clear that cooperation between scholars has grown in the last years due to the fact that FinTech and sustainable finance have become the fields of multidisciplinary research involving such areas as finance, information technologies, environment, and business management.

It becomes evident from the analysis of sources that publications belong to the journals specializing in finance, sustainability, technologies, and business management. It reveals the interdisciplinary aspect of the field and its importance for the development of sustainable financial system.

Concluding from this review, the literature in question has made a consistent progression in the theoretical sense, and it has developed into an increasingly relevant area for scientific research. The increasing trends of publication and collaboration are clear signs that FinTech is a key player in the development of sustainable finance.

4.2 RQ2: What are the major research themes and emerging directions in the literature on FinTech for sustainable finance?

From the analysis of keywords co-occurrences, several recurring themes can be found that characterize the state of contemporary research. The main recurring themes include FinTech, sustainable finance, blockchain, artificial intelligence, green finance, ESG, digital banking, financial inclusion, and sustainable investments. All these themes illustrate the growing fusion of digital technologies with sustainability goals in finance.

The thematic analysis also shows that blockchain technology has received much attention since it increases transparency, security, and traceability of financial transactions. On the other hand, the relevance of artificial intelligence grows as it has a number of applications in risk management, fraud detection, customer service, and investment decision making. ESG research keeps expanding as well.

Another important trend in the literature is the rising importance of financial inclusion through digital financial services. The provision of mobile payment services, digital lending, and other innovative financial products has led to increased access to financial services in developing economies. There has been an increasing interest in the areas of climate finance, renewable energy financing, and green finance instruments.

Several emerging research areas for future investigation can also be identified from the analysis. Future research can focus on the implications of generative artificial intelligence, decentralized finance, central bank digital currencies, sustainable digital banking, cybersecurity, and regulation on the development of sustainable financial systems. Further investigations might focus on the comparative analysis of the impact of FinTech innovations on sustainability.

In general, the findings suggest that FinTech research into sustainable finance has advanced from concentrating mainly on technological advancement to tackling the wider issue of sustainability. The theoretical framework in the

discipline remains dynamic as different technologies, policies, and sustainability considerations affect global financial systems.

5. Conclusion

This research paper conducts bibliometric analysis on research papers related to FinTech for Sustainable Finance between the years 2015 and 2025. It is apparent that the integration of technology in the sustainable finance domain has been receiving more academic attention due to the increasing number of publications, international cooperation, and varied research topics related to this multidisciplinary subject matter.

The findings address both research questions formulated at the beginning of this study. Research question one focused on the developments in the literature through examining publication trends, contributors, and network of collaboration. The answer is the increasing scholarly interest in technology-based sustainable finance. Research question two aimed at exploring the prevailing research topics, which are blockchain technology, artificial intelligence, ESG, green finance, digital banking, and financial inclusion.

With a description of the intellectual structure of the domain, the paper gives an insight into the evolution of the field and identifies the gaps that need further exploration. The outcomes can be helpful to those scientists who want to engage themselves in the research process and may help in developing strategies for policymakers, banks, and FinTech companies to create more sustainable financial system.

There are some limitations of this paper. First of all, the analysis has been performed only for publications retrieved from the Scopus database. This means that there are some papers that have been missed because they were located in another bibliographic base. Secondly, the findings have been obtained using the particular search strategy and timeframe.

Future studies may build on the above findings by examining multiple databases and conducting comparative bibliometric analyses in different countries/regions, and even researching the new themes of decentralized finance, generative AI, sustainable digital banking, and innovation in regulation. This will help to better understand how the FinTech sector can facilitate the creation of resilient, inclusive, and sustainable financial ecosystems.

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A Study on Gen Z Consumer Decision-Making: Value-Driven vs. Price-Driven Purchase Behaviour in Urban Bengaluru

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Urban Bengaluru market

ABSTRACT

In light of their socialized and digitally savvy upbringing Generation Z is influencing consumer behaviour in such a manner that some existing marketing beliefs based on other generations are being challenged. Despite price sensitivity still being a factor in consumer decisions making among a generation know for having little disposable income (Gunawan, 2023), it appears that brand trust value are also becoming consideration for Gen Z are they make purchasing decisions (kaboor & Muthu 2026; Theocharis & Teskouropoulos, 2025). Social media adds yet another dimension to this trend in that peer-based electronic word-of-mouth and value have been identified as factors affecting purchase intention (Eandhizhai, 2025).

In this research, an empirical descriptive approach will be used to evaluate the purchase behaviours of Gen Z consumers in urban Bengaluru Based on the Value-driven and price-driven paradigm. The primary data collection method will be the use of structured questionnaires administered to Gen Z consumer Who fall between the ages of 18 and 27 years within Bengaluru, While the secondary data collection technique will be include relevant literature review on the purchase's behaviour of different generations. The research will seek to identify factors that significantly influence the purchasing behaviour of Gen Z consumers including brand ethics, social media influence, peer influence, product quality, and Price among others. Statistical techniques like correlation and regression analyses will be applied to test for the relationship between value and orientation, price sensitivity, and purchase behaviour

The results of the research will offer evidence-based information on how marketers can develop positioning, pricing, and communications strategies for the Gen Z consumers in urban markets in India. The use of primary data collection techniques in this research, therefore, makes the research an additional contribution of quantifiable information about the values-oriented digital natives to an ever-growing international body of literature (Ridwana et al., 2025).

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1. Introduction

Generation Z, which refer to people who were born between the middle of the 1990s and the early 2010s, has turned out the among the most extensively researched consumer groups in modern marketing science. This particular group has been brought up in age of digitization; thus, its purchasing behaviour has been influenced by many factors that are not typical of Millennials and people of other generations, including the importance of online influence, transparency, and the necessity to make decisions based on budget limitations (Singh & Singh, 2025). The questions of Whether Generation Z's purchasing behaviour is driven by price considerations or value congruence id becoming increasingly relevant. An emerging trend in the existing research on this topic is the conflict between Gen Z's preference for ethical, credible and authentic brands and their financial constraints due to lack of disposable income for some purchases (gunawam,2023). The former is explained by the view that for this generation, price still remains

the most important factor in decision-making, while both perceived value and promotion play a significant role in forming intentions of repeat purchasing (Kaboor & Muthu, 2026). The latter is supported by the findings stating that brand trust and authenticity matter more than price in cosmopolitan and digitally enabled urban areas, where social influence and electronic word-of-mouth prevail (Theocharis & Tsekouropoulos, 2025; Eandhizhai, 2025).

Another feature of this issue under consideration is that systematic reviews of Gen Z's online shopping behaviour reveal that decision-making among these people is based not on one factor, but on several factors working simultaneously (price, brand trust, social validation and value). As one of the most prominent cosmopolitan and technology-based cities in India, Bengaluru serves as an interesting subject in terms of understanding the dynamics of this phenomenon. Being a city with a considerable number of digitally savvy young people and a variety of retailers ranging from international brands to Indian brands, Bengaluru becomes a perfect representation of the value versus price debate taking place among Gen Z consumers in India (Raghavendra & Ravanam, 2024). Currently, there is not enough academic literature on how consumers in Bengaluru buy things online and make purchase offline. More specifically, most consumer behaviour studies in Bengaluru are concerned with online purchases and brand loyalty in particular categories, such as clothing (Paria, 2026). Therefore, this gap is what the current study intends to fill by exploring how 18- to 27-year-old consumers behave when making their purchase decisions. It would be useful to determine which of the two factors prevails – price-driven purchases or value-driven purchases – across different product categories.

2. Review of Literature

1. Gunawan (2023), in "Generation Z and Price Sensitivity: Dynamic Pricing Strategy as Key to Product Attractiveness", conducted research into how dynamic pricing can influence product desirability for members of Generation Z in Indonesia. It was discovered that Generation Z is very sensitive to dynamic pricing strategies since they directly correlate with low levels of disposable income of this generation. It was found out that dynamic pricing plays an important role in keeping product desirability. This article is an example of evidence supporting price-related dimension of the current research since even though value-based approach becomes more important, the issue of affordability cannot be ignored.
2. Nair & Seshanna (2024), in "Understanding the Buying Behaviour of Generation Z Consumers in India: The Parasocial Mediating Role of Consumption Tendency", conducted a study that examined the parasocial mediating effect of influencers on the purchasing inclination of the Gen Z consumers in India using questionnaires that were filled out by 750 participants ages 12 to 22, where 620 valid responses were considered using regression analysis. Influencer's attractiveness, authenticity, and social validation have been found to influence the perception of product value and purchase intention by functioning through the parasocial relationship. This suggests that the purchasing action influenced by influencers is based on the perception of relationship rather than mere persuasion.
3. Raghavendra & Ravanam (2024), in "A Study on Purchasing Behaviour of Online Buyers with Reference to Bengaluru City, Karnataka", conducted research on the purchasing behaviours of online shoppers in Bengaluru city, Karnataka. The research findings pointed out that convenience, reliability of e-payment systems, and availability of a diverse range of urban shoppers in this geographical area. This paper is one of the very few papers which have directly conducted research in the Bengaluru region and hence validates the geographical scope of the current study, though Gen Z was not separately considered in this research.
4. Cipto (2025), in "Gen Z Consumer Behaviour and Sustainability Identity in Green Marketing", the link between sustainability identity of Generation Z and their receptivity to green marketing claims was also examined in this research. It was discovered that the consumers who had a more pronounced self-perception of sustainability orientation reacted to green marketing claims in a more positive way, but this reaction depends on the level of their environmental literacy. Those consumers who were less environmentally aware were less responsive to sustainability claims made in marketing communications. Therefore, it is not true to assume that Generation Z consumers react in the same way to sustainability claims.

5. Eandhizhai (2025), in “Gen Z Consumers Psychology on Social Media: The Influence of Electronic Word of Mouth (E-WOM) and Perceived Value on Purchase Intention,” examined the psychology of Gen Z consumers using social media and how their purchase intention was influenced by e-WOM and perceived value. Results proved that generated comments are more likely to be influential than brand-generated advertisements.

Perceived value also played a role in acting as mediator between social media use and purchase intention. The research further reiterates that there is growing consensus on the fact that the trust architecture of Gen Z is peer-based and not brand-based.

6. Ridwana et al. (2025), in “Decision-making Behaviour of Generation Z in Online Purchases: A Systematic Literature Review,” A systematic review was carried out concerning Generation Z decision-making in online purchases. The result of synthesis from several publications conducted between 2019 and 2026 suggests that none of these factors exists separately while affecting the decision-making process of Gen Z in online purchases – all of them, such as price, social approval, brand trust, and value are independent and should not be separated. This discovery is of particular importance for the methodology of the current research, as it underlines the necessity of applying the multi-factors approach.
7. Singh & Singh (2025), in “A Comparative Study on the Buying Behaviour of Generation Z and Millennials,” carried out a comparative analysis on the distinctions in the shopping patterns of the two generations. It was observed from their analysis that the Gen Z population is more affected by peer approval, short-form digital content, and instant social proof before making a buying decision, whereas the Millennial generation still holds onto their past influences of brand legacy, loyalty schemes, and brand relations.

This shows that the difference in the decision-making process of these two generations is not only superficial but runs deeper, and therefore Gen Z needs to be studied separately from other generations.

8. Theocharis & Tsekouropoulos (2025), in “Sustainable Consumption and Branding for Gen Z: How Brand Dimensions Influence Consumer Behaviour and Adoption of Newly Launched Technological Products,” conducted research into the role of brand dimensions in shaping the uptake of newly introduced technological products by Generation Z using the sustainability and branding perspective. The results revealed that online brand experience, brand experience, brand image and brand trust have the highest influence on purchase intention, whereas brand awareness played a secondary role in terms of influence and brand engagement had a lower impact on it. Notably, their study revealed that messages about sustainability positively affect purchase intention only when they are viewed as genuine and credible; otherwise, consumers might get disengaged. In other words, sustainability serves as a trust-based value driver for Generation Z.
9. Theocharis et al. (2025), in “Empirical Categorization of Factors Affecting Online Consumer Behaviour of Gen Z Regarding Newly Launched Technological Products and Moderating Impact of Perceived Risk,” studied the determinants of Generation Z’s online consumer behaviour with regard to new technological products, specifically the moderating effect of risk perception. Results showed that risk perception significantly moderates the effects of behavioural determinants on the adoption of technological products, such that the same set of marketing stimuli could lead to different purchase decisions according to the risk perception of each individual consumer. The study has therefore provided significant insight into value-based purchase studies in the sense that risk perception, rather than value congruence alone, act as the gatekeeper for purchase decisions.
10. Bari (2026), in “Impact of Social Media Advertising on Purchase Decisions of Gen Z Consumers,” this study explored the influence of social media advertisements on Gen Z individual’s purchasing decisions in India. It was discovered that there is an influence of social media advertisement on Gen Z individual’s purchasing decisions in India; however, this influence occurs in cases where advertisement is not overly promotional but rather lifestyle-based. The paper is located in the body of literature on digital engagement, based on previous studies about lifestyle and electronics endorsement. This paper is important to this study’s exploration of the intersection between digital marketing channels and value and price-based decision-making among Gen Z individuals in India.

11. Kaboor & Muthu (2026), in "Impact of Price Sensitivity and Value Perception on Gen Z's Repeat Purchase Intention in Branded Fashion Textiles," explored the impact of both price sensitivity and perceived value on repeat purchase intentions among branded fashion textiles. Results revealed that value for money perception was a better determinant of repeat purchase behaviour than price sensitivity on its own, since promotional activities were more of mediating than independent variables. This implies that the Generation Z population does not consider price on its own but takes into account quality and value in the process. The study is pertinent to the current study as it focuses on value versus price issue.
12. Kumar & Tripathi (2026), in "Influence of Socio-Behavioural Approach on Gen Z's Online Purchase Behaviour of Urban and Rural Women Consumers," explored the effect of socio-behavioural factors on the online purchase behaviour of Gen Z differentiating urban and rural female consumers in India. It was observed that there is significant variation based on demographic characteristics, wherein urban consumers found to be more sensitive to digital marketing stimuli, whereas the rural consumers placed more emphasis on community-based social signals in their decision-making process. Thus, this study emphasizes that Gen Z is not a homogenous demographic cohort, which makes it even more necessary to take into consideration the context of the current study, i.e., urban Bengaluru.
13. Paria (2026), in "Brand vs Trend: The Economics of Apparel Consumption among Urban Youth," investigated fashion consumption behaviour amongst urban youth between the ages of 18 and 30 years in Bengaluru, based on primary data generated by interviewing 150 people using structured survey tools. The paper highlights that although brand loyalty is still an important variable, rapid changes in fashion have started competing with, and even superseding, brand loyalty within this segment. The current paper provides empirical evidence of local relevance; however, it is applicable only to the clothing category, and there are open questions about other product categories.
14. Sudrajat et al. (2026), in "A Purchase Decision Behaviour Model by Generation Z: The Mediating Role of Consumer Motivation," conducted research to test the purchase decision behaviour model analysing the mediatory role of consumer motivation for Generation Z. It was found that digital advertising had a significant direct impact on purchase decision making but not affiliate marketing and that consumer motivation had no significant mediatory impact on the association between marketing stimuli and purchase decision making. This implies that the external stimuli could have more impact on Generation Z consumer's decision-making behaviour than their internal motivational factors which could be contrary to what has been assumed before.
15. Vilkaite-Vaitone (2026), in "It's Not Just About Price: What Drives Gen Z to Choose Sustainable Stays?" Gen Z tourist's motivation behind choosing green purchases in the context of touristic accommodation were investigated using quantitative research on the same target group of tourists in Spain, Norway, and Lithuania, analysed via the Partial

Least Squares Structural Equation Modelling approach. The findings indicated that functional value driven by the price factors as well as emotional value had an impact on the formation of attitudes towards the purchase of sustainable accommodation; meanwhile, environmental awareness and subjective knowledge affect green trust, which was influential in purchasing behaviour. It is important to mention that value driven by the price was still significant in the context of sustainability decision making.

16. Wahi & Moid (2026), in their paper titled "A Comparative Study of Brand Loyalty among Gen Z Consumers," they examined brand loyalty among Gen Z consumers based on the information collected from academic journals, industry publications, and online sources. In their analysis, they found out that social media presence, quality of product, pricing approach, use of influencer marketing, and customer experience were the key drivers for brand loyalty among Gen Z consumers. Their focus was that Gen Z consumers highly depend on the technological aspect in their process of building relationships with brand and loyalty is now being created based on constant online interaction. Being a conceptual review, it provides a good basis for identifying the right variables for studying value-driven purchasing behaviour.

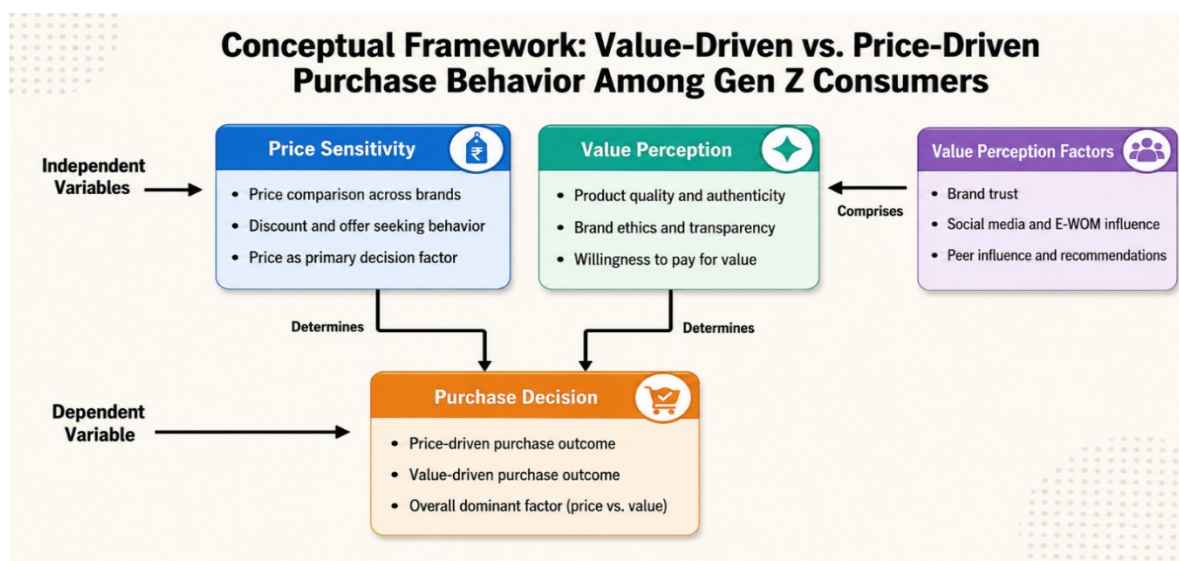
3. Research Gap

Existing literature has examined online shopping behaviour, price sensitivity, and value perception in various contexts, yet very little of this work has focused specifically on Gen Z consumers within Bengaluru. (Raghavendra and Ravanani, 2024), for instance, studied online buyers in Bengaluru as a broad category, without treating Gen Z as a distinct consumer segment worth examining on its own.

Other studies have looked at price sensitivity and perceived value, but usually in isolation from each other, or tied to a single product category such as fashion apparel, technology, or travel. (Gunawan, 2023), demonstrates that price sensitivity plays a meaningful role in Gen Z's purchasing behaviour, yet this work stops of examining how that sensitivity interacts with perceived value – particularly within a Bengaluru-specific context.

This points to a clear need for research that brings price sensitivity and value perception together within a single framework, applied specifically to Gen Z consumers in Bengaluru. Studying both variables jointly, within this particular demographic and geographic setting, is what allows for genuinely focused and locally relevant findings.

4. Conceptual Framework



The above conceptual framework shows how price sensitivity and value perception, which is influenced by brand trust, social media/E-WOM, and peer influence, function as independent variables that influence the purchase decision of Gen Z consumers, which is the dependent variable, in the city of Bengaluru.

4.1 Key Relationships Illustrated

- Price Sensitivity → Purchase Decision** Price sensitivity is measured using price comparisons among brands, being price-sensitive, and making price the main decision-making criteria, and influences purchase decision directly.
- Value Perception → Purchase Decision** Value perception, as perceived by means of product quality, authenticity, brand ethics, and readiness to pay for value, determines the purchase decision outcome independently from price sensitivity.
- Factors Affecting Value Perception → Value Perception** (consists of) The actual value perception is determined by three factors including brand trust, social media and e-WOM effects, and peer effects/influence. They are not individual predictors of purchase decision, but dimensions forming the value perception.

4. Convergence to Purchase Decision Price sensitivity and value perception converge on the purchase decision construct which can be measured based on three dimensions including purchase due to price, purchase due to value, and the dominant factor among the two.

5. Research Methodology

5.1 Objectives of the Study

1. To study the influence of price sensitivity on the purchase of Gen Z consumers in urban Bengaluru.
2. To analyse the influence of value perception – including brand trust, product quality, and social/peer influence – on the purchase decisions of Gen Z consumers in urban Bengaluru.
3. To study whether price-driven or value-driven factors dominate the purchase decision-making of Gen Z consumers in urban Bengaluru.

5.2 Research Design

The study adopted a descriptive/quantitative research design appropriate for determining the comparative influence of price-related and value-related determinants on Gen Z consumer buying behaviour. The cross-sectional research design method was employed using primary data collected in one instance from consumers who were located in Bengaluru city using a structured questionnaire. The secondary data used in the study came from the reviewed literature, which guided the determination of the variables and development of the questionnaire.

5.3 Population and Sampling Frame

The target population included Gen Z consumers who were between the ages of 18 to 27, lived in the city of Bengaluru, and had made one or more discretionary purchase, for example, fashion clothes, electronics, food & beverages, and personal care product, in the recent past. The limitation of the sampling frame to the city of Bengaluru resolves the issue of geography that was pointed out above, while the age range will ensure that only Gen Z members make up the sample.

5.4 Sampling Technique and Sample Size

Non-probability convenience sampling was used, with the survey being disseminated through college contacts, social media platforms popular with Gen Z consumers in Bengaluru. The survey received 102 valid responses from participants who were filtered according to their age and residential city. Although the number of respondents in this case may be small compared to the Gen Z population in Bengaluru, it will be sufficient for the descriptive, correlational, and regression analyses to be conducted and is consistent with other studies in the literature review that focus on Gen Z consumer behaviour.

5.5 Data Collection Method

Primary Data: The collection of primary data was conducted by distributing the questionnaire in a structured manner through Google Forms among Gen Z respondents residing in the city of Bengaluru for a period of three to four weeks.

Secondary Data: Collection of secondary data was carried out by referring to academic peer reviewed journals and research papers, as well as industry reports.

5.6 Scope of the Study

1. Geographical restriction of the research is Gen Z consumer base from Bengaluru city.
2. The research will only cover Generation Z consumers within an age group of 18 to 27 years.
3. Price sensitivity, value perception, and buying decision relationship are analysed in the research without considering a particular product category.

4. Category-neutral approach is followed without considering a particular product category (fashion, technology, food, etc.).
5. Primary and secondary data sources will be used for the research.

5.7 Limitations of the Study

1. This research is limited to Bengaluru, an urban city. Results obtained from the study may not necessarily apply to other consumers in other geographical locations within the Gen Z segment.
2. Non-probability convenience sampling method was employed for data collection. This could lead to biased samples.
3. The sample size used for the research (N = 102) is considered fairly small and may not provide comprehensive results regarding the purchase behaviour of Gen Z segment.
4. Self-reported information was obtained using a structured questionnaire. The responses provided could be prone to bias.
5. The study uses a category-blind research method and therefore ignores the variations of price-value dominance within different product categories

5.8 Variables of the Study

Independent variables: price sensitivity, value perception, brand trust, social media and electronic word of mouth influence, and peer influence.

Dependent variable: purchase decision outcome, triangulated with the single-item measure of the overall dominant factor, which asks respondents directly whether price or value/quality prevails when the two are in conflict.

6. Data Analysis and Interpretation

6.1 Introduction

This chapter presents the analysis and interpretation of primary data collected for the study titled “A Study on Gen Z Consumer Decision-Making: Value-Driven vs. Price-Driven Purchase Behaviour in Urban Bengaluru.” A total of 102 valid responses were collected from Gen Z respondents residing Bengaluru through a structured, self-administrated questionnaire, and all 102 cases were used in every subsequent procedure.

The chapter follows a deliberate analytical sequence rather than presenting statistical outputs on the order they were run in SPSS. Following the structure recommended for survey-based dissertations (Pallant, 2020; Sekaran & Bougie, 2016), the chapter first establishes who the respondents are (sample profile), then establishes whether the measurement instrument is trustworthy (reliability), then describes the overall pattern of responses (descriptive statistics and preliminary correlations), and only after this foundation is in place moves to inferential, objective-wise hypothesis testing (correlation → regression → paired-comparison). This order matters: a regression coefficient means little to a reader who had not first been told whether the scale that produces it was reliable, and a reliability coefficient means little without first knowing the composition of the sample it was computed on.

Data were analysed using SPSS. The techniques used were descriptive statistics, Cronbach’s Alpha reliability analysis, Pearson correlation, simple linear regression, multiple linear regression, and a paired-samples t-test, applied respectively to the three research objectives of the study.

6.2 Demographic Profile of Respondents

Before testing the research objectives, the demographic composition of the 102 respondents is presented. This step is placed first because it frames every result that follows – for instance, the fact that the sample is dominated by students in the 21 – 23 age bracket is relevant context for interpreting price-conscious behaviour later in the chapter.

Table 4.1 Demographic Profile of Respondents (N = 102)

Variable	Category	Frequency	Percent (%)
Age Group	18–20 years	19	18.6
	21–23 years	64	62.7
	24–27 years	19	18.6
Gender	Female	38	37.3
	Male	63	61.8
	Prefer not to say	1	1.0
Occupation	Student	78	76.5
	Working professional	17	16.7
	Both (studying & working)	3	2.9
	Unemployed	4	3.9
Monthly Income (₹)	Below 5,000	57	55.9
	5,001–15,000	20	19.6
	15,001–30,000	14	13.7
	Above 30,000	11	10.8

Interpretation

the sample is concentrated in the 21 – 23 age bracket (62.7%), with the 18 – 20 and 24 – 27 brackets equally represented at the two ends (18.6% each). This gives the sample a slight skew toward the middle of the Gen Z / early-career range rather than an even spread across the full 18 – 27 band.

Male respondents (61.8%) outnumber female respondents (37.3%) by a margin that should be kept in mind when generalizing the findings, and one respondent preferred not to disclose gender.

The sample is heavily student-dominated (76.5%), with working professionals a distant second (16.7%). This is consistent with the income profile: 55.9% of respondents report a monthly income below ₹5,000, and a further 19.6% fall in the ₹5,001–15,000 band – together, together, three-quarters of the sample have limited discretionary income. This concentration of low-income students is directly relevant to Objective 1: it provides a plausible explanation for why price sensitivity is elevated in this sample, and it is boundary condition that should be stated explicitly when the price-consciousness finding is discussed – the result describes a low-income, student-heavy Gen Z sub-segment more precisely than it describes Gen Z in Bengaluru as a whole.

6.3 Reliability Analysis of Research Constructs

With the sample profile established, the next step is to confirm that the multi-item scales used to measure each construct are internally consistent. Cronbach's Alpha was computed for each construct, following the conventional threshold of $\alpha \geq .70$ for "acceptable" reliability (Nunnally, 1978; Hair et al., 2019), while recognising that values in the 60 – 70 range are commonly treated as acceptable for exploratory consumer-behaviour research (Hair et al., 2019).

Table 4.2 Reliability Analysis of Research Constructs

Construct	No. of Items	Cronbach's Alpha	Interpretation
Price Sensitivity	3	0.765	Acceptable
Value/Quality Perception	2	0.727	Acceptable
Brand Trust (revised)	2*	0.652	Acceptable for exploratory research
Social/Peer Influence	4	0.676	Marginal / acceptable for exploratory research

Interpretation

Price Sensitivity ($\alpha = .765$) and Value/Quality Perception ($\alpha = .727$) both meet the conventional .70 threshold and can be treated as reliable without qualification.

Brand Trust required a correction. The original 3-item scale returned a low alpha of .566, which is below acceptable limits. Rather than retaining a weak scale, the low-performing item was removed on the basis of its poor item-total correlation, which raised reliability to .652 for the remaining 2 items – an acceptable level for exploratory work. This revised 2-item measure is the one actually used throughout the rest of the chapter, so the reliability figure reported here now matches the measure being analysed. This is a legitimate and commonly used scale-purification step (Hair et al., 2019), but it should be disclosed in the methodology write-up as a deviation from the originally planned 3-item scale.

Social/Peer Influence ($\alpha = .676$) falls just short of .70. This is treated as acceptable for an exploratory study (Hair et al., 2019) and the full 4-item scale was retained, since no single item's removal offered a meaningful improvement (the highest "alpha-if-deleted" value was

.683 for the Peer Influence item – a negligible gain that does not justify losing a conceptually important item).

Taken together, the reliability analysis confirms that three of the four constructs are sound as measured, and that Brand Trust is sound once corrected to two items. All four constructs are therefore carried forward into the descriptive and inferential analysis below.

6.4 Descriptive Statistics and Preliminary Correlation of Major Constructs

Having confirmed the constructs are reliably measured, their overall distribution is examined next, before any hypothesis testing is attempted. This step checks two things: what the general pattern of responses looks like, and whether the data meet the assumptions of the parametric tests (Pearson correlation, regression, paired t-test) used later in the chapter.

Table 4.3 Descriptive Statistics and Normality Check for Major Research Constructs

Construct	N	Mean	Std. Deviation	Skewness
Price Sensitivity	102	3.57	1.03	-.639
Value/Quality Perception	102	3.91	0.94	-.926
Brand Trust (2-item, revised)	102	3.87	0.89	-.507
Social/Peer Influence	102	3.57	0.80	-.375

Interpretation

All four constructs recorded mean scores above the scale midpoint (3.00 on the five-point Likert scale), and all show mild-to-moderate negative skew – respondents lean toward agreement rather than disagreement, which is a common and expected pattern in attitude scales of this kind.

Using the commonly cited ± 1 guideline for acceptable skewness in social-science survey data (George & Mallery, 2010), three of the four constructs are comfortably within range and Value/Quality Perception ($-.926$) sits just inside it. None of the values indicate a serious departure from normality. Combined with the sample size ($N = 102$, comfortably above the $N > 30$ threshold at which the Central Limited Theorem is generally invoked), this supports the use of Pearson correlation, linear regression, and the paired-samples t-test in the section that follow (Pallant, 2020; Field, 2013).

Value/Quality Perception recorded the highest mean (3.91), followed by Brand Trust (3.87). Price Sensitivity and Social/Peer Influence were tied at 3.57. This early pattern – value and trust scoring above price sensitivity – foreshadows the Objective 3 finding developed later in this chapter.

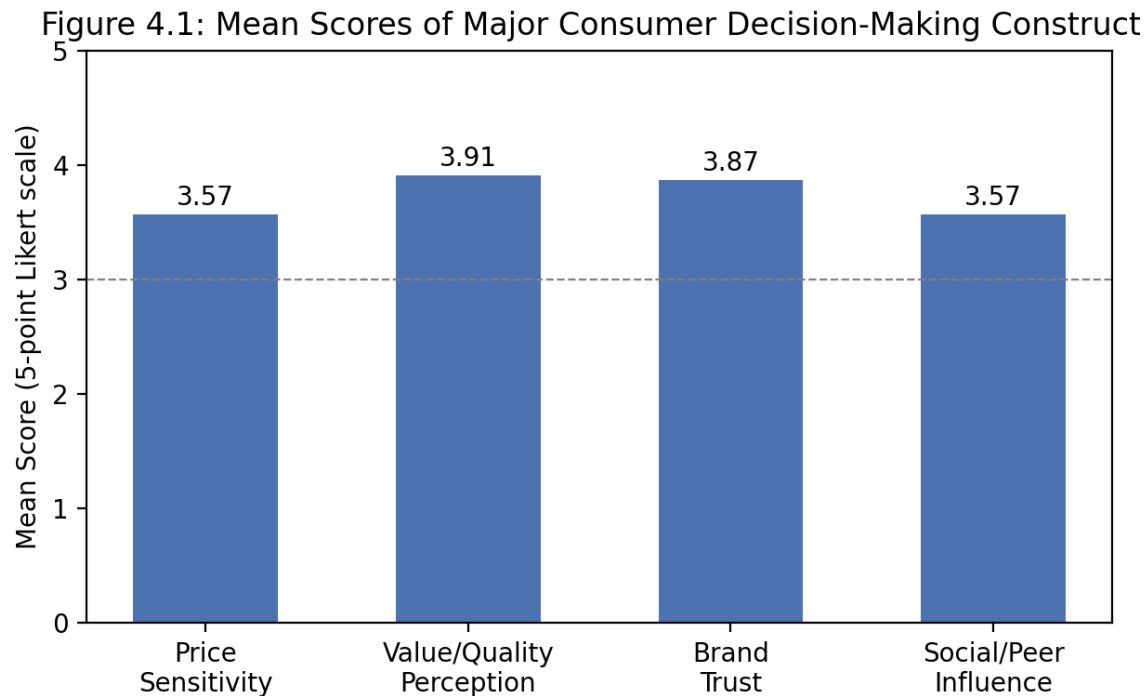


Table 4.4 Inter-Construct Correlation Matrix (Pearson r)

Construct	Price Sensitivity	Value/Quality	Brand Trust	Social/Peer
Price Sensitivity	1	.528**	.456**	.506**
Value/Quality	.528**	1	.626**	.389**
Brand Trust	.456**	.626**	1	.415**
Social/Peer	.506**	.389**	.415**	1

**Correlation is significant at the 0.01 level (2-tailed). $N = 102$ for all pairs.

Interpretation

All six pairwise correlations among the four constructs are positive and significant at $p < .01$, ranging from moderate ($r = .389$, Value/Quality-Social/Peer) to moderately strong ($r = .626$, value/Quality-Brand Trust). This is a useful preliminary check for two reasons. First, it confirms the construct are related in the direction the conceptual framework predicts – respondents who are more price-sensitive also tend to score higher on value, trust, and social influence, rather than these being unrelated or contradictory orientations. Second, none of the correlations approach the .80 - .90 range that would indicate the constructs are statistically indistinguishable from one another; the strongest pair (Value/Quality and Brand Trust, $r = .626$) is high enough to expect some shared variance in the

Objective 2 regression – which is exactly what the VIF check in Section 4.6 will confirm is still within acceptable limits – but not enough to threaten discriminant validity. This groundwork makes the correlation and regression results to threaten discriminant validity. This groundwork makes the correlation and regression results reported under each objective easier to interpret, since the reader already knows the four predictors are related but distinct.

6.5 Objective 1: Influence of Price Sensitivity on Purchase Decisions

Objective 1: To examine the influence of price sensitivity on the purchase decisions of Gen Z consumers in urban Bengaluru.

This objective is addressed in three stages: descriptive analysis of the individual price sensitivity items, Pearson correlation between Price Sensitivity and recent price-driven purchase behaviour, and simple linear regression to establish predictive influence.

6.5.1 Descriptive Analysis of Price Sensitivity

Table 4.5 Individual Price Sensitivity Items

Price-related statement	Mean
I actively compare prices across brands/platforms before making a purchase.	3.78
I wait for sales, discounts, or offers before buying a product I want.	3.49
Price is the most important factor in my final purchase decision.	3.43
Overall Price Sensitivity	3.57

Interpretation

Respondents are clearly price-conscious, with the highest mean (3.78) recorded for actively comparing prices across brands and platforms. However, the item stating that price is the most important factor scored lowest (3.43) – an important distinction; Gen Z respondents monitor and compare prices without necessarily letting price dominate every decision. The overall Price Sensitivity score of 3.57 indicates a moderately high, but not extreme, level of price consciousness.

6.5.2 Pearson Correlation Analysis

Table 4.6 Correlation Between Price Sensitivity and Price-Driven Purchase Behaviour

Variables	Pearson r	Sig. (2-tailed)	N
Price Sensitivity ↔ Recent Price-Driven Purchase	0.542	<0.001	102

Interpretation

There is a moderate, statistically significant positive relationship between Price Sensitivity and Recent Price-Driven Purchase Behaviour ($r = .542$, $p < .100$). Respondents who score higher on price sensitivity report stronger price-driven behaviour in their most recent purchase. Correlation indicated association, not predictive influence, so regression was conducted next.

6.5.3 Simple Linear Regression

Dependent Variable: Recent Price-Driven Purchase | Independent Variable: Price Sensitivity

Table 4.7 Model Summary — Price Sensitivity and Price-Driven Purchase

R R Square Adjusted R Square Std. Error 0.542 0.294 0.287 1.018

Table 4.8 ANOVA — Price Sensitivity Regression Model

Model F Sig. Regression 41.700 <0.001

Table 4.9 Regression Coefficients — Price Sensitivity

Predictor	B	Beta (β)	t	Sig.
Constant	1.013	—	2.767	.007
Price Sensitivity	0.637	0.542	6.458	<0.001

Interpretation

The R^2 of .294 shows Price Sensitivity explains 29.4% of the variance in recent price-driven purchase behaviour, and the model is statistically significant ($F = 41.700$, $p < .001$). Price Sensitivity has a positive, significant effect on Recent Price-Driven Purchase ($\beta = .542$, $t = 6.458$, $p < .001$): a one-unit increase in Price Sensitivity is associated with an estimated 0.637- unit increase in the Recent Price-Driven Purchase score.

6.5.4 Assumption Check

Before accepting this model, its regression assumptions were checked using the SPSS residual and collinearity diagnostics (Field, 2018; Tabachnick & Fidell, 2019). Tolerance/VIF = 1.000 (a single-predictor model cannot have multicollinearity). The standardized residuals range from -2.93 to 2.04 with a mean of 0.00 and SD close to 1, consistent with the normality-of-residuals assumption. Cook's Distance ranged from .000 to .095 – well below the commonly used concern threshold of 1.0 – including no single respondent unduly influenced the model. On this basis, the simple regression result above can be reported with reasonable confidence that it is not an artefact of outliers or a violated assumption.

6.5.5 Conclusion for Objective 1

Objective 1 is supported. Price sensitivity significantly predicts price-driven purchase behaviour among the surveyed respondents. However, as Section 4.2 noted, his sample is heavily weighted toward low-income students, so this price-sensitivity it best read in that context rather than as a generic Gen Z trait. Later sections in this chapter show that this price consciousness does not translate into price dominating overall purchase orientation.

6.6 Objective 2: Influence of Value Perception on Purchase Decisions

Objective 2: To examine the influence of value perception – including brand trust, product quality, and social/peer influence – on the purchase decisions of Gen Z consumers in urban Bengaluru.

The predictors examined are Value/Quality Perception, Brand Trust (revised 2-item measure, per Section 4.3), and Social/Peer Influence; the dependent variable is Recent Value-Driven Purchase Behaviour. The analysis proceeds through descriptive statistics, Pearson correlation and multiple linear regression.

6.6.1 Descriptive Analysis of Value-Driven Factors

Table 4.10 Mean Scores of Value-Driven Factors

Factor	Mean	Interpretation
Value/Quality Perception	3.91	High
Brand Trust	3.87	High
Social/Peer Influence	3.57	Moderately high

Interpretation

Value/Quality perception (3.91) and Brand Trust (3.87) but score notably higher than Social/Peer Influence (3.57), suggesting quality and trust weigh more heavily than social signals in respondent's self-reported value orientation.

6.6.2 Individual Value-Related Items

Table 4.11 Descriptive Results of Value and Brand-Related Statements

Statement	Mean
Willing to pay more for better quality	3.78
Product delivers value beyond just its price	4.03
Prefer brands that are transparent/authentic	3.75
More likely to repurchase a trusted brand even if a cheaper option exists	3.99

Interpretation

The highest mean (4.03) belongs to the belief that a product should deliver value beyond its price – respondents view value as broader than a low-price tag. The mean of 3.99 for repurchasing a trusted brand even when a cheaper alternative exists reinforces this: brand trust can outweigh price at the point of decision. Note that both items retained in the revised Brand Trust measure (transparency/authenticity and repurchase-despite-cheaper-alternative) appear in this table; the dropped online-brand-trust item is intentionally excluded, consistent with 4.3.

6.6.3 Pearson Correlation Analysis

Table 4.12 Correlation Between Value-Related Factors and Recent Value-Driven Purchase

Predictor	Pearson r	Sig.	Interpretation
Value/Quality → Recent Value-Driven Purchase	0.527	<0.001	Moderate positive, significant
Brand Trust → Recent Value-Driven Purchase	0.544	<0.001	Moderate positive, significant
Social/Peer → Recent Value-Driven Purchase	0.292	0.003	Weak positive, significant

Interpretation

All three value-based factors are significantly, positively correlated with recent Value-Driven Purchase. Brand Trust shows the strongest bivariate relationship ($r = .544$), closely followed by Value/Quality ($r = .527$); Social/Peer Influence is weaker but still significant ($r = .292$, $p = .003$). Correlation does not indicate independent contribution, so multiple regression was run next.

6.6.4 Multiple Linear Regression

Dependent Variable; Recent Value-Driven Purchase | Independent Variables: Value/Quality, Brand Trust, Social/Peer Influence

Table 4.13 Model Summary — Value-Driven Purchase Behaviour

R R Square Adjusted R Square Std. Error 0.595 0.354 0.335 0.814

Table 4.14 ANOVA — Multiple Regression Model

Model F Sig. Regression 17.940 <0.001

Table 4.15 Regression Coefficients — Value-Driven Purchase Behaviour

Predictor	B	Beta (β)	t	Sig.	VIF
Constant	1.043	—	2.337	.021	—
Value/Quality	0.319	0.300	2.836	.006	1.700
Brand Trust	0.386	0.343	3.199	.002	1.743
Social/Peer Influence	0.041	0.033	0.363	.717	1.250

Interpretation

The model is significant ($F(3, 98) = 17.940, p < .001$) and explains 35.4% of the variance in Recent Value-Driven Purchase ($R^2 = .354$; adjusted $R^2 = .335$). Value/Quality ($\beta = .300, p = .006$) and Brand Trust ($\beta = .343, p = .002$) are both significant positive predictors, with Brand Trust the strongest independent predictor. Social/Peer Influence is not a significant independent predictor once the other two factors are controlled for ($\beta = .033, p = .717$), despite its significant bivariate correlation in Table 4.12 – its explanatory power is effectively absorbed by Value/Quality and Brand Trust, with which it is moderately correlated (Table 4.4). VIF values range from 1.250 to 1.7434, well below the common threshold of 5 (Hair et al., 2019), so multicollinearity is not a concern for this model.

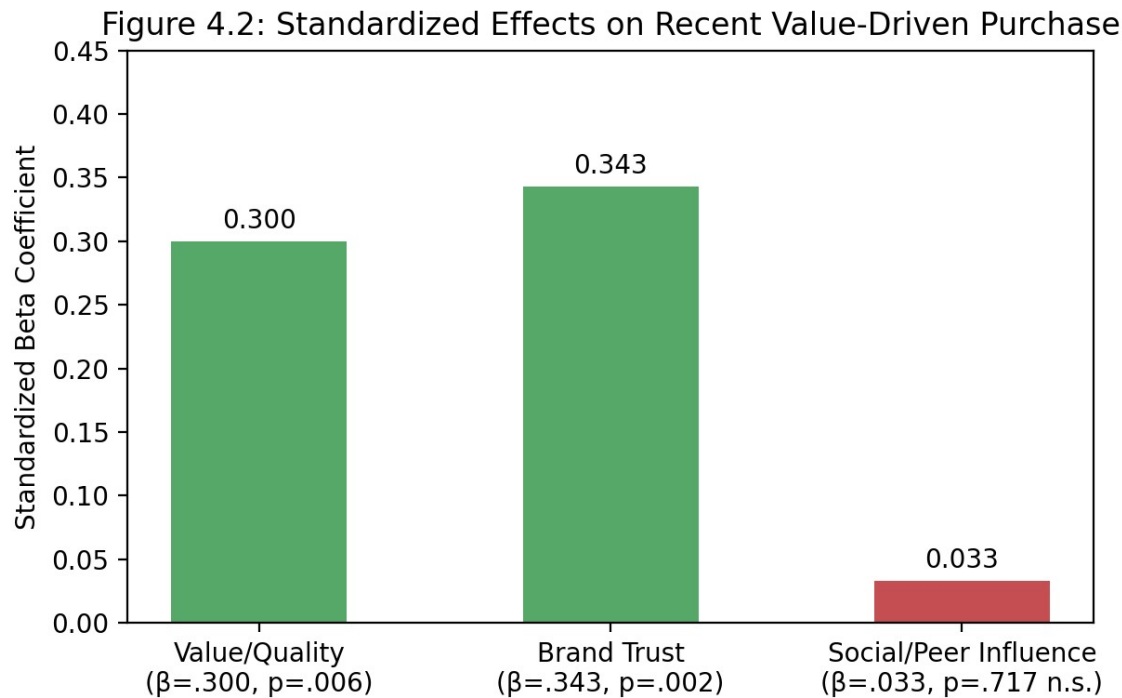


Figure 4.2: Standardized Effects of Value-Related Factors on Recent Value-Driven Purchase Behaviour

6.6.5 Assumption Check

The three-predictor model was similarly checked for regression assumptions (Field, 2018; Tabachnick & Fidell, 2019). VIF values (1.250-1.743) are well below the conservative threshold of 5 used by Hair et al. (2019), so the moderate inter-predictor correlations noted in Table 4.4 (particularly Value/Quality-Brand Trust, $r = .626$) do not distort the coefficient estimates. Cook's Distance and the standardized residual plots did not flag any case as an undue- values, supporting the linearity and homoscedasticity assumptions. The model can therefore be interpreted at face value.

6.6.6 Conclusion for Objective 2

Objective 2 is supported overall, with a more specific conclusion: Value/Quality and Brand Trust significantly predict value-driven purchase behaviour, Brand Trust is the strongest of the three predictors, and Social/Peer influence does not have a significant independent effect once the other two factors are controlled for.

6.7 Objective 3: Price-Driven vs. Value-Driven Dominance

Objective 3: To determine whether price-driven or value-driven factors dominate the purchase decision-making of Gen Z consumers in urban Bengaluru.

Because the same 102 respondents reported both their recent price-driven and value-driven purchase behaviour, the two mean scores are directly comparable within-subject, and a paired-samples t-test was used rather than an independent-samples test.

6.7.1 Descriptive Comparison

Table 4.16 Comparison of Price-Driven and Value-Driven Purchase Behaviour

Purchase Orientation	Mean	Std. Deviation	N
Recent Price-Driven Purchase	3.28	1.205	102
Recent Value-Driven Purchase	3.93	0.998	102
Mean Difference	-.647	1.539	102

Interpretation

Recent Value-Driven Purchase (3.93) is considerably higher than Recent Price-Driven Purchase (3.28), a gap of roughly 0.65 points on the five-point scale, pointing to a stronger value orientation among respondents. Worth noting: the two variables correlate only weakly with each other ($r = .033$, $p = .7433$, from the paired -samples correlation) – respondent's price-driven and value-driven tendencies are largely independent behaviour rather than opposite ends of a single scale, which supports treating them as two separate purchase orientations rather than one bipolar construct.

Figure 4.3: Price-Driven vs Value-Driven Purchase Behaviour

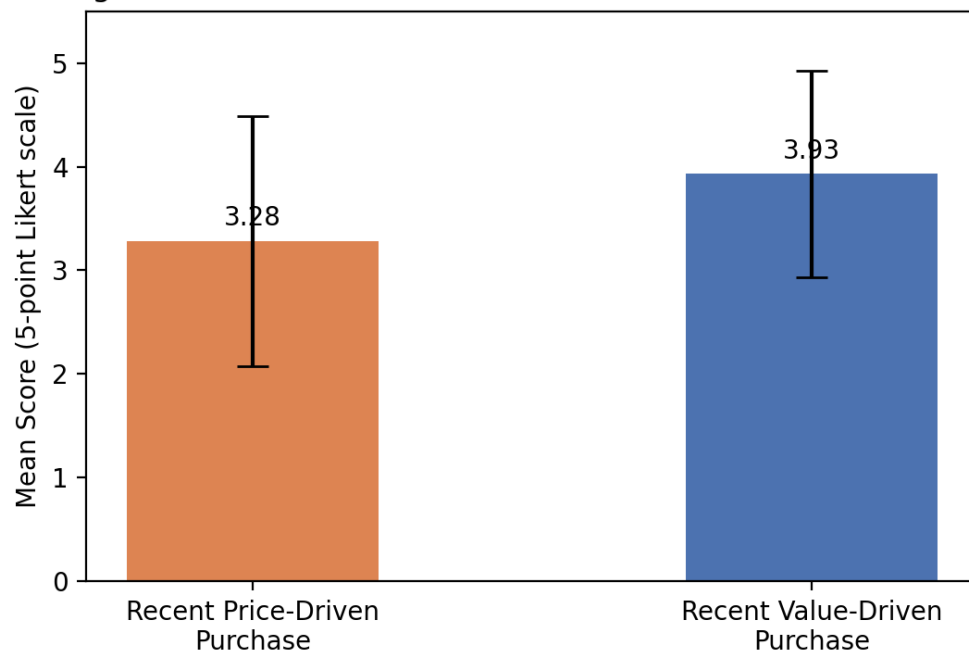


Figure 4.3: Comparison of Price-Driven and Value-Driven Purchase Behaviour

6.7.2 Paired-Samples t-Test

Table 4.17 Paired-Samples t-Test

Comparison Mean Difference t df Sig. (2-tailed) Price-Driven – Value-Driven -.647 -4.246 101 <0.001

95% Confidence Interval of the Difference: -.949 to -.345

Interpretation

The difference between price-driven and value-driven behaviour is statistically significant, $t(101) = -4.246$, $p < .001$. The negative t-value simply reflects SPSS calculating the difference as Price-Driven minus Value-Driven; since the value-driven mean (3.93) exceeds the price-driven mean (3.28), the negative sign confirms that value-driven behaviour is the higher-scoring, dominant orientation.

6.7.3 Conclusion for Objective 3

Objective 3 is supported. Although respondents show a measurable degree of price sensitivity, their reported recent purchase behaviour is significantly more value-driven than price-driven.

6.8 Overall Objective-Wise Statistical Summary

Table 4.18 Summary of Statistical Analysis by Research Objective

Objective	Statistical Technique	Key Result	Conclusion
Objective 1: Price sensitivity and purchase behaviour	Pearson correlation + Simple Linear Regression	$r = .542$; $\beta = .542$; $R^2 = .294$; $p < .001$	Supported
Objective 2: Value/Quality, Brand Trust and Social/Peer influence	Pearson correlation + Multiple Linear Regression	$R^2 = .354$; $p < .001$	Supported overall
Objective 3: Price-driven vs. Value-driven dominance	Descriptive statistics + Paired t-test	Value $M = 3.93$; Price $M = 3.28$; $t(101) = -4.246$; $p < .001$	Value-driven dominates

6.9 Overall Interpretation of the Data

Read together, the three objectives tell a single, coherent story rather than three separate ones. Respondents are not indifferent to price – Objective 1 confirms that price sensitivity is real and predicts price-driven behaviour ($R^2 = .294$) – and this is unsurprising given that three-quarters of the sample are students with a monthly income under ₹15,000 (Section 4.2). But Objective 2 shows that value/quality and, in particular, brand trust independently and more strongly explain value-driven behaviour ($R^2 = .354$), and Objective 3 settles the question the study set out to ask:

value-driven purchase behaviour ($M = 3.93$) is significantly higher than price-driven purchase behaviour ($M = 3.28$), $t(101) = -4.246$, $p < .001$.

A discriminant pattern from the correlation matrix (Table 4.4 and the item-level correlations underlying it) reinforces this reading: Brand Trust correlates strongly with Recent Value-Driven purchase ($r = .544$, $p < .001$) but is essentially unrelated to Recent Price-Driven ($r = .099$, $p = .322$). This is not a marginal result – it indicates Brand Trust behaves as a value-side constructs specifically, not as a general purchase driver, which strengthens the case that price-driven and value-driven behaviour for functioning as genuinely distinct orientations in this sample rather than two labels for the same underlying attitude.

The overall conclusion supported by this chapter's data is that Gen Z respondents in this urban Bengaluru sample are price-conscious but value-driven: they notice and compare prices, but when price and value pull in different directions, value – anchored specifically in product quality and brand trust – is what more consistently wins out in their reported recent purchases. Because the sample skews toward low-income students in the 21 – 23 age bracket (Section 4.2) and relies on convenience sampling, this conclusion is best framed as descriptive of that specific sub-segment rather than generalised to all Gen Z consumers in Bengaluru.

Chapter 5 builds on this summary table to state the study's findings formally against each objective; that chapter is addressed separately.

7. Findings

Objective 1 – Price Sensitivity to Price Driven Purchase

The variable price sensitivity is found to be an important determinant of price driven purchase behaviour ($r = .542$; $\beta = .542$; $R^2 = .294$; $F(1,100) = 41.700$, $p < .001$). The variable explains around 29% of the variance in price driven purchases of late. Objective 1 is established – yet the 75% of the sample being low-income students, it is true of only this sub-segment.

Objective 2 – Perceived Value → Value-Based Purchasing

Perceived Value ($\beta = .300$, $p = .006$) and Brand Trust ($\beta = .343$, $p = .002$) are two statistically significant, independent predictors of value-based purchasing behaviour, accounting for 35.4% of its variance ($R^2 = .354$; $F(3,98) = 17.940$, $p < .001$). The latter emerges as the most powerful single predictor of the construct. Although Social Influence is found to be associated with value-based purchasing behaviour ($r = .292$, $p = .003$), the association becomes insignificant after controlling for the effects of Perceived value and Brand Trust ($\beta = .033$, $p = .717$).

Objective 3 – Dominance of Price vs. Value Orientation

There is a significant difference between the value-driven purchases orientation (Mean = 3.93, Standard Deviation = 0.998) and price-driven purchase orientation (Mean = 3.28, Standard Deviation = 1.205), $t(101) = -4.246$, $p < .001$, 95% CI [-.949, -.345]. The correlation coefficient between the two orientations is very low ($r = .033$, $p = .743$), indicating that the two operate independently of each other.

Trust in Brand exhibits high correlation with value-based purchase ($r = .544$, $p < .001$), while there is practically no correlation between it and price-based purchase ($r = .099$, $p = .322$) – proving that Trust in Brand influences exclusively the value aspect of purchase.

8. Conclusion

This group of Gen Z participants within the Bengaluru sample is sensitive to pricing (Objective 1), but ultimately more oriented towards value than pricing itself, as when price and value are at odds, value wins out (Objectives 2 and 3). Sensitivity to price and value do not lie at opposite ends of the same continuum but are two distinct behaviours, both of which exist and differ in importance, but with value being the greater influencer on the recent purchases made by the participants.

Because of the skewed nature of the sample in terms of the demographic of low-income individuals between the age of 21 and 23 years (convenience sampling, $N = 102$, 76.5% students, 55.9% earning less than ₹5,000 a month), this should be regarded as a description of a particular sub-population.

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Patient Relationship Management as a Strategic Capability for Economic Sustainability in Ayurvedic Clinics

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ABSTRACT

The purpose of this research was to explore how Patient Relationship Management helped independent Ayurvedic clinics achieve economic sustainability in a resource-constrained environment. Conceptual research design was used in this study, with independent Ayurvedic clinics and theoretical literature used as the conceptual sample rather than empirical samples. Relationship marketing theory, resource-based view, service-dominant logic, health care service, and associated literature of Ayurveda were summarized into a conceptual system and propositions between Patient Relationship Management and economic sustainability. Results of analysis indicated that relationship mechanisms such as trust communication responsiveness, continuity of care leading to patient satisfaction, followed by patient retention also leading to repeat consultation, referral-based patient acquisition, in turn led to increased revenues enabled independent Ayurvedic clinics to achieve economic sustainability. Theoretical contributions of the study include 1) demonstrated the relevance of customer relationship management theories and models in the health care sector; 2) demonstrated the resource-as-asset approach to resources of health care service sectors; and 3) demonstrated the relationship capital as strategic resource of independent Ayurvedic clinics for sustainable long-term economic success. Practical implications include 1) proposed a setup for building patient relationships for independent Ayurvedic clinics; and 2) the suggested mechanisms through which the relationship capital could help independent Ayurvedic clinics achieve economic sustainability.

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1. Introduction

The health care industry is a shifting model first and foremost driven by technological advancements, increasing consumer expectations and widening competition within the industry. Patients are now more conscious, demanding, and accustomed to getting responsive and high-quality experiential service as in other sectors of the modern service industry. This has exerted external competition among health care providers both within the mainstream health care industry and outside in alternative and traditional health care systems like the Ayurveda (Bodeker & Kronenberg, 2002; Payyappallimana, 2010). The small and independent Ayurvedic clinics operate in this dynamic environment with constraints of economics and operating conditions (Ministry of Micro, Small and Medium Enterprises, 2024; Ramesh, 2023). Independent traditional clinics are usually constrained by resources of a smaller budget, fewer technological capacities, lower institutional support, while Ayurveda itself offers unique features and benefits when compared to mainstream health care system (Patwardhan et al., 2005). Ayurvedic health care is based on a relationship centered health care management way of thinking that is based on trust, continuity, and a high level of service. Ayurvedic treatment commonly involves long-term relationship with the patients with lifestyle modifications, behavior change, long-term consultations and follow-ups, and regime compliance. Because of this, good patient relationships are crucial in delivering positive health outcomes in Ayurveda (Rao et al., 2011; Shankar & Manohar, 2017). In contemporary business settings, Customer Relationship Management (CRM) has become one of

the most important managerial approaches to strengthening customer relationships and so gain competitive advantages (Buttle, 2004; Payne & Frow, 2005; Peelen & Beltman, 2013). Yet, in health care settings, CRM seems to have narrowed down to technology-based approaches like automation, analytics, and artificial intelligence for managing patients and service delivery (Baird et al., 2011). But, neglecting the non-technological approach does not seem right, mostly in independent Ayurvedic clinics. This paper aims at exploring how Patient Relationship Management (PRM) can be used as a strategic managerial capability to achieve economic sustainability. To be exact, the paper aims to establish that for low-tech health care settings, relationship-based managerial practices such as communication trust follow-ups and continuity of care are major determinants of patient retention and as a result, economic sustainability. So, this paper attempts to challenge the ideology of technology-based CRM by exploring how non-technological PRM strategy could be adopted as a managerial capability in independent Ayurvedic clinics.

2. Review of Literature

Conceptual ideas discussed in this paper are constructed based on various theoretical ideas and literatures. Relationship Marketing Theory is based on long-term relationships with customers instead of short-term focus (Berry, 1983; Morgan & Hunt, 1994). It's mainly about realization of customer delight, customer loyalty, trust, and value. RBV is one of the popular theories, which states that an entity can sustain a competitive advantage if it has resources and capabilities that are valuable, rare, inimitable, and non-substitutable (Dangelico et al., 2017; Ramesh, 2023). Service-Dominant Logic is a theory on exchange relationships, which is used as a tool to connect value co-creation between provider and consumer (Vargo & Lusch, 2004). SERVQUAL is a widely used service quality model, which assumes that service quality is the result of five dimensions: reliability, empathy, responsiveness, assurance, and tangibility (Parasuraman et al., 1988). These qualities are found together with its solution like communication, patient education and responsive patient care, providing the core cornerstone of patient relationship management (Dagger et al., 2007; Mosadeghrad, 2014).

2.1 Conceptual Evolution from CRM to PRM

In this context, there's an enormous gap of reference to the individual who incepted the concept of CRM the new definition of the CRM involves many dimensions like the new notion of the marketing management, the new marketing concept of the consumer customer, the management's ways to satisfy the customer needs and the rise of the CRM as an interactive, customer driven dynamics. Customer Relationship Management was first introduced as a business strategy for managing customers and cultivating long-term profitable relationships with them (Buttle, 2004; Payne & Frow, 2005). Conventional approaches and technologies of CRM are customer-centric and seek to maximize 'customer delight', lifetime 'value' and long-term 'loyalty' through the implementation of customer-focused systems and processes like customer database, multichannel communication, and sales-force automation (Peelen & Beltman, 2013). Though, the 'patient' relationships won't be able to be managed in the same way as the 'customer' relationships because 'patient' are not 'customers'. The doctor and patient relationship is built on dependence, trust, accountability, and even continuity of care (Andaleeb, 2001; Rao et al., 2011). So, CRM structures and implementing technologies need to be modified to meet the needs of health care market in the form of Patient Relationship Management. In short, the distinction between CRM and Patient Relationship Management is that CRM is motivated by customer satisfaction whereas the objective of Patient Relationship Management is patient satisfaction with building of long-term, trusting, and accountable relationship.

The description of the health care system itself indicate a holistic approach to treatment, with long consultation time and long term relationships with the patient Patwardhan et al. 2005 and Shankar & Manohar, 2017 (Patwardhan et al., 2005; Shankar & Manohar, 2017). Compared to the high tech short term relationships seen in the conventional, allopathic health care system, Ayurveda can be said to be "the long-doctor relationships" or even the "personal doctor connection". In the AYUSH sectors, studies evidence how the patient tends to remain loyal to a certain doctor for reasons like perception of doctor credibility, achieved health and personal attention (Bodeker & Kronenberg, 2002; Payyappallimana, 2010; Rao et al., 2011). Because of this, for an Ayurvedic treatment, the relationship with the patient plays an important role in service delivery. This is an even more relevant aspect of service management in

the Ayurvedic independent practice, where the patient retention and referrals constitute the main source of the ongoing business. Studies of quality in health care services have also highlighted the effectiveness of relationship mechanisms like communication, responsiveness, and trust in health care service delivery (Andaleeb, 2001; Mosadeghrad, 2014). On top of the importance of general mechanisms of relationship building, Ayurvedic health care is also known for more interpersonal communication and consultation between patient and practitioner. In this aspect, Patient Relationship Management draws from Customer Relationship Management, health care Relationship Management and Relationship Marketing to work as the theoretical foundation for managing patient relationships in Ayurvedic clinics. More in particular, Patient Relationship Management is focused on communication and consultation, trust, and relationship-building and focusing on long term relationships with patients in Ayurveda. Because of this when it comes to Ayurvedic health care, the economic sustainability is mainly driven by building effective and long lasting patient relationships.

3. Theoretical framework

Patient Relationship Management (PRM) in within competitive environment wherein the playing field is shared by mainstream hospital and corporate healthcare organizations who enjoy competitive advantages vis-à-vis independent clinics (Ministry of Micro, Small and Medium Enterprises, 2024). The technologically and financially resource-constrained independent Ayurvedic clinics find it difficult to compete effectively against corporate players or other extensively resource endowed corporate competitors. Most of the literature on HealthCare Relationship Management has been about the large systems or institutional health care organization CRM deals (Baird et al., 2011; Payne & Frow, 2005). The focus on institutional health care organization makes the role of relationship management based practices for sustain ability of low-tech independent Ayurvedic clinics less understood. Lack of good Patient Relationship Management mean missed opportunities for good patient retention, continuance of care, good follow-up culture and ultimately poor revenues. This signifies the need to investigate how Relationship Management Practices in the form of Patient Relationship Management (PRM) can be harnessed to bring about the advantages of competitive advantage, and Next ensure economic sustainability.

4. Operationalising the Concept of Economic Sustainability

In an independent Ayurvedic clinic context, the concept of economic sustainability refers to the ability of the clinic to sustain its operations and delivery of services to patients despite the competition prevailing in the healthcare industry. Different from the big corporate hospitals, independent Ayurvedic clinics relied mostly on patient retention and referral systems for continuous change and economic sustainment. The operational model of economic sustainability, adopted to this research, can be expressed through Patient Retention Rate, Repeat Client Visits, number of Patient Referrals, Revenue Productivity, Average Revenue per Patient, Clinic Surviving Status, ensuring the continuous productivity of the clinics. Based on this model, we can make these conceptual statement that can be a model to determine the meaning of economic sustainability when talking about this research: "A clinic will be considered economically sustainable when it has the ability to maintain enduring flow of patients and revenues for its survival and growth". The indicators mentioned above can be used to measure the degree of achievement of this sustainability in one specific Ayurvedic clinic. People assume when the independent Ayurvedic clinics experience high rates of Patient retention and referrals, they will earn stable revenues; that means, this study presumed economic sustainability as being achieved in the independent Ayurvedic clinics. This hypothesis was formulated as an estimate, which people think is supported by the data of this research:

H1: Patient Relationship Management Practice will impact on patient satisfaction, patient retention and this way the economic sustainability of independent Ayurvedic clinics. Following the theoretical discussion above, to define IBSM we could use Patient Relationship Management on the basis that it's a strategic organizational capability that could be useful in supporting the economic sustainability of independent Ayurvedic clinics. This study, proposed this hypotheses for examination:

H2: communication quality of Patient Relationship Management will be positively related to patient satisfaction on independent Ayurvedic clinics (Andaleeb, 2001; Mosadeghrad, 2014) (Andaleeb, 2001).

H3: trust will be positively related to patient satisfaction on independent Ayurvedic clinics (Morgan & Hunt, 1994; Rao et al., 2011).

H4: responsiveness will be positively related to patient satisfaction on independent Ayurvedic clinics (Parasuraman et al., 1988).

H5: personalized care will be positively related to patient satisfaction on independent Ayurvedic clinics (Patwardhan et al., 2005).

H6: Patient satisfaction will be positively related to patient retention (Andaleeb, 2001; Gupta & Lehmann, 2003).

H7: Patient satisfaction will be positively related to patient referral intentions and positive word of mouth (Berry, 1983; Morgan & Hunt, 1994).

H8: Patient retention will be positively related to the economic sustainability of independent Ayurvedic clinics (Gupta & Lehmann, 2003).

H9: patients' retention will be positively related to patient referrals and Repeat Consultation Frequency of independent Ayurvedic clinics.

H10: Patient satisfaction will mediate between Patient Relationship Management and patient retention (Dagger et al., 2007).

H11: Patient retention will mediate between Patient Relationship Management and economic sustainability.

H12: The use of as a strategic organizational capability of Patient Relationship Management will be positively related to the economic sustainability of independent Ayurvedic clinics. These hypotheses in the present paper are illustrating the benefit of Patients' Relationship Management as a strategic organizational capability for improving the economic sustainability of independent Ayurvedic clinics. Primarily, it's predicting that following Patient Relationship Management practices will lead to higher patients' satisfaction and retention that eventually yield more revenues and because of this a higher economic sustainability.

Patient Relationship Management Practices >> Patient Satisfaction>> Patient Retention>> Economic sustainability

5. Patient Relationship Management Practices

5.1 Mediating Variable: Patient Satisfaction

Patients' Satisfaction reflects the extent to which patients believe that their expectations have been met or exceeded (Andaleeb, 2001; Parasuraman et al., 1988). Because of this, if the PRM practices are implemented effectively then it should result in higher levels of patient satisfaction since they're focused on communication consultation care personalization and building permanent relationships with patients. Patient retention signifies the capacity of the clinic to retain its existing clientele (Bhatnagar, 2007; Sivakumar & Thiyagarajan, 2024). It measures how well a clinic manages to persuade patients to revisit for a follow-up visit or otherwise. Patient retention is shown to be an important component of the long-term economic viability of an independent Ayurvedic clinic. The mediating variables are separated into Patient Satisfaction and Patient retention. The literature suggests that a successful PRM practice will influence economic sustainability mainly through these two variables. These variables influence revenues mainly through the increase in Patient Satisfaction and Patient Retention bringing sustainable revenues.

5.2 Dependent Variable

5.2.1 Dimensions of Patient Relationship Management

The study conceptualized Patient Relationship Management in terms of the following dimensions:

Fig. 1. Dimensions of patient relationship management.

PRM Dimensions	Description
Communication Quality	Clarity, Empathy, Responsiveness
Personalised care	Individual attention and personalised guidance
Continuity of practice	Follow up system and treatment tracking
Trust Building	Transparency and emotional assurance
Service Environment	Comfort, hygiene, reception quality
Patient Engagement	Education and participatory care
Responsiveness	Timely communication and support

6. PRM and Economic Sustainability

In the paper it's argued that properly managing PRM practices in an efficient manner can bring economic sustainability. This means that, retained patients not only generate high and steady revenues but also imply lesser expenditure on the clinic's efforts of attracting new ones (Gupta & Lehmann, 2003). Thanks to word-of-mouth growth of satisfied patients resulting in increased demand (Berry, 1983) reputation improves, and clinic flow increases patients who are satisfied with and understand their condition are less likely to discontinue treatment. Well-informed and engaged patients should go through the entire multi-year treatment cycles. Longer-term relationships with patients allow predictable consultation flow and income few use a lot of technology and utilise customer relationship management (CRM) to optimise a business' profitability and doctor productivity (Baird et al., 2011; Peelen & Beltman, 2013).

6.1 Practical PRM for Low-Tech Ayurvedic Clinics

A low cost, practical system of Patient Relationship Management (PRM) focusing on relationship-based and patient-centred care that does not involve expensive digital CRM tools or patient segmentation techniques. With its unique skills in delivering Ayurvedic healthcare (focus not only on the medical but also the social context)

6.1.1 Patient Acquisition

An Ayurvedic clinic can grow through promotion of its services and shared interest of its patients to the health and wellbeing and community-oriented living (Gupta & Lehmann, 2003). Clinics can build health awareness programmes on WhatsApp to share information and educate people around using its services for long-term treatment. Increase visibility on Google business profiles so more people can find it when people search for health services online. Activities Like community health camps, wellness event's and other pillar effective mechanism to boost the reach and convince practitioner's competency costs that encouraging the happy customer – patient referrals and maintaining regular network with the community. local dwellers can be instrumental in acquiring the customer at lower costs. Making patient engagement the core – pillar of Patient Relationship Management (Sivakumar & Thiagarajan, 2024; Vargo & Lusch, 2004) Ayurvedic treatment last lengthier duration and enables conducting effective engagements with the patient than actual talking to the patient in the formal visit and examining them. Addressed with accountability; casual discussions around treatment progress, Life style changes, the balanced diet and diagnostic preventive with present health state can add on the participation. Through providing the educational material through call/sms/message and following up individually for refresher and appointment reminders. The Consultation clarification, and repeat checkup reminds further helps in patient active participation. Communication as management is all to Patient Relationship Management practical experience to improve. In lack of resources in form of technological tools in may effective practices low cost WhatsApp Business can be.

7. Other Significant Contributions

This paper redefines the concept of Patient Relationship Management (PRM) away from being technology driven application of Customer Relationship Management (CRM) principles (Buttle, 2004; Payne & Frow, 2005) to a strategic capability in healthcare organizational context. Unlike the mainstream CRM literature, which has yet to seriously focus on relationship management in healthcare setting, the present study suggests that PRM in independent Ayurvedic clinics rests in the practitioner–patient relationship, trust building, continuity of care, personalized contact and long term relationship building (practitioner–patient) apart from technology driven CRM tools. The current study also suggests long term relationship centered managerial practices would have a positive influence on patient satisfaction compliance recollection and recommendation behavior, which are relatively more critical for Ayurvedic clinics where treatment success is not only based on the efficacy of Ayurveda but also on the continuity of practitioners–patients relationship (Shankar & Manohar, 2017). Through the current conceptualization of PRM, I postulate that in resource constraint healthcare environment, which is a paucity of advanced technological needs, massive advertising campaigns and large marketing budgets, relationship management capabilities could provide an alternative source of sustainable competitive advantage and business performance.

8. Discussion

The fruitful practitioner–patient relationships could induce not only multiple repeat visits, and positive word-of-mouth recommendations, but also patient loyalty that would help to lessen dependence on costly marketing practices and technological over-advancement. To make these theories operational for managerial practice, the paper suggests a practical system of PRM to cover various marketing tools, namely communication management, patient involvement, continuity-of-care, follow-up tracking, trust building and service quality improvement. Together these arguments establish that Patient Relationship Management will function as an essential strategic organizational capability that improves therapeutic outcomes and organizational effectiveness of the independent Ayurveda clinics. Extending traditional CRM theory into the subject-specific practice of Patient Relationship Management, this paper has contributed new insights into the burgeoning body of healthcare management literature, as well as provided a conceptual base in the direction of future empirical investigations.

Significance of the system and, besides adding to field and action research, the outlined system is also significant of practical importance to the owners of clinics and healthcare providers who want to develop existing levels of patients' loyalty, service quality and economic sustainability in developing low technology and low resource healthcare settings. The structure proposes that CRM of Patients' Relationship Management (PRM) in independent Ayurvedic clinics should be developed as a competency of strategic organization rather than a routine activity function. In independent Ayurvedic clinics' under high relationship orientation, patient relationships can be a strategic resource and source of sustainable competitive advantage built on trust, continuity, and customers'/patients' loyalty. Unlike traditional and automation driven CRM systems in western healthcare systems, almost all Ayurvedic clinics rely heavily on face-to-face interpersonal approach to the delivery of service and the relationship with customers.

Because of this, the setup expanded CRM concept into resource-scarcity culture dominated healthcare environments where human relationships are organizational resource resources and the carriers of competitive advantage. This system implies that relationship capital derived from successful implementation of PRM activities will contribute to patients' higher satisfaction levels, higher propensity to repeat visits, stronger referrals, and more sustainable profit contribution to Indian Ayurvedic clinics. In this way, the system offers a way of thinking shift from transactional healthcare perspectives toward the relational operational logic of healthcare (Berry, 1983; Vargo & Lusch, 2004).

9. Contributions to the Literature

1. Firstly, it demonstrates the extension of traditional CRM theory into a healthcare-specific Patient Relationship Management setup appropriate for relationship-intensive healthcare contexts (Payne & Frow, 2005; Peelen &

Beltman, 2013). , 2017; Ramesh, 2023). , 1988) into a comprehensive theoretical conception of Ayurvedic healthcare sustainability.

2. Fourthly, it advances the theoretical domain of healthcare relationship management studies by conceptualising economic sustainability as another PRM outcome (Gupta & Lahmann, 2003).

10. Managerial Implications

The proposed structure has several managerial implications for independent Ayurvedic clinics in resource-limited contexts. To begin with, clinics should implement formal patient follow-up processes to maintain continuity of care and develop durable patient relationships. Formal follow-up processes can help treatment adherence, improve customer satisfaction and generate repeat visitation. Secondly, practitioners, and administrative staff should be equipped considering the inherent palliative and relationship-centred approach to Ayurvedic health care, interaction quality should be a key driver for patient satisfaction and loyalty.

Clinicians should also focus on establishing and maintaining continuity of care through regular monitoring, personalised advice and on-going practitioner contact. Such touch points contribute to community building and familiarity with Ayurvedic doctors and vice versa. , 2005) Research finds further that low-resource clinics can improve non-clinical environments by introducing low-cost and efficient digital communication apps like WhatsApp Business or simple mobile phone-cum-computer based patient records database to achieve the benefits of modern technology without jeopardising the holistic nature of Ayurvedic practice. Lastly, full interactive services characterised by adequate hygiene and comfort, courteousness, and professionalism of staff, appreciation, and respect for each patient should be promoted.

Perception of services arises not only from experience of health outcomes but also the environment of the health care service delivery process. Mechanisms for management of patient feedback and complaints should also be developed to truly boost and continuously improve patient satisfaction. So, these results support a view that PRM should be considered a strategic imperative on top of being an operational activity that can be instrumental in providing sustainable economic viability over the long term. This conceptual setup presented here remains untested empirically (Kothari & Garg, 2019); perhaps the nature of PRM relationships in these studies might also be influenced by variations across clinic size, practitioner experience, geographic location, patient profiles, or practice orientation integrative versus non-integrative.

Future empirical research should study such contextual moderators of the conceptual system of PRM. My conceptual argument is that managerial PRM capability represents a sustainable long-term competitive advantage in a low-technology Ayurvedic healthcare context. Unlike a technologically-centred, infrastructure-driven hospital where competition rests on diagnostics capacity robotics, and automation, independent Ayurvedic clinics survive through the twin pillars of trust and hierarchy of relational benefits, mostly continuous, ongoing relationships where emotion and care are central. So, PRM cannot be perceived simply as the adoption of a package of software but represents a strategic managerial orientation that is pervasive and intangible and infuses every stage of the interactive process.

Clinics with superior PRM capabilities will probably outperform financially even more clinically superior but relationally weaker competitors as prescriptive treatment regimens can result in greater patient adherence, positive word-of-mouth, and increased loyalty related to provider consistency and patient-trust (Berry, 1983; Morgan & Hunt, 1994). Finally, the paper implies that in mainstream healthcare systems where technology is mostly focused, relationship centered management could offset technological shortcomings for long-term viability of the clinics. While the current study brings conceptual underpinnings to develop a position of understanding of Patient Relationship Management as a strategic capability of the independent Ayurvedic clinics, there are several avenues for further research. Perhaps the most significant avenue would be to empirically test the proposed conceptual system by conducting qualitative and quantitative studies with Ayurvedic practitioners and their patients.

11. Limitations and Directions for Future Research

Future research would involve developing and validating a questionnaire to measure ad hoc Patient Relationship Management practices adopted by the holistic therapists in the traditional healthcare context. Such research instruments are needed to conduct a rigorous empirical test of relationships as indicated by the current system. Studying Ayurveda healthcare systems and other healthcare systems (including that of allopathic healthcare) like AYUSH sector to compare the effectiveness of relationship centered practices as a strategic capability would be noteworthy. Same here, conducting studies on the influence of regional/cultural/demographic variations on the effectiveness of Physician-Patient relationships on the Practitioner-Patient Relationship Management processes and outcomes would help improve understanding of the factors influencing their dynamics.

Finally, future research could employ advanced quantitative measures, like Structural Equation Modelling (SEM), to test the direct and indirect links between the PRM factors, the practitioner-patient relationship, business outcomes such as business retention, patient satisfaction and the long-term, economic sustenance aspect of the Ayurvedic clinics.

12. Conclusion

This research extends mainstream CRM theory and models with a focus on healthcare relationships and claim that under a low-technology treatment environment like Ayurveda trust continuity, customization, and participation have emerged as effective measures of the sustainability of a healing process (Berry, 1983; Patwardhan et al., 2005; Payne & Frow, 2005).PRM can exist as a relationship management ideology instead of an enterprise-wide information technology support system with a perspective of sustainable competitive advantage for long-term holistic care management and economic success by creating more value in patient satisfaction, length of relationship, positive WOM, and returns on investments. Knowing PRM in a brand-new managerial way in this research by positioning PRM as a relationship centric philosophy helps to extend theory on a healthcare format in the future and also contributes a practical insight for Ayurvedic clinics.

Indo-German Collaboration in Green Technology: Pathways to Global Sustainable Development

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ABSTRACT

Environmental sustainability has, over the years, become one of the key pillars on which international partnerships are being built. Countries around the world are leaning into it --- not just as a moral imperative but as a practical pathway to fight climate change, shift toward cleaner energy, and pursue growth that does not come at the planet's expense. Within this broader trend, the Indo-German relationship offers a particularly interesting case. Both nations have made sustainability a centerpiece of their cooperation, yet the question of how deeply this commitment actually runs --- and what it looks like on the ground --- has not been explored as thoroughly as one might expect. Most of the existing literature stays at the level of policy dialogue and diplomatic frameworks. What is less understood is how bilateral partnerships translate into tangible corporate sustainability performance. That gap is what this study sets out to address, by examining the role environmental sustainability plays in strengthening Indo-German ties --- through the specific channels of green technology, renewable energy, climate finance, and sustainable development.

The study follows a descriptive and comparative case study design and relies entirely on secondary data gathered between 2021 and 2025. At the policy level, the analysis is anchored in the Green and Sustainable Development Partnership --- the flagship bilateral agreement between India and Germany. At the corporate level, it examines the comparative sustainability profiles of four selected firms: RWE AG and thyssenkrupp nucera from Germany, and Reliance Industries Limited and Adani Green Energy Limited from India. The comparison draws on a range of indicators spanning financial performance, environmental outcomes, operational metrics, and green technology adoption.

What the findings reveal is that environmental sustainability has moved well beyond rhetoric in the Indo-German context --- it now represents a genuinely substantial area of engagement.

At the same time, the two sides bring different strengths to the table. German firms tend to lead on technological advancement, green hydrogen capabilities, R&D intensity, and the maturity of their sustainability reporting. Indian firms, on the other hand, stand out in the sheer scale of their renewable energy operations and their capacity to pull off large-scale infrastructure projects at speed. The most promising avenues for deeper cooperation between the two countries include green hydrogen, renewable energy deployment, climate finance, technology transfer, and joint research. That said, real challenges remain. Legal and regulatory frameworks are not always in sync. The cost of green technology is still high. Financing mechanisms are not as accessible as they need to be. Workforce readiness varies across sectors, and ESG reporting standards differ in ways that make cross-country comparisons difficult.

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1. Introduction

Environmental sustainability has become one of the most important priorities for governments, businesses, and international organizations as the world continues to face climate change, biodiversity loss, and increasing environmental degradation. Sustainable development requires countries to balance economic growth with environmental protection while ensuring social well-being for present and future generations. As global environmental challenges become more complex, international cooperation has emerged as an essential strategy for promoting clean technologies, reducing greenhouse gas emissions, and achieving the Sustainable Development Goals (SDGs).

India and Germany have developed a strong strategic partnership in the field of environmental sustainability over the past several years. Germany is recognized globally for its leadership in renewable energy, green hydrogen, environmental governance, and advanced sustainable technologies. India, on the other hand, has become one of the fastest-growing economies while making significant investments in renewable energy, solar power, wind energy, electric mobility, and climate-resilient infrastructure. Through initiatives such as the Green and Sustainable Development Partnership (GSDP), both countries have strengthened cooperation in areas including clean energy, green hydrogen production, climate finance, circular economy practices, sustainable urban development, and technological innovation.

The growing collaboration between India and Germany demonstrates how international partnerships can accelerate sustainable economic development while addressing environmental challenges. Germany contributes advanced technological expertise, financial assistance, research capabilities, and policy frameworks, whereas India provides large-scale implementation opportunities, expanding renewable energy markets, and manufacturing capacity. This complementary relationship enables both countries to exchange knowledge, develop innovative environmental solutions, and promote sustainable industrial development.

At the corporate level, sustainability has become a strategic priority for organisations seeking long-term competitiveness and responsible business growth. Companies increasingly invest in renewable energy projects, carbon emission reduction, environmental, social and governance (ESG) initiatives, green hydrogen technologies, and sustainable manufacturing processes. Organisations such as RWE AG, thyssenkrupp nucera, Reliance Industries Limited, and Adani Green Energy Limited represent significant contributors to sustainable development within their respective countries through continuous investment in clean energy technologies and environmental innovation.

Despite considerable progress, several challenges continue to affect Indo-German environmental cooperation. Differences in regulatory frameworks, sustainability reporting standards, climate financing mechanisms, technological costs, and policy implementation create barriers to achieving greater collaboration. Furthermore, rapidly changing environmental regulations and increasing global sustainability expectations require governments and corporations to continuously innovate while maintaining economic competitiveness.

The increasing importance of sustainability has also generated significant academic research focusing on renewable energy development, ESG performance, climate policy, green technology, and international environmental partnerships. However, relatively fewer studies have comprehensively examined Indo-German sustainability cooperation by integrating bilateral policy initiatives with comparative corporate sustainability performance. Therefore, this study aims to provide a holistic understanding of environmental sustainability in Indo-German relations by examining government initiatives, corporate sustainability performance, green technology cooperation, and future opportunities for strengthening bilateral environmental collaboration

2. Literature Review

Various scholars have investigated the strategic alliance between India and Germany, focusing on renewable energy projects, climate finance mechanisms, and international cooperation in green technology. These investigations offer significant perspectives on how geopolitical partnerships, innovative technologies, and bilateral commerce contribute to the advancement of global sustainable development.

Kuszevska-Bohnert (2025) analyzed the transformation of German policy toward India, shifting from an economic emphasis to a comprehensive partnership that highlights security, democratic principles, and the green economy. The research noted that shifting global geopolitics compel both nations to prioritize security and supply chain resilience, with sustainability serving as a foundational element of their cooperation. The study determined that integrating India's developmental potential with Germany's technical proficiency is vital for tackling global issues, despite persistent difficulties in aligning national interests with varied political strategies.

García Bermejo (2023) explored the transition of Indo-German relations from a conventional donor-recipient model to a strategic alliance centered on renewable power and digital networks. The inquiry observed that Germany provides assistance through organizations such as BMZ, KfW, and GIZ, emphasizing environmental and social systems in India, including the KfW-funded Sakri Solar Power Plant. It was concluded that collaborative efforts, aligned with the EU Green Deal, effectively lower emissions while delivering clean energy and fostering sustainable urban growth.

Kuszevska-Bohnert (2025) contended that Germany is transitioning from its traditional role as a civilian power toward pragmatic realism, influenced by a multipolar environment and international conflicts. The analysis mentioned that via the 2024 "Focus on India" framework, Germany identifies India as a crucial democratic partner in the Indo-Pacific, seeking intensified cooperation in defense, commerce, and environmental sectors. The report concluded that Germany emphasizes strategic defense and connectivity to assist India against regional pressures, notwithstanding ideological differences regarding democratic governance.

Chakravorty (2023) mapped regional advancements in India regarding SDG 7 objectives for accessible and clean power. The document noted that while national electrification has improved, significant geographic gaps remain in clean fuel access and regional energy distribution. It determined that resolving these disparities requires addressing underperforming utility providers and expanding local solar initiatives rather than just implementing national policies, pointing to effective state-level models.

Jaspal (2024) detailed India-EU discussions on green recovery, noting that public funding for climate action is insufficient and requires private investment. The study analyzed the disagreement over the EU's Carbon Border Adjustment Mechanism (CBAM), viewed by India as a trade barrier while the EU deems it necessary for preventing carbon leakage. It was concluded that developing compromises, like shared reporting standards within "Climate Clubs," is essential for drawing private capital into low-cost markets for emission reduction without causing unilateral tension.

Agarwal (2024) investigated the evolution of India and Germany from a distant post-Cold War relationship to a robust alliance focused on trade, technology, and global solutions. The research noted that the partnership pairs India's massive market and workforce with Germany's industrial expertise and clean energy solutions. It concluded that future reliability in supply chains and sustainable growth depends on deeper integration to produce scalable environmental manufacturing solutions.

Aithal and Aithal (2016) described the vital role of green technology in mitigating pollution and climate change while driving economic expansion. The paper noted that implementing sustainable practices in renewable energy and waste management generates business prospects, fosters innovation, and enhances organizational sustainability. It concluded that sustained government backing through financial incentives and research funding is necessary to manage high costs and achieve widespread adoption in the current century.

Saravanan (2026) evaluated two decades of trade data, identifying Germany as a primary economic ally for India in the European Union. The study showed steady growth in bilateral trade despite global economic shifts, with India providing engineering and IT services while importing German machinery and environmental technologies. It determined that addressing trade obstacles and regulatory variations is vital for expanding this economic alliance and providing mutual benefits to both nations.

The Observer Research Foundation and Konrad Adenauer Stiftung (2024) explored the increasing cooperation between India and Germany to mitigate climate change and support responsible global development. The report noted that the alliance focuses on digital shifts and green innovation, combining German clean tech with India's growing economy. It concluded that bridging investment deficits and policy gaps is essential for strengthening this partnership and promoting international green multilateralism.

Kumar (2026) examined how India and Germany collaborate on development initiatives in African nations through triangular cooperation. The policy brief noted that this model merges Germany's technical and financial resources with India's cost-effective solutions and experience in the Global South in sectors like healthcare and renewable energy. It concluded that improved coordination, ongoing dialogue, and defined institutional roles are required to manage funding hurdles and foster inclusive sustainability in Africa.

The existing literature demonstrates that environmental sustainability has become a major focus of international cooperation. While numerous studies examine renewable energy, climate policy, ESG reporting, and green technologies individually, limited research integrates bilateral government initiatives with comparative corporate sustainability performance.

2.1 What previous studies covered

The reviewed literature indicates that previous studies have extensively examined renewable energy development, climate policy, ESG reporting, green hydrogen technologies, sustainable infrastructure, and Indo-German environmental cooperation. Similarly, international organizations such as OECD, IEA, UNEP, World Bank, and NITI Aayog have emphasized the importance of sustainability, climate finance, and technological innovation in achieving sustainable development.

3. Research Gap

However, the existing literature primarily investigates these themes separately. Most studies focus either on bilateral policy initiatives or on corporate sustainability practices. Limited research integrates government-level sustainability cooperation with a comparative assessment of Indian and German companies using financial, environmental, and sustainability indicators. Furthermore, very few studies simultaneously evaluate bilateral cooperation, corporate sustainability performance, and future opportunities and challenges within a single analytical framework.

3.1 How our study fills the gap

To address this gap, the present study combines policy-level analysis with a comparative evaluation of selected Indian and German companies. The study examines bilateral sustainability initiatives while assessing corporate sustainability performance through selected financial, environmental, and green technology variables. This integrated approach provides a broader understanding of the contribution of Indo-German collaboration toward sustainable development.

4. Objectives of the Study

The present study has been undertaken to examine the growing importance of environmental sustainability in Indo-German relations by analyzing bilateral cooperation, corporate sustainability performance, and future opportunities in green technology. The specific objectives of the study are:

1. To examine the role of environmental sustainability in strengthening Indo-German bilateral relations through green technology cooperation, renewable energy initiatives, and sustainable development policies.
2. To examine the comparative sustainability profiles of selected Indian and German companies using environmental, operational, financial, and sustainability indicators.
3. To identify the opportunities and challenges associated with Indo-German collaboration in renewable energy, green hydrogen, climate finance, and sustainable industrial development.

5. Research Methodology

5.1 Research Design

The present study adopts a descriptive and comparative research design to examine environmental sustainability in Indo-German relations. The research investigates how bilateral cooperation between India and Germany promotes renewable energy development, green technology innovation, climate action, and sustainable economic growth. A comparative analysis has also been conducted to evaluate the sustainability performance of selected Indian and German companies operating in the renewable energy and green technology sectors.

The study is based entirely on secondary data collected from authentic and reliable sources. The descriptive approach helps explain the existing sustainability initiatives and bilateral partnerships, while the comparative approach enables an evaluation of corporate sustainability performance across both countries. This research design provides a comprehensive understanding of the contribution of governments and businesses toward achieving environmental sustainability.

5.2 Scope of the Study

The study focuses on the environmental sustainability partnership between India and Germany. It examines bilateral initiatives such as GSDP, climate finance, renewable energy collaboration, and technology transfer, along with the sustainability performance of selected Indian and German companies. The analysis is based on secondary data covering the period from 2021 to 2025.

5.3 Research Questions

In accordance with the aforementioned objectives, this investigation is directed by the following research inquiries designed to explore the dimensions of Indo-German environmental partnership:

RQ1: In what ways has the focus on environmental sustainability enhanced the strategic alliance between India and Germany through advancements in green technology and renewable power ventures?

RQ2: To what extent do representative corporations from India and Germany differ when evaluated against financial, operational, and ecological sustainability metrics?

RQ3: Which primary drivers and systemic barriers impact the progression of bilateral efforts in areas such as climate finance, green hydrogen development, and renewable energy infrastructure?

5.4 Sample Selected

The study focuses on four leading companies that actively contribute to renewable energy development, green technology, and sustainable business practices in India and Germany.

5.5 Selected Companies

- RWE AG (Germany) → large-scale renewable-energy generation
- Thyssenkrupp nucera (Germany) → electrolyzer/green-hydrogen technology
- Reliance Industries Limited (India) → large-scale Indian investment in renewable and emerging clean-energy technologies
- Adani Green Energy Limited (India) → large-scale renewable-energy deployment in India

5.5.1 RWE AG

RWE AG is a leading German energy company headquartered in Essen, Germany. Founded in 1898, the company has transformed itself into one of Europe's largest producers of renewable energy through significant investments in offshore wind, onshore wind, solar power, battery storage, and green hydrogen projects. RWE plays a major role in Germany's energy transition and has established ambitious carbon reduction targets aligned with international climate goals. The company was selected for this study because of its leadership in renewable energy generation,

strong ESG initiatives, and comprehensive sustainability reporting, making it an appropriate representative of Germany's green energy sector.

5.5.2 Thyssenkrupp nucera

thyssenkrupp nucera AG & Co. KGaA is a German green technology company headquartered in Dortmund, Germany. It specializes in industrial-scale water electrolysis systems for green hydrogen production and is recognized as a global leader in hydrogen technologies. The company invests heavily in research and innovation to support industrial decarbonization and the transition to clean energy. It was selected for this study because of its technological leadership in green hydrogen and its relevance to Indo-German cooperation in sustainable industrial development.

5.5.3 Reliance Industries Limited

Reliance Industries Limited (RIL) is an Indian multinational conglomerate headquartered in Mumbai, India. Founded in 1973, the company has expanded beyond petrochemicals and refining into renewable energy, solar manufacturing, green hydrogen, battery storage, and clean energy infrastructure. Through its New Energy business, Reliance aims to support India's transition toward a low-carbon economy. The company was selected due to its substantial investments in green technologies, large-scale sustainability initiatives, and strategic role in India's renewable energy sector.

5.5.4 Adani Green Energy Limited

Adani Green Energy Limited (AGEL) is one of India's largest renewable energy companies, headquartered in Ahmedabad, Gujarat. Established in 2015, the company develops, owns, and operates utility-scale solar, wind, and hybrid renewable energy projects across India. AGEL has rapidly expanded its renewable energy capacity and plays a significant role in helping India achieve its clean energy targets. The company was selected because of its leadership in renewable energy deployment, extensive sustainability initiatives, and strong contribution to India's green energy transition.

The selected companies were chosen using purposive sampling because they represent leading organizations in renewable energy and green technology in their respective countries. They have significant investments in sustainability, regularly publish annual and sustainability reports, and actively participate in renewable energy and green hydrogen initiatives. Their publicly available disclosures make them suitable for comparative analysis.

These companies have been selected because of their significant investments in renewable energy, green hydrogen technologies, environmental sustainability, and innovation. They also provide sufficient publicly available information through annual reports, sustainability reports, and investor publications, making them suitable for comparative analysis.

The study further examines the environmental cooperation between India and Germany, particularly under initiatives such as the Green and Sustainable Development Partnership (GSDP), renewable energy collaborations, and climate-focused policy frameworks.

5.6 Sources of Data

The present study is based exclusively on secondary data collected from various reliable and authentic sources. Information has been gathered from:

- Annual Reports
- Sustainability Reports
- ESG Reports
- Official Company Websites
- Government Publications
- Ministry of External Affairs Reports

- Green and Sustainable Development Partnership (GSDP) documents
- International Energy Agency (IEA) Reports
- OECD Publications
- United Nations Environment Programme (UNEP) Reports
- World Bank Reports
- Research Journals
- Industry Reports
- Business Publications

The collected information includes financial performance, renewable energy capacity, carbon emissions, ESG performance, green investments, sustainability initiatives, environmental policies, and bilateral cooperation projects between India and Germany.

5.7 Justification for Company Selection

The four companies were purposively selected because they represent important dimensions of the India–Germany green-transition relationship. RWE AG represents large-scale renewable-energy generation in Germany; thyssenkrupp nucera represents green-hydrogen and electrolyzer technology; Reliance Industries Limited represents large-scale Indian investment in renewable and emerging clean-energy technologies; and Adani Green Energy Limited represents large-scale renewable-energy deployment in India. The companies were also selected because substantial information is publicly available through annual reports, sustainability reports, ESG disclosures, and investor publications covering the 2021–2025 study period.

5.8 Indicators Selected and Measurement Framework

For the purpose of analysis, **twelve variables** have been selected to evaluate corporate sustainability performance and Indo-German collaboration in green technology and sustainable development. The selected variables are:

Dimension	Indicator	Measurement
Bilateral cooperation	GSDP	Qualitative assessment
Technology	Technology transfer	Qualitative evidence
Renewable energy	Renewable/clean-energy capacity	GW, where applicable
Financial	Revenue	USD billion
Financial	Net profit	USD billion
Environmental	Scope 1+2 emissions	MtCO ₂ e
Sustainability	ESG score	Published ESG rating/score
Investment	Green investment	USD billion, where available
Hydrogen	Hydrogen projects	Number/status
Innovation	R&D	Reported expenditure/evidence
Climate finance	Climate finance	Qualitative/financial evidence
Cooperation	Renewable-energy collaboration	Qualitative evidence

The four companies were purposively selected because they represent important dimensions of the India–Germany green-transition relationship. RWE represents large-scale renewable-energy generation, thyssenkrupp nucera represents green-hydrogen and electrolyzer technology, Reliance Industries represents large-scale Indian investment in renewable and emerging clean-energy technologies, and Adani Green Energy represents large-scale renewable-energy deployment in India.

Because the selected companies operate under different business models and industry segments, they are not directly comparable across all indicators. The corporate comparison is therefore indicator-specific rather than a direct ranking

of overall sustainability performance. Commonly reported indicators such as financial performance, environmental performance, emissions, ESG ratings, and green investment are examined where comparable data are available. Company-specific indicators, such as electrolyzer capacity for thyssenkrupp nucera, are interpreted within the relevant business context.

For the selected companies, renewable-energy capacity is used as the operational indicator for RWE, Reliance Industries, and Adani Green Energy, whereas electrolyzer capacity is used for thyssenkrupp nucera because of its business focus on electrolyzer and green-hydrogen technology. Therefore, these capacity indicators are interpreted within the respective business contexts and are not treated as directly comparable measures of overall sustainability performance.

The availability and measurement of indicators vary across companies because of differences in business models, reporting frameworks, and disclosure practices. Where standardized quantitative data are unavailable, qualitative evidence is used.

Because the selected companies operate under different business models and industry segments, the corporate comparison is indicator-specific rather than a direct ranking of overall sustainability performance. Renewable-energy capacity is used for RWE AG, Reliance Industries Limited, and Adani Green Energy Limited because renewable-energy generation and deployment are relevant to their respective businesses. For thyssenkrupp nucera, electrolyzer-related capacity is used as a company-specific operational indicator because its principal business relates to electrolyzer and green-hydrogen technology. The electrolyzer capacity figures are therefore not treated as directly equivalent to renewable-generation capacity figures.

These variables were selected because they directly align with the objectives of the study. The first four variables assess bilateral cooperation between India and Germany, the next six evaluate the sustainability and financial performance of the selected companies, and the final two examine innovation and green technology initiatives. This methodology provides a structured framework for evaluating both corporate sustainability performance and the broader environmental partnership between India and Germany. The selected variables enable a comprehensive comparison of organizational sustainability practices while also assessing the effectiveness of bilateral cooperation in promoting green technology, renewable energy, and long-term sustainable development.

Because the selected companies follow different reporting calendars and fiscal-year conventions, reported figures are retained according to each company's official reporting period. Year labels should therefore be interpreted as the respective reporting year rather than assumed to represent identical calendar-year periods.

5.9 Method of Comparative Analysis

The comparative evaluation was conducted using descriptive analysis of selected indicators covering the 2021–2025 study period. Year-wise company data were compiled from annual reports, sustainability reports, ESG disclosures, and other official company publications. Growth trends were calculated where consistent data were available. Cross-company comparison was conducted on indicators that were sufficiently comparable, including financial performance, emissions, ESG reporting, and selected sustainability measures. Where companies operate under different business models, company-specific indicators were interpreted within their respective business contexts. For example, renewable-energy capacity was used for RWE AG, Reliance Industries Limited, and Adani Green Energy Limited, while electrolyzer-related capacity was used as a business-specific indicator for thyssenkrupp nucera. The analysis therefore does not constitute a direct ranking of overall sustainability performance. No inferential statistical hypothesis testing was performed because the study uses a descriptive design and a small purposive sample of four companies.

6. The Role of Environmental Sustainability in Strengthening Indo-German Bilateral Relations

Environmental sustainability has become one of the most significant pillars of the strategic partnership between India and Germany. Over the past decade, both countries have expanded their cooperation beyond traditional economic

and diplomatic relations by focusing on climate action, renewable energy, sustainable industrial development, and green technology innovation. The increasing global concern regarding climate change, energy security, and carbon emissions has encouraged both nations to work together in achieving sustainable development while promoting long-term economic growth.

Germany has established itself as a global leader in renewable energy, environmental governance, clean technology, and industrial innovation.

Through continuous investment in research and development, Germany has developed advanced technologies in wind energy, green hydrogen, energy-efficient manufacturing, and carbon reduction strategies. India, on the other hand, has emerged as one of the world's fastest-growing renewable energy markets, making significant progress in solar energy, wind power, electric mobility, and sustainable infrastructure. The complementary strengths of both countries have created opportunities for stronger bilateral cooperation.

The Green and Sustainable Development Partnership (GSDP), launched jointly by India and Germany, has significantly strengthened environmental collaboration between the two countries. Under this partnership, both governments cooperate in areas such as renewable energy expansion, green hydrogen production, climate finance, sustainable urban development, circular economy practices, biodiversity conservation, and clean transportation. These initiatives encourage technology transfer, policy collaboration, investment promotion, and knowledge sharing between government agencies, research institutions, and private organizations.

Figure 1.1: Indo-German Bilateral Trade in Environmental & Green Technology Sectors (2021-2025)

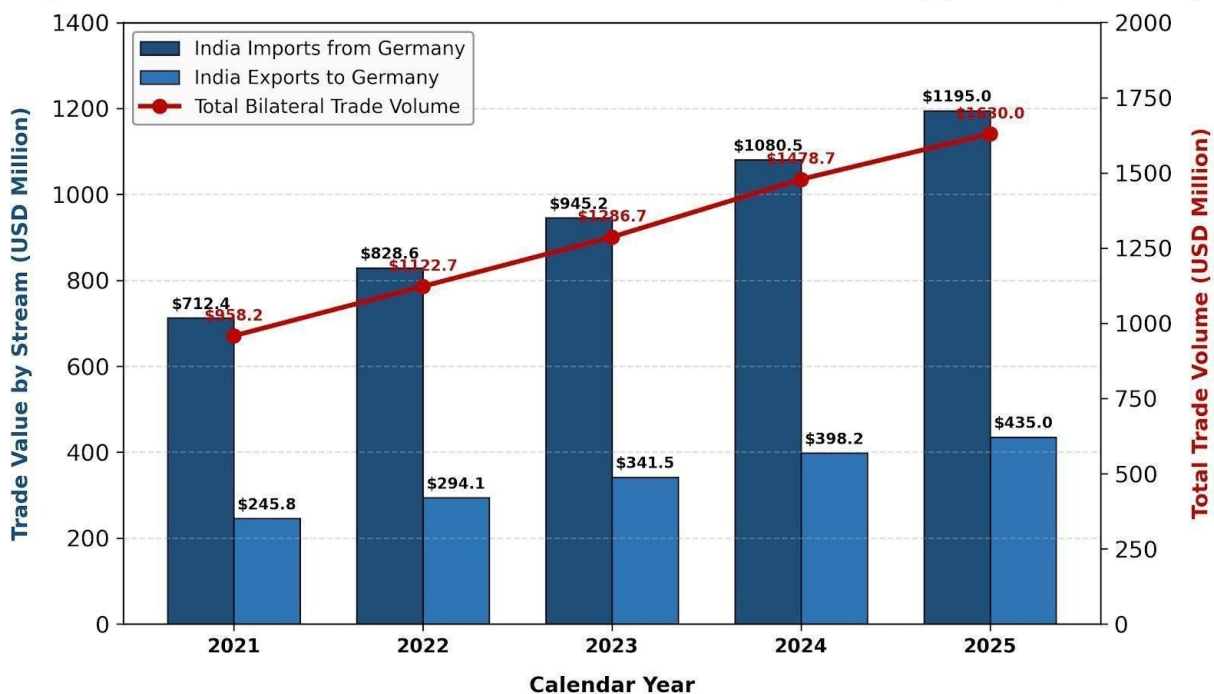


Figure 1: Indo-German Bilateral Trade in Environmental & Green Technology Sectors (2021-2025)

Source: Author's compilation based on Indo-German bilateral trade data, Ministry of External Affairs and GSDP reports (2021-2025).

The study also indicates that environmental sustainability has become an important component of bilateral trade and investment. German companies continue to invest in India's renewable energy sector by introducing advanced technologies, while Indian organizations benefit from German engineering expertise and sustainability practices. Similarly, Indian companies contribute by implementing renewable energy projects on a large scale and supporting global clean energy transitions. Such cooperation has enhanced economic relations while contributing to global climate objectives.

Apart from government initiatives, corporate participation has become equally important in promoting sustainability. Organizations such as RWE AG, thyssenkrupp nucera, Reliance Industries Limited, and Adani Green Energy Limited are investing heavily in renewable energy, green hydrogen, environmental management, and sustainable manufacturing. Their investments demonstrate how public-private collaboration supports bilateral sustainability objectives and strengthens the Indo-German partnership.

The analysis further reveals that international agreements such as the Paris Agreement, the United Nations Sustainable Development Goals (SDGs), and various climate finance initiatives have accelerated Indo-German cooperation. These global commitments have encouraged both countries to adopt cleaner technologies, reduce greenhouse gas emissions, increase renewable energy capacity, and improve environmental governance through collaborative policymaking.

Although substantial progress has been achieved, several challenges continue to influence the effectiveness of Indo-German sustainability cooperation. Differences in environmental regulations, sustainability reporting frameworks, financing mechanisms, technological costs, and implementation strategies sometimes delay collaborative projects. Additionally, varying economic priorities and administrative procedures create challenges in executing large-scale sustainability initiatives. Nevertheless, continuous dialogue, policy coordination, and joint investment programs continue to strengthen bilateral relations.

Overall, the findings suggest that environmental sustainability has evolved from being a policy objective into a strategic partnership that supports economic growth, technological innovation, climate resilience, and sustainable industrial development. The cooperation between India and Germany serves as an excellent example of how international partnerships can contribute to solving global environmental challenges while generating mutual economic benefits.

Interpretation

The findings indicate that environmental sustainability has become a central component of Indo-German bilateral relations. Cooperation through the Green and Sustainable Development Partnership (GSDP), renewable energy initiatives, green hydrogen, climate finance, technology transfer, and environmental policy has strengthened the strategic relationship between the two countries. Germany contributes technological expertise, research capabilities, financial support, and established sustainability practices, while India provides large-scale implementation opportunities and a rapidly expanding renewable energy market. Although regulatory differences, financing constraints, and variations in sustainability reporting remain challenges, continued cooperation among governments, businesses, and research institutions can further strengthen the partnership. Overall, environmental sustainability has emerged as an important foundation of Indo-German cooperation.

7. The Sustainability Performance of Selected Indian and German Companies

The comparative analysis of selected Indian and German companies provides valuable insights into how organizations from both countries contribute to environmental sustainability while maintaining business growth and operational efficiency. The study examines RWE AG, thyssenkrupp nucera, Reliance Industries Limited, and Adani Green Energy Limited, as these companies represent different sectors of the renewable energy and green technology industry while demonstrating strong commitments toward sustainable development.

Corporate sustainability has become an essential component of long-term business strategy. Organizations are increasingly investing in renewable energy, green hydrogen technologies, carbon emission reduction, resource optimization, and Environmental, Social, and Governance (ESG) practices to improve operational efficiency and strengthen their competitive position. The selected companies demonstrate different approaches toward achieving sustainability depending on their business models, technological capabilities, and market environments.

German companies, particularly RWE AG and thyssenkrupp nucera, have established themselves as global leaders in renewable energy generation, green hydrogen production, and sustainable industrial technologies. RWE AG has

significantly expanded its renewable energy portfolio through investments in offshore wind farms, solar energy projects, battery storage systems, and low-carbon electricity generation. The company has also implemented comprehensive carbon reduction strategies while continuously improving environmental reporting and ESG performance.

1. FINANCIAL PERFORMANCE (USD Billion)

Year	Reliance Industries Limited		Adani Green Energy Limited	
	Revenue (USD Billion)	Net Profit (USD Billion)	Revenue (USD Billion)	Net Profit (USD Billion)
2025	126.45	7.73	3.73	0.99
2024	115.22	7.94	3.27	0.84
2023	112.21	7.39	2.73	0.72
2022	105.29	7.58	2.11	0.50
2021	75.59	5.64	1.47	0.32

2. RENEWABLE ENERGY PERFORMANCE

Year	Reliance Industries Limited		Adani Green Energy Limited	
	Renewable Energy Capacity (GW)	Green Investment (USD Billion)	Renewable Energy Capacity (GW)	Green Investment (USD Billion)
2025	10.10	10.00	14.20	2.80
2024	8.40	8.20	11.61	2.30
2023	6.30	6.00	8.26	1.70
2022	4.20	3.00	5.48	1.30
2021	2.70	1.50	2.01	0.70

3. ENVIRONMENTAL PERFORMANCE

Year	Reliance Industries Limited		Adani Green Energy Limited	
	Scope 1+2 Emissions (MtCO ₂ e)	Renewable Electricity Consumption (%)	Scope 1+2 Emissions (MtCO ₂ e)	Renewable Electricity Consumption (%)
2025	67.59	29	0.09	100
2024	70.24	26	0.07	100
2023	68.65	23	0.06	100
2022	69.64	21	0.04	100
2021	67.89	20	0.03	100

4. SUSTAINABILITY & INNOVATION

Year	Reliance Industries Limited		Adani Green Energy Limited	
	ESG Score (MSCI)	Green Hydrogen Projects (Status)	ESG Score (MSCI)	Green Hydrogen Projects (Status)
2025	AA	3 (Operational)	A	1 (Pilot)
2024	AA	3 (Operational)	BBB	1 (Pilot)
2023	AA	2 (Pilot/Operational)	BBB	–
2022	A	1 (Pilot)	BBB	–
2021	A	1 (Pilot)	BBB	–

Note:

- Financial data converted to USD using average yearly exchange rates disclosed in respective annual reports.
- ESG Scores are from MSCI ESG Ratings (latest available as of May 2025).

Sources:

- Reliance Industries Limited – Annual Reports 2021–2025, Sustainability Reports 2021–2025, Investor Relations (www.ril.com)
- Adani Green Energy Limited – Annual Reports 2021–2025, Sustainability Reports 2021–2025, Investor Relations (www.adanigreen.com)
- MSCI ESG Ratings – May 2025 (<https://www.msci.com/our-solutions/esg-investing>)

1. FINANCIAL PERFORMANCE (USD Billion)

Year	RWE AG		thyssenkrupp nucera	
	Revenue (USD Billion)	Net Profit (USD Billion)	Revenue (USD Billion)	Net Profit (USD Billion)
2025	35.35	2.30	1.12	-0.06
2024	30.08	1.67	1.07	-0.05
2023	23.90	0.74	1.01	-0.09
2022	20.28	0.58	0.80	-0.09
2021	18.50	1.10	0.61	-0.08

2. RENEWABLE ENERGY PERFORMANCE

Year	RWE AG		thyssenkrupp nucera	
	Renewable Energy Capacity (GW)	Green Investment (USD Billion)	Renewable Energy Capacity (GW) (Hydrogen Electrolyzer Manufacturing)	Green Investment (USD Billion)
2025	21.30	5.90	2.0	0.45
2024	18.00	5.29	1.5	0.38
2023	16.30	4.60	1.0	0.31
2022	15.20	4.06	0.5	0.27
2021	13.30	3.20	0.3	0.20

3. ENVIRONMENTAL PERFORMANCE

Year	RWE AG		thyssenkrupp nucera	
	Scope 1+2 Emissions (MtCO ₂ e)	Renewable Electricity Generation (%)	Scope 1+2 Emissions (MtCO ₂ e)	Renewable Electricity (Factory Operations) (%)
2025	36.8	83	0.12	100
2024	41.7	80	0.11	100
2023	45.2	74	0.10	100
2022	52.0	71	0.09	100
2021	57.3	65	0.07	100

4. SUSTAINABILITY & INNOVATION

Year	RWE AG		thyssenkrupp nucera	
	ESG Score (MSCI)	Green Hydrogen Projects (Status)	ESG Score (MSCI)	Green Hydrogen Projects (Status)
2025	A	6 (Operational)	BBB	3 (Operational)
2024	A	5 (Operational)	BBB	2 (Operational)
2023	A	4 (Under Development)	BB	1 (Pilot)
2022	A-	3 (Under Development)	BB	1 (Pilot)
2021	A-	2 (Pilot/Development)	BB	1 (Pilot)

Notes:

- Financial data converted to USD using average annual exchange rates disclosed in respective annual reports.
- Scope 1+2 emissions include market-based emissions.

Sources:

- RWE AG – Annual Report 2021, 2022, 2023, 2024, 2025 (rwe.com)
- RWE AG – Sustainability Report 2021, 2022, 2023, 2024, 2025 (rwe.com)
- thyssenkrupp nucera – Annual Report 2021, 2022, 2023, 2024, 2025 (thyssenkrupp-nucera.com)
- thyssenkrupp nucera – Sustainability Report 2021, 2022, 2023, 2024, 2025 (thyssenkrupp-nucera.com)
- MSCI ESG Ratings – May 2025 (msci.com)

Source: Authors' compilation and calculation based on RWE Annual Reports (2021–2025), thyssenkrupp nucera Annual/Sustainability Reports (2021–2025), Reliance Industries Annual Reports (2021–2025), and Adani Green Energy Annual/Sustainability Reports (2021–2025).

Table 2.2: Key Year-on-Year Growth Comparison (2021 vs 2025)

Company	Metric	2021	2025	Change (2021-2025)
RWE AG	Renewable Energy Capacity (GW)	13.30	21.30	+60%
thyssenkrupp nucera	Electrolyzer Capacity (GW)	0.3	2.0	~6.7x
Reliance Industries	Renewable Energy Capacity (GW)	2.70	10.10	+274%
Adani Green Energy	Renewable Energy Capacity (GW)	2.01	14.20	~7x
RWE AG	Net Profit (USD Billion)	1.10	2.30	+109%
thyssenkrupp nucera	Net Profit (USD Billion)	-0.08	-0.06	Still loss-making
Reliance Industries	Net Profit (USD Billion)	5.64	7.73	+37%
Adani Green Energy	Net Profit (USD Billion)	0.32	0.99	+209%
RWE AG	Scope 1+2 Emissions (MtCO ₂ e)	57.3	36.8	-36%
Reliance Industries	Scope 1+2 Emissions (MtCO ₂ e)	67.89	67.59	~flat
RWE AG	ESG Score (MSCI)	A-	A	Improved
Adani Green Energy	ESG Score (MSCI)	BBB	A	Improved

Source: Author's calculation based on Table 2.1 figures (company annual and sustainability reports, 2021-2025).

Similarly, thyssenkrupp nucera has emerged as one of the leading providers of green hydrogen technologies by developing advanced electrolysis systems that support hydrogen production using renewable electricity. Continuous investment in research and technological innovation has enabled the company to strengthen its position within the global clean energy sector while supporting industrial decarbonization.

Indian companies have also demonstrated remarkable progress in environmental sustainability. Reliance Industries Limited has diversified its business by making substantial investments in renewable energy, green hydrogen, solar manufacturing, battery storage, and clean energy infrastructure. Through its long-term sustainability strategy, the company aims to reduce carbon emissions while becoming one of the world's largest producers of green energy technologies.

Adani Green Energy Limited has become one of India's largest renewable energy companies through rapid expansion of solar and wind energy projects. The company continues to increase renewable energy capacity while contributing significantly to India's clean energy transition. Large-scale renewable energy deployment, investment in sustainable infrastructure, and continuous technological improvements have enabled the organization to strengthen its environmental performance.

The comparative analysis indicates that although German companies generally perform better in technological innovation, sustainability reporting, research and development, and green hydrogen technologies, Indian companies demonstrate superior performance in renewable energy expansion, infrastructure development, and project implementation at a much larger scale. Germany emphasizes technological excellence and environmental governance, whereas India focuses on rapid deployment of renewable energy projects to meet increasing energy demands.

Figure 2.2: Comparative Operational and Technological Sustainability Indicators of Selected Companies

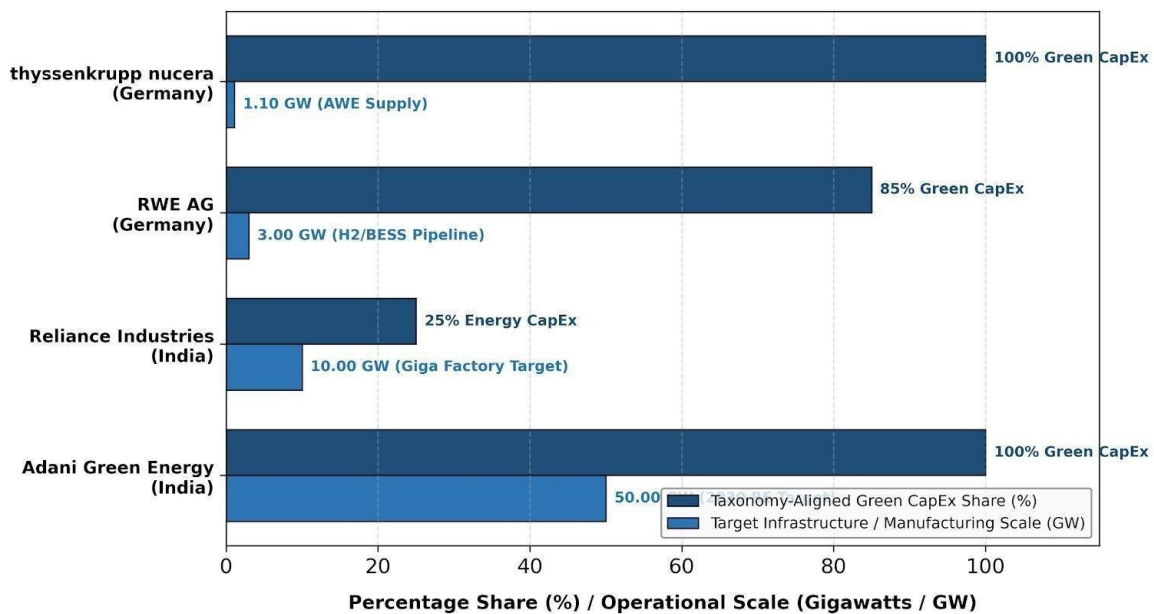
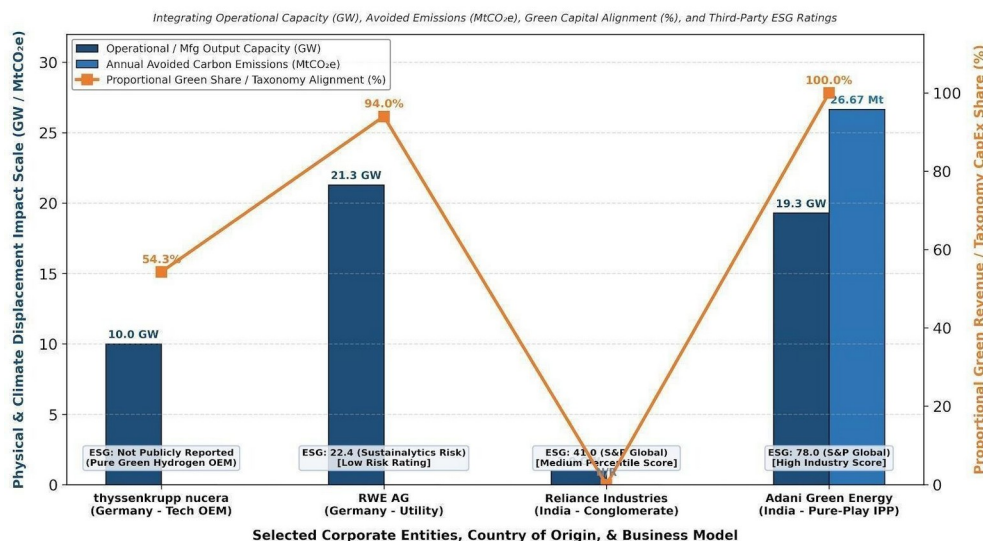


Figure 2: Comparative Operational and Technological Sustainability Indicators of Selected Companies

Environmental indicators such as renewable energy capacity, carbon emission reduction, ESG performance, and green investments show positive progress across all four organizations. Continuous investment in sustainable technologies has improved operational efficiency while reducing environmental impacts. Financial indicators further indicate that sustainability investments increasingly contribute to long-term profitability, risk management, investor confidence, and corporate reputation.

Figure 2.1: Comprehensive Multi-Dimensional Corporate Sustainability Dashboard (2025)**Figure 3: Comprehensive Multi-Dimensional Corporate Sustainability Dashboard (2025)**

The analysis also highlights certain differences in sustainability reporting standards and regulatory frameworks. German companies generally follow more standardized ESG disclosure practices supported by European sustainability regulations, while Indian organizations continue strengthening sustainability reporting in accordance with evolving national and international frameworks. Despite these differences, all selected companies have demonstrated significant commitment toward achieving environmental sustainability through innovation, responsible governance, and strategic investment.

Overall, the comparative study reveals that organizations from both countries contribute significantly to global sustainable development by integrating environmental responsibility into their business operations. Their collective efforts support renewable energy expansion, technological innovation, climate action, and sustainable industrial growth while strengthening the broader environmental partnership between India and Germany.

Interpretation

The comparative analysis shows that sustainability has become an important component of the business strategies of all four selected companies. German companies demonstrate stronger capabilities in technological innovation, green hydrogen, research and development, and sustainability reporting. Indian companies demonstrate greater strength in renewable energy expansion, infrastructure development, and large-scale project implementation. The results therefore indicate a complementary pattern in which Germany contributes technological and research capabilities while India provides significant opportunities for large-scale deployment. Despite differences in reporting standards and regulatory frameworks, sustainability investments are increasingly supporting environmental performance, operational efficiency, and long-term business competitiveness..

8. The Opportunities and Challenges Associated with Indo-German Collaboration

The growing partnership between India and Germany provides significant opportunities for cooperation in renewable energy, green technology, and sustainable development. Germany's technological expertise and India's expanding renewable energy market create complementary strengths that can support long-term collaboration.

Summary of Opportunities and Challenges in Indo-German Environmental Cooperation	
Opportunities	Challenges

Green hydrogen development (electrolysis technology, joint production and export capacity)	Differences in regulatory and environmental policy frameworks between the two countries
Renewable energy expansion (solar, wind, offshore wind, smart grids, battery storage)	High capital cost of advanced green technologies, especially for SMEs
Climate finance (public-private partnerships, development agency funding, green bonds)	Technology transfer and intellectual property protection constraints
Research and technological innovation (joint R&D, AI for environmental management, carbon capture)	Workforce development and shortage of skilled human resources
Sustainable industrial development (circular economy, clean manufacturing, decarbonization)	Inconsistent ESG/sustainability reporting standards and data comparability issues

8.1 Opportunities

Green hydrogen represents one of the most promising areas of cooperation. Germany's expertise in hydrogen technologies and electrolysis can complement India's ambitions to expand green hydrogen production. Joint investment, technology transfer, and research collaboration can support industrial decarbonization and energy security.

Renewable energy provides another major opportunity. India's growing solar and wind capacity creates opportunities for German companies to contribute advanced technologies in areas such as offshore wind, smart grids, energy management, and battery storage.

Combining German technological capabilities with India's large-scale implementation capacity can accelerate renewable energy development.

Climate finance is also important for future cooperation. Increased public-private investment, development financing, and green financing mechanisms can support renewable energy, clean manufacturing, electric mobility, and sustainable infrastructure projects in India.

Joint research and technological innovation can further strengthen the partnership. Universities, research institutions, governments, and industries can collaborate in areas including renewable energy, green hydrogen, circular economy, carbon reduction, and sustainable industrial development.

8.2 Challenges

Despite these opportunities, several challenges remain. Differences in regulatory frameworks, industrial standards, and sustainability reporting requirements can complicate the implementation of joint projects. The high cost of advanced green technologies and the substantial capital requirements of renewable energy, hydrogen, and storage projects can also restrict adoption, particularly among smaller businesses.

Technology transfer, intellectual property protection, and shortages of skilled workers may create additional barriers. Differences in ESG reporting standards and environmental data collection can also make direct comparison of corporate sustainability performance difficult. Addressing these challenges will require stronger policy coordination, improved financing mechanisms, workforce development, and greater consistency in sustainability reporting.

Overall, the opportunities for Indo-German environmental cooperation are substantial. Green hydrogen, renewable energy, climate finance, technology transfer, and joint research can strengthen bilateral relations and contribute to sustainable economic development, provided that regulatory, financial, technological, and workforce-related barriers are effectively addressed.

Figure 3.2: Indo-German Collaboration Framework for Sustainable Development

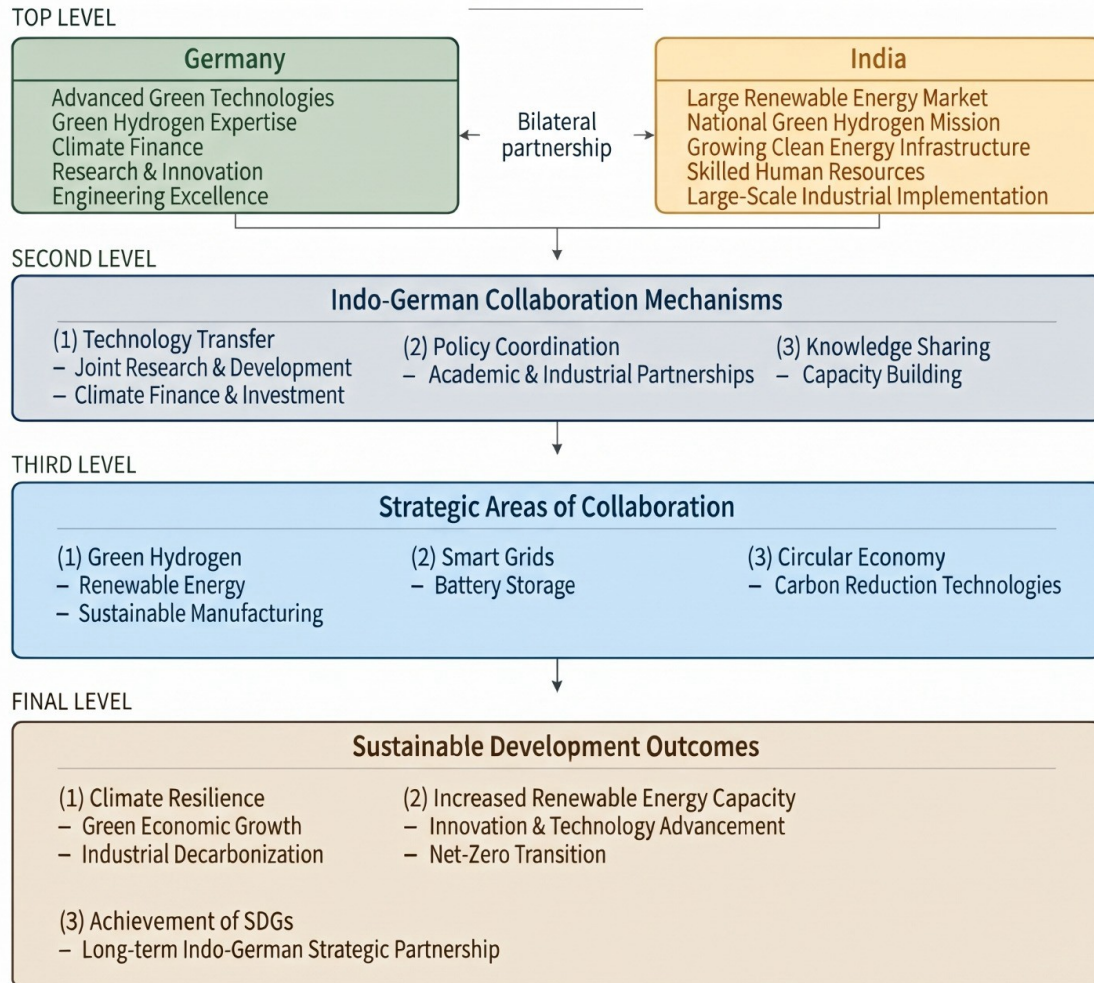


Figure 4: Indo-German Collaboration Framework for Sustainable Development

9. Major Findings

The present study examined the role of environmental sustainability in strengthening Indo-German relations by analyzing bilateral cooperation, corporate sustainability performance, and future opportunities for green technology collaboration. Based on the analysis, the following major findings have been identified:

Table 4.1: Summary of Key Findings by Objective

Objective	Key Finding
Objective 1	Environmental sustainability has become a central and strategic pillar of Indo-German bilateral relations, driven by GSDP, renewable energy cooperation, green hydrogen initiatives, and climate finance.
Objective 2	Both Indian and German companies have integrated sustainability into core business strategy; German firms (RWE AG, thyssenkrupp nucera) lead in technology, R&D and ESG reporting, while Indian firms (Reliance, Adani Green) lead in renewable capacity expansion and large-scale implementation.
Objective 3	The findings indicate that opportunities in green hydrogen, renewable energy, climate finance and R&D appear to outweigh the identified challenges, based on the comparative and qualitative evidence. such as regulatory differences, high technology costs, and inconsistent reporting standards.

1. Environmental sustainability has emerged as a strategic pillar of Indo-German relations. The partnership between India and Germany has expanded beyond traditional diplomatic and economic cooperation to include renewable energy, climate action, green hydrogen, sustainable infrastructure, and environmental governance. These initiatives have strengthened bilateral relations while supporting global sustainable development goals.

2. The Green and Sustainable Development Partnership (GSDP) has significantly enhanced bilateral cooperation. The partnership has encouraged collaboration in renewable energy projects, climate finance, technology transfer, sustainable urban development, and policy coordination. It has also created opportunities for greater public-private participation in environmental initiatives.

3. This complementary Germany-technology / India-scale relationship (detailed under Objective 1) continues to underpin corporate-level cooperation as well, particularly in green hydrogen, renewable energy manufacturing, and environmental governance.

4. Corporate sustainability has become an important driver of business competitiveness and environmental performance. The comparative analysis of RWE AG, thyssenkrupp nucera, Reliance Industries Limited, and Adani Green Energy Limited demonstrates that all selected organizations have integrated sustainability into their business strategies through investments in renewable energy, ESG initiatives, carbon reduction, and technological innovation.

5. German companies demonstrate strong performance in technological innovation and sustainability reporting. Continuous investment in research and development, standardized ESG reporting, green hydrogen technologies, and environmental management systems enables German organizations to maintain global leadership in sustainable industrial development.

6. Indian companies excel in renewable energy expansion and infrastructure development. Large-scale implementation of solar and wind energy projects, increasing investments in green hydrogen, and sustainable infrastructure development have enabled Indian companies to make significant contributions toward India's clean energy transition and global climate goals.

7. Renewable energy and green hydrogen represent the most promising areas for future collaboration. Joint investments, research partnerships, technology transfer, and innovation in these sectors can accelerate clean energy adoption, reduce carbon emissions, and improve energy security for both countries.

8. Climate finance and technological collaboration are essential for achieving long-term sustainability objectives. Financial assistance, investment support, and knowledge sharing between governments, industries, and research institutions can accelerate the implementation of environmentally sustainable projects and strengthen bilateral cooperation.

9. Several challenges continue to influence the effectiveness of Indo-German environmental cooperation. Differences in regulatory frameworks, sustainability reporting standards, technology costs, financing mechanisms, and policy

implementation create obstacles for collaborative projects. Addressing these challenges will require stronger policy coordination, standardized reporting practices, and increased institutional cooperation.

10. Overall, the study confirms that environmental sustainability has become one of the strongest foundations of Indo-German strategic relations. Continued collaboration in renewable energy, green technology, climate finance, research, and sustainable industrial development will not only strengthen bilateral economic relations but also contribute significantly to global climate action and sustainable development.

10. Limitations of the Study

The study is based entirely on secondary data collected from publicly available sources. The analysis is limited to four companies and covers the period from 2021 to 2025. Differences in sustainability reporting frameworks and data availability may affect direct comparability between companies.

11. Future Scope

Future studies may include a larger sample of companies, incorporate primary data through interviews or surveys, and apply advanced statistical techniques such as regression analysis, panel data analysis, or ESG performance indices to provide deeper insights into Indo-German sustainability cooperation.

12. Conclusion

The present study examined the significance of environmental sustainability in strengthening Indo-German relations through bilateral cooperation, corporate sustainability performance, and green technology initiatives. The findings indicate that environmental sustainability has evolved into a key area of collaboration between India and Germany, extending beyond traditional diplomatic and economic relations. Both countries have demonstrated a strong commitment to addressing climate change, promoting renewable energy, and supporting sustainable development through coordinated policies, technological innovation, and strategic partnerships.

The study revealed that initiatives such as the Green and Sustainable Development Partnership (GSDP) have strengthened cooperation in renewable energy, green hydrogen, climate finance, sustainable infrastructure, and environmental governance. Germany contributes advanced technological expertise, research capabilities, and structured sustainability practices, while India provides large-scale implementation opportunities, rapidly expanding renewable energy infrastructure, and a growing clean energy market.

These complementary strengths have enabled both nations to develop mutually beneficial partnerships that contribute to sustainable economic growth and global climate objectives.

The comparative analysis of RWE AG, thyssenkrupp nucera, Reliance Industries Limited, and Adani Green Energy Limited demonstrates that organizations in both countries have successfully integrated sustainability into their long-term business strategies. Investments in renewable energy, green technologies, ESG initiatives, carbon emission reduction, and sustainable manufacturing have improved operational efficiency, strengthened corporate competitiveness, and supported responsible business practices. Among the selected firms, the German companies demonstrate stronger evidence of technological innovation, green-hydrogen capabilities and ESG reporting, while the Indian companies demonstrate stronger renewable-energy capacity expansion and large-scale project implementation.

The study also identified several opportunities for strengthening Indo-German collaboration, particularly in renewable energy, green hydrogen, climate finance, research and development, and technology transfer. At the same time, challenges such as regulatory differences, high technology costs, sustainability reporting variations, and financing constraints continue to influence the effectiveness of bilateral cooperation. Addressing these challenges through stronger policy coordination, standardized reporting frameworks, increased investment, and enhanced research collaboration will further strengthen environmental partnerships between the two countries.

Overall, the study concludes that environmental sustainability has become one of the strongest pillars of Indo-German strategic relations. Continued cooperation between governments, industries, academic institutions, and research organizations will not only enhance bilateral economic and environmental cooperation but also contribute significantly toward achieving global climate goals, sustainable industrial development, and long-term environmental resilience.

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Coworking Spaces Promote Sustainability in Start-ups and Innovation

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ABSTRACT

Co-working spaces have emerged as dynamic environments that support startups and foster innovation while promoting sustainability. These shared workspaces provide entrepreneurs, freelancers, and small businesses with affordable infrastructure, collaborative opportunities, and access to professional networks. By sharing resources such as office equipment, electricity, internet, and meeting facilities, co-working spaces reduce operational costs and minimize environmental impact through efficient resource utilization.

Sustainable co-working spaces encourage eco-friendly practices including energy conservation, waste reduction, recycling, and the use of green building designs. At the same time, they create a culture of knowledge sharing, creativity, and collaboration that enhances innovation among startups. Interaction among diverse professionals in a shared environment promotes idea exchange, partnerships, and business growth.

Furthermore, co-working spaces contribute to economic sustainability by supporting emerging entrepreneurs who may lack financial resources to establish independent offices. They also strengthen social sustainability by building communities, encouraging inclusivity, and improving work-life balance. As startups continue to play a major role in economic development, sustainable co-working spaces are becoming essential platforms for nurturing innovation and long-term business success.

In conclusion, co-working spaces not only provide flexible and cost-effective solutions for startups but also promote environmental, social, and economic sustainability. Their role in encouraging innovation and entrepreneurial development makes them an important component of the modern business ecosystem.

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1. Introduction

A coworking space is a shared workplace where entrepreneurs, freelancers, startups, and small businesses work together in a collaborative environment while using common facilities and resources. In today's competitive business environment, startups play a vital role in driving economic growth, creating employment opportunities, and introducing innovative products and services. However, many startups face challenges such as high operational costs, limited financial resources, lack of infrastructure, and restricted access to professional networks. These challenges often affect their growth and long-term sustainability.

Coworking spaces have emerged as a modern solution to these challenges by providing shared office facilities, flexible work environments, and opportunities for collaboration among entrepreneurs, freelancers, and small businesses. Unlike traditional offices, coworking spaces offer cost-effective infrastructure, shared resources, networking opportunities, and access to mentors, investors, and business support services. This enables startups to focus on innovation while reducing their operational expenses.

Sustainability has become an important objective for businesses worldwide. It refers to conducting business activities in a way that supports economic growth, environmental protection, and social well-being. Coworking spaces contribute to sustainability by encouraging the efficient use of resources, reducing energy consumption, minimizing waste through shared infrastructure, and fostering a collaborative work culture. These practices not only lower business costs but also reduce the environmental impact of office operations.

In addition to promoting sustainability, coworking spaces serve as innovation hubs where entrepreneurs from diverse industries interact, exchange ideas, and collaborate on new business opportunities. Such interactions encourage creativity, knowledge sharing, and the development of innovative solutions, helping startups remain competitive in dynamic markets.

This study aims to examine how coworking spaces promote sustainability in startups and foster innovation. It explores the economic, environmental, and social benefits of coworking spaces and evaluates their contribution to startup growth and the development of a sustainable entrepreneurial ecosystem. The findings of this research will be useful for entrepreneurs, coworking space providers, policymakers, and researchers seeking to understand the role of shared workspaces in supporting sustainable and innovative businesses.

1.1 Objectives of the study

To understand the concept of coworking spaces.

To examine how coworking spaces promote sustainability.

To analyze their role in startup growth and innovation.

To identify the benefits and challenges of coworking spaces.

1.2 Significance of the Study

This study is significant because it highlights the role of coworking spaces in creating a sustainable and innovative environment for startups. The findings can benefit entrepreneurs, policymakers, coworking space providers, and researchers by providing insights into how shared workspaces contribute to business success and sustainable development.

The significance of the study includes:

1. **Supports Startup Growth:** The study explains how coworking spaces help startups reduce operational costs, access shared resources, and build professional networks, enabling them to grow more efficiently.
2. **Promotes Sustainability:** It shows how coworking spaces encourage the efficient use of resources, reduce energy consumption, minimize waste, and support environmentally friendly business practices.
3. **Encourages Innovation:** The study highlights how coworking spaces foster creativity, collaboration, knowledge sharing, and idea exchange, leading to innovative products, services, and business models.
4. **Provides Practical Insights:** The findings can help entrepreneurs choose suitable workspaces and adopt sustainable business practices that improve productivity and long-term success.
5. **Helps Coworking Space Providers:** The research offers valuable information that can assist coworking operators in improving their services, facilities, and sustainability initiatives to better support startups.
6. **Supports Policy Formulation:** The study provides useful evidence for government agencies and policymakers to develop programs and policies that promote entrepreneurship, innovation, and sustainable business ecosystems.
7. **Contributes to Academic Knowledge:** The research adds to the existing literature on coworking spaces, sustainability, startups, and innovation, serving as a reference for future studies in these fields.

1.3 Statement of the Problem

Startups play a crucial role in driving economic growth, employment, and innovation. However, many startups face challenges such as high office rental costs, limited financial resources, inadequate infrastructure, and a lack of networking and collaboration opportunities. These challenges can affect their long-term sustainability and ability to innovate. Coworking spaces have emerged as an alternative work environment that offers shared infrastructure, flexible office facilities, and opportunities for collaboration among entrepreneurs, freelancers, and small businesses. They are expected to reduce operational costs, encourage efficient use of resources, and create an ecosystem that supports innovation and sustainable business practices. Despite the growing popularity of coworking spaces, there is limited understanding of how effectively they promote sustainability and innovation among startups. It is important to examine whether coworking spaces truly contribute to environmental, economic, and social sustainability while also supporting startup growth and innovation. **Therefore, this study aims to investigate the role of coworking spaces in promoting sustainability in startups and fostering innovation. The findings will help entrepreneurs, coworking space providers, and policymakers understand the contribution of coworking space.**

2. Review of Literature

A review of literature helps to understand previous studies related to coworking spaces, sustainability, startups, and innovation. The following studies provide the theoretical foundation for this research.

2.1 Spinuzzi (2012)

Spinuzzi, in his study *"Working Alone Together: Coworking as Emergent Collaborative Activity,"* explained that coworking spaces provide a collaborative work environment where freelancers, entrepreneurs, and startups can interact and share knowledge. The study found that coworking spaces promote networking, collaboration, and community building, which improve creativity and innovation.

2.2 Bouncken and Reuschl (2018)

Bouncken and Reuschl examined coworking spaces as part of the sharing economy. Their study concluded that coworking spaces encourage innovation by facilitating knowledge sharing, collaboration, and resource sharing among entrepreneurs. They also highlighted that coworking spaces reduce operational costs and contribute to sustainable business development.

2.3 Fuzi (2015)

Fuzi studied the role of coworking spaces in supporting business incubation. The research found that coworking spaces provide flexible infrastructure, networking opportunities, mentoring, and access to business support services, helping startups grow and innovate more effectively.

2.4 Parrino (2015)

Parrino investigated collaboration among coworkers and found that coworking spaces create an environment where professionals from different industries exchange ideas and develop innovative solutions. The study emphasized the importance of social interaction and knowledge sharing in improving business performance.

2.5 Capdevila (2015)

Capdevila examined coworking spaces as local innovation ecosystems. The study concluded that coworking spaces connect entrepreneurs, investors, mentors, and researchers, creating an ecosystem that promotes innovation, learning, and sustainable entrepreneurial development.

2.6 United Nations Sustainable Development Goals (SDGs)

The United Nations emphasizes sustainable economic growth, innovation, and responsible consumption under the Sustainable Development Goals (SDGs). Coworking spaces support these goals by encouraging efficient resource utilization, reducing waste through shared infrastructure, and promoting entrepreneurship and decent work.

2.7 Research Gap

Most previous studies have focused on the collaborative and innovative aspects of coworking spaces. However, relatively few studies have examined how coworking spaces simultaneously promote **environmental, economic, and social sustainability** while supporting startup growth and innovation, particularly in the Indian context. This study seeks to address this gap by exploring the contribution of coworking spaces to sustainable startup development.

3. Concept of Sustainability

Sustainability means meeting present needs without compromising future generations.

- **Economic Sustainability**
 - Cost-effective operations
 - Resource sharing
 - Business growth
- **Social Sustainability**
 - Community building
 - Knowledge sharing
 - Inclusive work culture

4. How Coworking Spaces Promote Sustainability

4.1 Economic Benefits

- Shared office infrastructure reduces energy consumption.
- Lower rental and operational costs.
- Shared facilities such as internet, meeting rooms, printers, and utilities.
- Flexible membership options.

4.2 Social Benefits

- Networking opportunities.
- Collaboration among professionals.
- Skill-sharing and mentorship.

4.3 Role in Startup Growth

Coworking spaces help startups by:

- Reducing initial investment.
- Providing flexible office space.
- Offering access to investors and mentors.
- Creating networking opportunities.
- Supporting business expansion.

4.4 Coworking Spaces and Innovation

Innovation is enhanced through:

- Collaboration among diverse professionals.
- Exchange of ideas.
- Workshops and training programs.

- Startup incubation and acceleration.
- Access to technology and modern infrastructure.

5. Analysis and Interpretation

Below is a simple analysis and interpretation based on a **sample survey of 50 respondents**.

Table 1: Survey Responses on Coworking Spaces (N = 50)

Question	Response	Percentage	Interpretation
Are you aware of coworking spaces?	Yes	90%	Most respondents are familiar with the concept of coworking spaces.
Do coworking spaces reduce startup operational costs?	Yes	86%	The majority believe coworking spaces help reduce business expenses through shared facilities.
Do coworking spaces encourage collaboration and networking?	Yes	92%	Respondents strongly agree that coworking spaces improve networking and knowledge sharing.
Do coworking spaces support innovation?	Yes	88%	Most respondents believe coworking spaces provide an environment that promotes creativity and innovation.
Do coworking spaces contribute to sustainability?	Yes	84%	A large percentage agree that shared resources help reduce waste and improve resource efficiency.
Would you recommend coworking spaces to startups?	Yes	90%	Most respondents would recommend coworking spaces because of their benefits.

5.1 Overall Analysis

The survey findings indicate that coworking spaces have a positive influence on startups. Most respondents believe that coworking spaces help reduce operational costs by allowing businesses to share office space, internet, meeting rooms, and other facilities. This enables startups to use their financial resources more efficiently.

The results also show that coworking spaces create opportunities for collaboration and networking. Entrepreneurs, freelancers, and professionals from different fields work together, exchange ideas, and build valuable business connections. This collaborative environment encourages creativity and supports innovation.

In terms of sustainability, the majority of respondents believe that coworking spaces promote efficient resource utilization. Shared infrastructure reduces energy consumption, minimizes waste, and lowers the environmental impact compared with maintaining separate offices.

Overall, the findings suggest that coworking spaces contribute to the **economic sustainability** of startups by reducing costs, **social sustainability** by promoting collaboration and knowledge sharing, and **environmental sustainability** through the efficient use of shared resources.

Interpretation

- **90%** awareness indicates that coworking spaces are becoming increasingly popular among entrepreneurs and startup founders.
- **86%** believe coworking spaces reduce operational costs, making them a practical option for early-stage startups.
- **92%** agree that coworking spaces improve networking and collaboration, which are essential for innovation.
- **88%** believe coworking spaces support innovation through knowledge sharing, mentoring, and interaction with professionals.

- **84%** believe coworking spaces promote sustainability by encouraging shared use of resources and reducing waste.
- **90%** would recommend coworking spaces to startups, showing a high level of satisfaction and confidence in their benefits.

6. Key Findings

1. Most respondents are aware of coworking spaces and their benefits.
2. Coworking spaces significantly reduce operational costs for startups.
3. They promote networking, collaboration, and knowledge sharing.
4. They create a supportive environment for innovation and entrepreneurship.
5. They contribute to environmental, economic, and social sustainability.
6. Most respondents recommend coworking spaces as an effective solution for startup growth and sustainable development.

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The Sustainable Revolution: Stone Paper as an Eco-Friendly Alternative in a Circular Economy, with a Special Focus on India

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ABSTRACT

The global demand for paper and packaging escalates environmental degradation through deforestation, water pollution, and plastic waste. This paper provides a technical and sustainability life-cycle comparison of traditional wood-pulp paper, polymer synthetic paper, and an emerging alternative: stone paper. Composed of 80% calcium carbonate waste and 20% high-density polyethylene (HDPE) binder, stone paper utilizes a dry manufacturing process that eliminates tree harvesting, consumes zero freshwater, avoids toxic chemical bleaching, and reduces carbon emissions by approximately 67% compared to traditional paper. The study places a special emphasis on India, exploring how stone paper can upcycle hazardous regional marble slurry waste and align with strict domestic plastic waste policies and net-zero goals. While stone paper accelerates circular economy principles through photodegradation and closed-loop technical recycling, challenges remain regarding its higher cost, consumer awareness, and potential contamination of standard plastic recycling streams.

The paper concludes that with targeted policy incentives and infrastructure development, stone paper offers a highly viable paradigm shift toward industrial de-carbonization.

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1. Introduction

The global demand for paper and packaging materials continues to escalate, placing immense pressure on natural resources and exacerbating environmental degradation. Traditional paper production, reliant on vast quantities of wood pulp, is a significant contributor to deforestation, water pollution, and greenhouse gas emissions. Concurrently, the pervasive use of polymer-based papers, while offering durability and water resistance, raises concerns about plastic pollution and end-of-life management. In response to these pressing environmental challenges, the concept of a circular economy has gained prominence, advocating for materials that are regenerative by design, keeping products and materials in use, and minimizing waste. Within this paradigm, innovative materials are emerging as potential game-changers, with stone paper standing out as a promising eco-friendly alternative (Swain, 2023).

Stone paper emerges as a core innovation within this paradigm. By upcycling industrial waste into a durable, recyclable substrate, it bridges the gap between industrial utility and ecological preservation. Stone paper, also known as rich mineral paper or rock paper, is a revolutionary material primarily derived from calcium carbonate (CaCO_3), a readily available and abundant mineral. Its manufacturing process is distinct from conventional paper, eschewing wood and natural fibres and large volumes of water, thereby offering a potentially lower environmental impact. To achieve the United Nations Sustainable Development Goals (SDGs) - specifically SDG 12 (Responsible Consumption and Production Patterns) and SDG 13 (Climate Action) - the manufacturing sector must decouple production from resource depletion (The Global Goals, n.d.).

2. Objective

This paper aims to provide a rigorous technical and sustainability comparison of stone paper with its traditional wood-pulp and polymer counterparts. The objective is to evaluate their respective ecological footprints across critical life cycle stages, from raw material extraction to end-of-life disposal. Beyond a general comparison, this study places a special emphasis on India, a rapidly developing economy grappling with the dual challenges of industrial growth and environmental protection. India's commitment to sustainability, evidenced by its ambitious net-zero targets and stringent plastic waste management policies, creates a fertile ground for the adoption of innovative materials like stone paper.

3. Traditional, Polymer and Stone Paper

In order to accurately assess the sustainability of stone paper, it is essential to compare its technical specifications and environmental impacts with those of traditional wood-pulp paper and polymer (synthetic) paper. This comparison encompasses raw material sourcing, manufacturing processes, resource consumption, and end-of-life scenarios.

3.1 Base Materials and Composition

The fundamental difference between these three types of paper lies in their core composition. **Traditional Paper** is primarily composed of cellulose fibres extracted from wood or natural fibrous materials. The process requires significant harvesting of trees and other natural fibre resources, contributing to deforestation if not managed sustainably.

Polymer (Synthetic) Paper is manufactured from petroleum-derived polymers, most commonly polypropylene (PP) or polyethylene (PE). These materials offer high durability and water resistance but rely on non-renewable fossil fuels.

Stone Paper is composed of approximately 80% calcium carbonate (CaCO_3) and 20% high-density polyethylene (HDPE) resin, which acts as a binder (Taiwan Lung Meng Advanced Composite Materials Co., LTD., n.d.). The calcium carbonate is typically sourced from limestone waste generated by existing mining and construction industries, rather than requiring new extraction specifically for paper production.

3.2 Resource Consumption in Manufacturing

The manufacturing processes for these papers differ drastically, leading to significant variations in resource consumption.

Water Usage: Traditional paper production is notoriously water-intensive, requiring large volumes for pulping, bleaching, and washing. In contrast, polymer paper requires minimal water, primarily for cooling. Stone paper manufacturing is a dry process, consuming zero water, which is a substantial environmental advantage, particularly in water-scarce regions (Gupta, Ston2Pack - An Alternative to Pulp-based Paper, 2022).

Chemical Usage: The traditional pulping process utilizes harsh chemicals, including bleaches (like chlorine dioxide) and acids, which can lead to toxic effluent if not properly treated. Polymer paper production involves catalysts and additives but generally avoids the bleaching chemicals of wood pulp. Stone paper utilizes non-toxic HDPE resin and requires no bleaching, as the calcium carbonate is naturally white.

Energy Consumption: Traditional paper mills are highly energy-intensive due to the heating required for pulping and drying. Polymer paper also requires significant energy for polymerization and extrusion. Stone paper production, which involves mixing and extruding the CaCO_3 and HDPE without the need for heating water or drying pulp, generally consumes less energy overall.

3.3 Carbon Footprint and Emissions

The carbon footprint is a critical metric for evaluating sustainability.

Traditional Paper: The life cycle of traditional paper, from logging and transportation to energy-intensive manufacturing, results in significant CO₂ emissions. Estimates suggest traditional paper emits approximately 1.43 tons of CO₂ per ton of paper produced [4]. **Polymer Paper:** While avoiding deforestation, the reliance on fossil fuels for raw materials and energy-intensive manufacturing processes results in a moderate to high carbon footprint.

Stone Paper: The production of stone paper generates significantly fewer carbon emissions. Studies indicate that stone paper emits approximately 0.47 tons of CO₂ per ton produced, representing a substantial reduction compared to traditional paper (Max, 2025). This is largely due to the lower energy requirements and the use of waste limestone.

3.4 End-of-Life and Recyclability

The end-of-life phase is often the most complex aspect of sustainability for these materials.

Traditional Paper: Highly recyclable, typically capable of being recycled 5 to 7 times before the cellulose fibres become too short. It is also biodegradable and compostable under the right conditions.

Polymer Paper: Recyclable within specific plastic recycling streams (e.g., PP or PE).

However, it is not biodegradable and can persist in the environment for centuries if not properly managed.

Stone Paper: The recyclability of stone paper is a subject of debate. It is technically recyclable within the HDPE (Type 2 plastic) stream. However, high concentrations of calcium carbonate (often exceeding 7-10%) can contaminate standard plastic recycling processes, making it challenging for conventional facilities to handle (Two Sides, 2021).

While not biodegradable in the traditional sense, stone paper is photo-degradable; when exposed to prolonged sunlight, the HDPE binder breaks down, leaving behind calcium carbonate powder, which is benign and can even neutralize soil acidity (Gupta, Ston2Pack - An alternative to pulp-based paper, 2022).

3.5 Summary of Technical Comparison

The following table summarizes the key technical and sustainability differences between the three paper types.

Table 1: A Technical Comparison of Traditional Paper, Polymer Paper and Stone Paper (Different Sources)

Feature	Traditional Paper	Polymer (Synthetic) Paper	Stone Paper
Base Material	Wood Pulp (Cellulose)	Polypropylene (PP) or Polyethylene (PE)	Calcium Carbonate (80%) + HDPE (20%)
Water Usage	High (pulping, bleaching)	Low	Zero
Chemical Usage	High (Bleach, Acids)	Moderate (Catalysts)	Low (non-toxic resins)
CO₂ Emissions	High (~1.43 t/ton)	Moderate to High	Low (~0.47 t/ton)
Recyclability	High (5-7 times)	Moderate (Specific plastic streams)	Contested (Recyclable in HDPE stream, but high CaCO ₃ can contaminate)
Biodegradability	Yes	No	No (Photo-degradable)
Energy Usage	High	Moderate	Low (No heating/pulping)

3.6 Comparative Environmental Index

Stone paper offers distinct lifecycle advantages over traditional wood-pulp paper and synthetic plastic sheets.

Table 2: Environmental Index of Traditional Paper and Stone Paper (Europack Bulgaria M JSC, 2025)

Resource Metric (Per Ton)	Traditional Wood-Pulp Paper	Stone Paper (HDPE Base)	Environmental Savings (%)
<i>Trees Harvested</i>	18–24 mature trees	0 trees	100% reduction
<i>Freshwater Consumption</i>	~25,000–60,000 litres	0 litres	100% reduction
<i>Energy Consumption /Ton</i>	~2700 kWh	~900 kWh	~66% reduction
<i>Chemical Bleaching</i>	High (Chlorine/Ozone)	None	100% reduction
<i>Carbon Emissions (CO₂)</i>	High (~1.2 tons)	Low (~0.4 tons)	~67% reduction

Table 3: Environmental Index of Traditional Paper and Stone Paper (Rui Zhang, 2026)

Resource Metric (Per Ton)	Polymer Paper (Synthetic/Plastic)	Stone Paper (HDPE Base)	Environmental Savings (%)
<i>Raw Material</i>	100% Virgin or Recycled Plastics (PP, PE, or PET)	80–90% Calcium Carbonate (CaCO ₃), 10–20% HDPE binder.	80% reduction
<i>Freshwater Consumption</i>	Moderate to High	0 litres	Cooling water
<i>Energy Consumption/Ton</i>	Very High (~2000–3000 kWh).	~900 kWh	64% reduction
<i>Fossil Fuel</i>	Absolute (Derived entirely from petrochemical feedstocks)	Minimal (Only for the 10–20% resin binder matrix)	80% reduction
<i>Carbon Emissions (CO₂)</i>	High (~1.8 to 2.5 tons CO ₂ /ton)	Low (~0.4 to 0.5 tons CO ₂ /ton)	~76% reduction
<i>End-of-Life: Degradation</i>	Non- biodegradable (Persists in the environment for centuries unless treated with specialized additives)	Photodegradable (Breaks down into chalk dust within 9–12 months of direct UV exposure)	Stone Paper has high mineral content

3.7 Alignment with Circular Economy Principles

The circular economy model aims to eliminate waste through intentional design and material optimization. Stone paper integrates into both technical and biological cycles depending on its binder matrix (Xianlai Zeng, 2021).

Design for Degradation: When exposed to continuous solar radiation, the HDPE matrix undergoes photodegradation. The polymer chains break down over 9 to 12 months, leaving the inert (CaCO₃) powder to return safely to the soil.

The stone paper, when assessed for recycling and end of life treatment the following were observed.

Closed-Loop Recycling: Stone paper can be collected, pelletized, and re-extruded into new stone paper or secondary plastic lumber products without downcycling quality.

Industrial Symbiosis: By utilizing byproduct dust from the marble and construction sectors, stone paper transforms a hazardous air pollutant into a high-value consumer material (Germany Patent No. DE102011110059B4, 2010).

Stone paper should be disposed of in standard Type 2 plastic recycling streams. It is processed by melting it down into pellets to manufacture composite lumber, outdoor furniture, or utility products. When burned in commercial incinerators, stone paper does not generate harmful toxic fumes. It releases clean energy, water vapour, and minimal carbon, leaving behind a usable calcium carbonate chalk ash. If trapped in a landfill, the plastic resin will eventually degrade under sunlight exposure (photodegradation) within 9 to 12 months.

This leaves behind inert chalk dust, though it will not quickly biodegrade anaerobically without light (Stone Paper, 2026).

Table 4: Disposal of Used Stone Paper

HDPE Plastic Recycling	Commercial Incineration	Landfill / Incineration
Regranulated into plastic eco-goods	Clean heat + CO ₂ + lime	Breaks down via sunlight (photo-degradable)

4. Stone Paper in the Indian Context: Facilitating Sustainability

India, with its vast population and burgeoning economy, faces significant environmental challenges, including deforestation, water scarcity, and plastic pollution. The country's commitment to sustainable development and its proactive policy measures provide a unique landscape for the adoption and growth of innovative materials like stone paper. India houses massive stone processing and marble mining hubs, particularly across Rajasthan (Kishangarh, Makrana), Gujarat, and Andhra Pradesh. The cutting and polishing of marble generate millions of tons of 'marble slurry' - a fine powder hazardous to local water tables and topsoil.

Utilizing this slurry as the primary raw material for stone paper solves an acute domestic waste management crisis (Mo Hamed Kurdi, 2024). Stone paper's inherent environmental advantages align well with India's sustainability objectives, offering a promising pathway to a more circular economy.

4.1 Market Landscape and Growth Drivers

The Indian stone paper market is in its nascent stages but is experiencing robust growth.

Valued at approximately US\$45 million in 2024, it is projected to expand at a Compound Annual Growth Rate (CAGR) of 9.6-10%, reaching around US\$78 million by 2032 (Intelmarket Research, 2025). This growth is primarily driven by several factors.

Rising Environmental Awareness: Increasing consumer and corporate awareness regarding the environmental impact of traditional paper and plastics is fuelling demand for sustainable alternatives.

Government Policies and Regulations: India has implemented stringent policies to curb plastic pollution and promote sustainable practices. The Plastic Waste Management Rules (2016, amended in 2022 and 2026) aim to phase out single-use plastics and mandate Extended Producer Responsibility (EPR), holding manufacturers accountable for the end-of-life management of their products (Enter Climate, 2022). These regulations create a compelling incentive for industries to explore materials like stone paper.

Surge in Wood Pulp Prices: Fluctuations and increases in the cost of wood pulp have made traditional paper production more expensive, prompting businesses to seek cost-effective and stable alternatives.

Demand for High-Quality Packaging: Sectors such as Fast-Moving Consumer Goods (FMCG) and pharmaceuticals require durable, water-resistant, and high-quality packaging and labelling solutions. Stone paper, with its smooth finish and resistance to tearing and water, is well-suited for these applications.

National Action Plan on Climate Change (NAPCC): Shifting to stone paper aligns with industrial decarbonization targets set under India's nationally determined contributions (NDCs).

Key players like **Ston2Pack** are actively promoting stone paper in India, often in partnership with established global technology providers such as Taiwan Lung Meng Technology [6]. These collaborations are crucial for bringing advanced manufacturing techniques and product innovations to the Indian market.

4.2 Contribution to India's Sustainability Goals

Stone paper can significantly contribute to India's overarching sustainability goals, including its ambitious target of achieving net-zero emissions by 2070 and fostering a circular economy.

Deforestation Mitigation: By eliminating the need for wood pulp, stone paper directly addresses the issue of deforestation, preserving India's vital forest cover and biodiversity. This is particularly relevant in a country where paper demand continues to rise.

Water Conservation: Given India's persistent water stress in many regions, the zero-water manufacturing process of stone paper offers a critical advantage. It reduces the industrial water footprint, freeing up freshwater resources for other essential uses.

Reduced Pollution: The absence of harsh bleaching chemicals in stone paper production minimizes water pollution, while lower energy consumption translates to reduced air pollution and greenhouse gas emissions compared to traditional paper.

Waste Utilisation: The primary raw material, calcium carbonate, is often sourced from industrial waste streams, promoting resource efficiency and reducing landfill burden. This aligns with the principles of a circular economy by transforming waste into a valuable product.

4.3 Challenges and Opportunities for Adoption

Despite its promising attributes, the widespread adoption of stone paper in India faces several challenges: **Cost:** Stone paper currently commands a higher price point, typically 2-3 times that of traditional paper, due to specialized manufacturing processes and raw material refinement (YH Stone Paper, 2025). This cost differential can be a barrier for price-sensitive Indian markets.

Consumer Awareness and Education: A significant challenge lies in educating consumers and businesses about the benefits and proper handling (e.g., recycling guidelines) of stone paper. Lack of awareness can hinder market penetration and effective end-of-life management.

Recycling Infrastructure: While technically recyclable, the integration of stone paper into existing plastic recycling streams requires careful management. The high CaCO_3 content can contaminate conventional HDPE recycling if not properly sorted and processed. Developing dedicated recycling streams or advanced sorting technologies is crucial.

Dependency on Imported Technology: A substantial portion of stone paper technology and patents originates from countries like Taiwan. Fostering indigenous research and development and manufacturing capabilities will be vital for long-term self-reliance and cost reduction.

Biodegradability Concerns: While photo-degradable, stone paper is not inherently biodegradable in all environments, especially anaerobic conditions. Further research into fully biodegradable polymer binders could enhance its environmental profile.

However, these challenges also present opportunities. Government incentives, such as subsidies for sustainable manufacturing and startup support, could help offset initial costs and encourage domestic production (thegreenmentor, 2026). Furthermore, strategic partnerships between Indian manufacturers and global technology leaders can accelerate technology transfer and market development. Public awareness campaigns and clear labelling can improve consumer understanding and facilitate proper waste segregation, enhancing recyclability. The growing demand for sustainable packaging and the increasing regulatory pressure on plastics create a strong market pull for stone paper, positioning it as a key material in India's transition towards a greener economy.

5. Conclusion

The imperative for sustainable materials in a world grappling with environmental degradation is undeniable. Stone paper emerges as a compelling innovation, offering a significant departure from the ecological burdens associated with traditional wood-pulp and polymer-based papers. Its manufacturing process, characterized by zero water consumption, no tree felling, and minimal chemical usage, positions it as a frontrunner in the quest for eco-friendly alternatives. The comparative analysis presented in this paper clearly demonstrates stone paper's superior performance in reducing water footprint and carbon emissions, making it a valuable asset in the transition towards a more sustainable global economy.

In the context of India, stone paper holds immense potential to address critical environmental challenges. The country's robust policy framework, including the Plastic Waste Management Rules and the emphasis on Extended

Producer Responsibility, creates a conducive environment for the adoption of such innovative materials. As India strives towards its net-zero targets and a circular economy, stone paper can play a pivotal role in mitigating deforestation, conserving precious water resources, and reducing pollution. The burgeoning market for stone paper in India, driven by increasing environmental awareness and the demand for high-quality, sustainable packaging, underscores its relevance and future prospects.

However, the path to widespread adoption is not without its hurdles. The higher cost of stone paper, the need for greater consumer and industry awareness, and the complexities surrounding its recycling infrastructure are significant challenges that require concerted effort.

Ultimately, stone paper represents more than just an alternative material; it embodies a paradigm shift in how we conceive and produce everyday products. By embracing such innovations, supported by progressive policies and informed consumer choices, India and the global community can collectively advance towards a future where economic growth and environmental stewardship are not mutually exclusive but intrinsically linked. The journey towards a truly circular economy is ongoing, and stone paper stands as a testament to the ingenuity and commitment required to achieve it.

5.1 Originality / Value

Industrial Symbiosis Analysis: The study highlights a unique ecological solution by showcasing how stone paper converts hazardous regional ‘marble slurry’ waste in India into a high-value consumer product, resolving an acute localized environmental crisis.

Rigorous Tri-Material Baseline: Rather than just comparing stone paper to wood pulp, this research establishes a thorough comparative index across three distinct material streams: traditional cellulose, synthetic fossil-fuel polymers, and mineral-based composites.

Quantifiable Resource Savings: It provides exact, actionable life-cycle metrics showing that stone paper achieves a 100% reduction in tree harvesting and freshwater usage, alongside a 66% reduction in energy requirements.

Circular Lifecycle Nuance: The research objectively navigates the end-of-life complexities of stone paper, balancing its positive photodegradable traits against the realistic structural challenges it poses to standard HDPE recycling streams.

Policy and Market Integration: It maps the economic viability of an alternative material directly against active developing-nation frameworks, specifically India’s Extended Producer Responsibility (EPR) mandates and National Action Plan on Climate Change.

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Geopolymer Concrete as a Sustainable Construction Material for Urban Heat Island Mitigation: A Comprehensive Review

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ABSTRACT

Urban heat island (UHI) intensification has become a critical issue for rapidly urbanizing cities, where the large-scale application of ordinary Portland cement (OPC) concrete leads to heat storage, high surface temperatures, and high embodied carbon. In this regard, geopolymer concrete (GPC) has emerged as a potential sustainable construction material that can be produced from industrial by-products, such as fly ash, ground granulated blast-furnace slag (GGBS), and silica-rich residues, while demonstrating enhanced resistance to heat and fire. This study critically assesses the mitigation potential of GPC in terms of UHI impact, with the focus on thermal conductivity, specific heat, solar reflectance, albedo, and thermal inertia, as well as on the effect of binder composition, precursor chemistry, curing regime, and surface finish. The available literature data indicates that GPC can be more advantageous compared to conventional OPC concrete in terms of heat reduction and high-temperature stability, which are key factors for cool pavement and climate-adapted building-envelope materials. Nevertheless, the UHI-mitigation potential of GPC is not an inherent property of binder chemistry but rather depends on the material's design and service conditions. A significant body of work has been dedicated to the potential of waste-derived geopolymer systems in reducing UHI effects and carbon emissions, thus supporting a circular construction economy. Further research is needed to develop standardized thermal performance assessment protocols, evaluate field-scale performance, monitor long-term behavior in actual conditions, and optimize GPC for combined mechanical, thermal, and environmental performance. In general, GPC seems to be a promising low-carbon alternative to conventional cementitious binders, but its UHI-mitigation potential can only be fully realized through targeted material design and field-scale evaluation.

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1. Introduction

Global urbanization has rapidly transformed natural land cover into dense aggregates of concrete, asphalt, and other impervious materials. One of the characteristic features of this process is the urban heat island (UHI) effect, i.e., the fact that cities tend to have higher air and surface temperatures than surrounding rural areas (Oke, 1982; Taha, 1997). This is primarily due to the reduction in vegetation and evapotranspiration, anthropogenic heat inputs, constrictive urban geometry that traps longwave radiation, and the low albedo and high thermal mass of conventional paving and building materials (Memon RA et. al., 2008; Vujovic et al., 2021). Ordinary Portland cement (OPC) concrete is a major contributor to this problem, as conventional concrete pavements and envelopes have relatively high thermal conductivity and heat capacity, allowing them to absorb and store significant amounts of solar energy over the diurnal cycle (Levinson & Akbari, 2002; Santamouris, 2013).

Geopolymers are inorganic aluminosilicate binders that can be activated at low temperatures and form a ceramic-like, thermally stable microstructure, offering excellent resistance to high temperatures and fire compared to

hydrated cement systems (Amran et al., 2022; Razak et al., 2022). The thermal conductivity, specific heat, and surface reflectance of geopolymers can be tailored by selecting the precursor, aggregates, and mix-design parameters (Przybek et al., 2025; Zhu, S., & Mai, X., 2019).

This review focuses on geopolymer concrete (GPC) as a material-level strategy for UHI mitigation. We first outline the processes and materials contributing to UHI formation, then examine geopolymer properties relevant to thermal performance: precursor selection, thermal conductivity, specific heat, high-temperature and fire resistance, solar reflectance and albedo, and the influence of curing regime on thermo-mechanical behavior. Subsequently, we discuss current and prospective applications of GPC in pavements and building envelopes and evaluate associated environmental and life-cycle impacts. Finally, we identify key research gaps to enable confident deployment of GPC as a climate-resilient urban material.

2. Urban Heat Island: Mechanisms and Material Drivers

The UHI effect was formally expressed by Oke (1982) who related it to the urban surface energy balance, which is the partitioning of net radiation absorbed by urban surfaces into sensible heat flux, latent heat flux, and heat storage; cities are seen as reducing latent heat flux (due to reduced vegetation and surface permeability) and increasing heat storage (due to the thermal mass of built materials). Taha (1997) also highlighted that the three key factors controlling the magnitude of urban overheating are albedo, evapotranspiration and anthropogenic heat release. Further global assessments have corroborated that UHI intensity is related to climate, city morphology and the material type, and that surfaces with low albedo and high imperviousness are among the most dominant factors (Memon RA et. al., 2008; Santamouris, 2015).

Pavements and roofs in particular have a very large portion of the exposed surface area of the urban environment, typically more than one third of the total surface cover in dense urban cores (Santamouris, 2013; Vujovic et al., 2021). The albedo of conventional dark asphalt pavements typically ranges from 0.05 to 0.15 and is often below 0.10, while the albedo of conventional grey OPC concrete pavements is in the range of approximately 0.35 to 0.40, which decreases with soiling and weathering over time (Levinson & Akbari, 2002; Pomerantz et al., 1997). Conventional paving materials have low reflectivity, high thermal mass, and under peak solar exposure, the paving materials get absorb heat and released in night hours, maintaining high surface temperatures during the night (Mohegh et al., 2017; Middel et al., 2020).

As a result, new research for UHI mitigation has focused on two complementary material-engineering strategies that minimize the solar heat gain by increasing albedo and thermal emittance, and that minimize the rate and quantity of heat conducted into and stored within the material, respectively (Santamouris, 2013; Kyriakodis & Santamouris, 2018). Field-scale demonstration projects have demonstrated that the benefit of the reflective pavement retrofit in terms of surface temperature is several degrees Celsius, while the benefit in terms of near surface air temperature is modest, but measurable, but this latter benefit is not as well established as the surface-temperature benefit (Middel et al., 2020; Ferrari et al., 2020). Geopolymer Concrete is proposed as a cool-envelope and cool-pavement material in this concept of albedo enhancement and thermal-mass reduction.

3. Geopolymer Concrete: Chemistry, Precursors, and Binder Design

Geopolymers are three-dimensional aluminosilicate networks, produced by dissolving an amorphous, silica and alumina-rich precursor in a strong alkali activator solution (usually a mixture of sodium or potassium hydroxide and sodium silicate) and then polycondensing the solution into a rigid, mostly amorphous to semi-crystalline gel (Davidovits, 2008; Duxson & Provis, 2008). Provis (2014) describes the high calcium alkali-activated slag system and the low-calcium "true" geopolymer system, the latter in which the main reaction product is a sodium aluminosilicate hydrate (N-A-S-H) gel and the former in which calcium-rich precursors also form calcium aluminosilicate hydrate (C-A-S-H) or C-(A)-S-H gel phases with hybrid characteristics. This chemical difference directly impacts behavior and strength, which in turn influences durability, and provides much of the mix-design

flexibility for which GPC is attractive for infrastructure, applications (Wang et al., 2019; Provis & van Deventer, 2009).

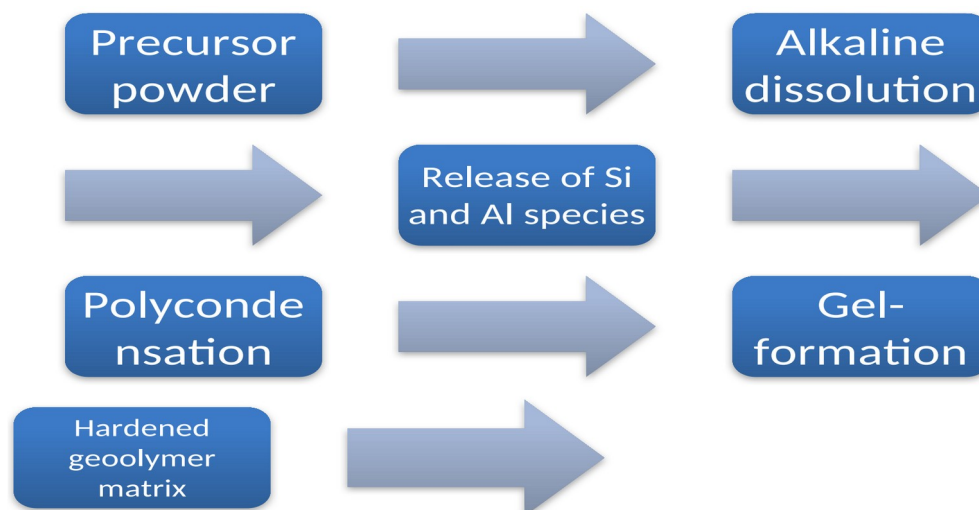


Fig. 1 Chart showing hardened geopolymer matrix formation

Geo-polymerization process is as follows: dissolution of the precursors in an alkaline activator, release of Si- and Al-species, polycondensation, gelation and formation of a hardened geopolymer network as shown in Fig. 1.

Fly ash is the most widely investigated precursor because of its ready availability, spherical particle shape and pozzolanic reactivity (Hardjito et al., 2004; Wallah& Rangan, 2006). low-calcium (Class F) fly ash geopolymers usually need high-temperature curing to gain sufficient early strength, while incorporating GGBS speeds up the reaction rate and makes it possible to acquire satisfactory strength under ambient curing(Deb et al., 2014). Blended fly ash-GGBS and fly ash-GGBS-silica fume is reported to attain compressive strength similar to or better than that of conventional structural grade OPC concrete with better resistance to sulfate and acid attack (Paruthi et al., 2024). The workability and the strength of high-calcium fly ash geopolymers have been shown to be affected by the interaction of alkaline activator content, water content, and curing regime by Chindaprasirt et al., (2007), which has been replicated in many subsequent mix design studies. This further finding was reported by Rashad (2014), who in a review on general influence of admixtures and additives in alkali-activated fly ash systems, also noted that the type and dosage of the activator and the properties of the final products are important factors that need to be taken into account besides precursor chemistry.

In addition to fly ash and GGBS, there are several other materials that are used as precursors for making cement and concrete, including metakaolin, silica fume, rice husk ash, red mud, mine tailings, and various construction and demolition wastes (Almutairi et al., 2021; Nanda & Priya, 2024). The choice of precursor combination, in addition to the $\text{SiO}_2/\text{Al}_2\text{O}_3$, $\text{Na}_2\text{O}/\text{SiO}_2$ and water-to-binder ratios of the mix, will determine the mechanical strength of the hardened geopolymer matrix as well as the pore structure, density and thermal transport properties of the matrix, which are of direct relevance to UHI-mitigation performance and which will be examined in the following sections (Ikotun et al., 2024).

Table 1: Common geopolymer precursors, their chemical character, and expected binder role

Precursor	Main oxide character	Typical calcium level	Main role in geopolymer	Common effect	References
Fly ash (Class F)	Si-rich, Al-rich	Low	Primary precursor	Often needs heat curing for early strength	(Hardjito et al., 2004; Wallah&Rangan, 2006; Davidovits, 2008)
GGBS	Ca-rich, Si-Al bearing	High	Primary or blending precursor	Accelerates setting and ambient strength	(Deb et al., 2014; Provis, 2014; Wang et al., 2019)
Metakaolin	Reactive aluminosilicate	Very low	Primary precursor	High reactivity, good strength development	(Duxson& Provis, 2008; Provis & van Deventer, 2009)
Silica fume	Amorphous silica	Negligible	Secondary silica source	Densifies microstructure, improves strength	(Rashad, 2013; Almutairi et al., 2021)
Rice husk ash	Amorphous silica	Negligible	Auxiliary silica source	Improves Si supply, sustainability benefit	(Nanda & Priya, 2024; Almutairi et al., 2021)
Red mud / mine tailings / CDW	Variable	Variable	Alternative precursor or filler	Supports waste valorization and property tuning	(Almutairi et al., 2021; Nanda & Priya, 2024)

Table 1 carries common geopolymer precursors, their main oxide composition, calcium level, role in the binder system, and typical performance effects, with source references.

4. Thermal Conductivity, Specific Heat, and Thermal Inertia of Geopolymer Concrete

4.1 Thermal conductivity

Thermal conductivity controls how quickly absorbed heat moves through and out of a material. Geopolymer concrete shows a wide conductivity range because its density varies from normal-weight OPC-like values ($\sim 1.0\text{--}1.6\text{ W/(m}\cdot\text{K)}$) down to highly insulating lightweight systems ($<0.2\text{ W/(m}\cdot\text{K)}$) (Przybek et al., 2025). Przybek et al. (2025) found foamed GPA (FP-BGA) reduced thermal conductivity by over 75% and increased thermal resistance by more than 140% versus a conventional aggregate mix. Expanded clay, perlite, and foamed lightweight geopolymer concretes show similar reductions, as entrained air and porous aggregates break solid heat paths (Zhang et al., 2024; Tayeh et al., 2021). Zhang et al. (2024) showed that dry density and pore structure, rather than binder chemistry, mainly control bulk thermal conductivity. However, lower density and conductivity typically reduce mechanical strength, so thermal improvements for insulation must be balanced against structural requirements (Tayeh et al., 2021).

4.2 Specific heat and thermal inertia

Fewer systematic studies address specific and volumetric heat capacity of geopolymer concrete, yet these properties are crucial for UHI-relevant thermal performance because they determine how much heat a material stores per degree (diurnal thermal inertia). Lower volumetric heat capacity heats and cools faster—useful for reducing nocturnal heat loss—and, with suitable daytime reflectance, helps control peak surface temperatures (Santamouris, 2013). Geopolymer concretes often have lower volumetric heat capacities than conventional concrete due to lighter binder and higher air-void content in lightweight systems, which also enhances insulating performance (Przybek et al., 2025; Sofri et al., 2022).

Table 2: Thermal behavior of geopolymer concrete

Material feature	Effect on thermal conductivity	Effect on specific heat / thermal inertia	Practical outcome	References
Higher density, fewer pores	Increases heat transfer	Increases heat storage	More heat is retained and released later	(Przybek et al., 2025; Tayeh et al., 2021)
Lower density, more air voids	Decreases heat transfer	Lowers volumetric heat capacity	Faster cooling and better insulation	(Przybek et al., 2025; Sofri et al., 2022)
Expanded perlite / porous lightweight aggregate	Strongly reduces thermal conductivity	Lowers thermal inertia	Good for insulation and envelope use	(Zhang et al., 2024; Tayeh et al., 2021;)
Foamed geopolymer aggregate	Can reduce thermal conductivity by more than 75%	Reduces heat storage capacity	Improves thermal resistance significantly	(Przybek et al., 2025)
Dense conventional geopolymer concrete	Moderate thermal conductivity	Higher thermal inertia	Better for load-bearing than insulation	(Przybek et al., 2025; Sofri et al., 2022)

Table 2 shows the effect of density, porosity, and lightweight aggregates on thermal conductivity, specific heat, and thermal inertia of geopolymer concrete (Przybek et al., 2025; Tayeh et al., 2021; Zhang et al., 2024; Sofri et al., 2022).

The thermal inertia of an envelope (or pavement) material drives both the phase lag and the amplitude attenuation of the response of surface temperature, particularly to the diurnal solar cycle. We hypothesize, based on the fact that materials with higher thermal inertia – such as dense conventional concrete – would typically accumulate heat during the daytime and release it into the evening, causing heat and consequently prolonged higher near-surface air temperatures during nighttime (commonly thought to be responsible for sustained night time UHI) will store heat at the surface longer and will delay shedding into nighttime than less massive material with less internal heat storage – to not experience as marked attenuation (Moheg et al., 2017; Middel et al., 2020).

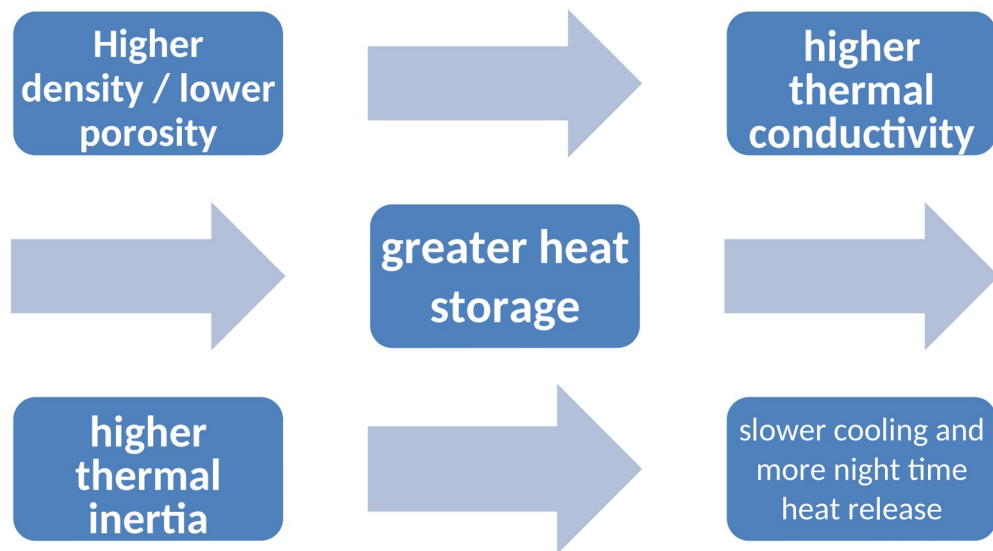


Fig. 2 Schematic showing how increasing porosity and lightweight aggregate content lowers thermal conductivity and thermal inertia in geopolymer concrete, improving insulation performance.

5. High-Temperature Behavior and Fire Resistance

Geopolymer concrete is significantly more stable under high temperatures and direct fire than OPC, giving better fire resistance and long-term durability after repeated heating. In OPC, bound water cannot escape before C–S–H dehydration and portlandite decomposition (≈ 300 – 500 °C), causing pore pressure, microcracking, and explosive spalling (Kong & Sanjayan, 2010; Amran et al., 2022). In a simulated fire test on same-grade OPC and geopolymer

specimens exposed for two hours at 500 and 1200 °C, geopolymer samples lost 7.6% and 7.77% mass while OPC lost 8.75% and 12.5%; geopolymer retained 116% and 67% of strength versus OPC's 73% and 39% at those temperatures. At 1200 °C OPC specimens cracked and spalled, whereas geopolymers showed ~7.77% mass loss, ~67% strength retention, and no cracking or spalling (Razak et al., 2022). SEM evidence suggests the geopolymer matrix consolidates rather than disintegrates, possibly via further geopolymerization and sintering at high temperature. Amran et al. (2022) concluded fire resistance depends on precursor and alkali type and dosage, aggregate makeup, and fillers/fibres, with low-CaO precursors outperforming high-CaO ones due to fewer volatile/expansive products. Developments with bamboo-ash and lightweight geopolymers show excellent strength retention after heating to 800 °C, reinforcing geopolymer advantages over OPC in high-temperature/fire conditions (Przybek et al., 2025).

Table 3: Fire and high-temperature performance of geopolymer vs OPC concrete

Temperature range	OPC concrete behavior	Geopolymer concrete behavior	Typical residual strength trend	Key observations	References
Ambient–200 °C	Minor dehydration; small strength loss	Minimal microstructural change; some systems show slight strength gain	OPC: slight decrease; GP: stable or slight increase	Water loss and early microcracking begin in OPC	(Kong & Sanjayan, 2010; Amran et al., 2022)
200–500 °C	Progressive C–S–H dehydration; portlandite decomposition above ~300–400 °C	Continued geopolymerization and sintering; matrix densification	OPC: moderate decrease; GP: often stable or improved up to ~500 °C	Fly ash-based GP can show higher residual strength than OPC at 500 °C	(Kong & Sanjayan, 2010)
500–800 °C	Severe cracking, spalling risk; significant strength loss	Retains largely intact aluminosilicate framework; reduced spalling	OPC: large decrease; GP: moderate decrease, still substantial	Geopolymer shows less cracking and no/low spalling compared to OPC	(Razak et al., 2022)
800–1200 °C	Extensive degradation, explosive spalling, very low residual strength	Matrix densifies and sinters; retains >50% compressive strength in some systems	OPC: very low; GP: considerably higher than OPC at 1200 °C	GP exhibits lower mass loss and higher structural integrity after fire	(Razak et al., 2022)

Table 3 provides Comparative high-temperature and fire behavior of geopolymer and OPC concrete-including microstructural response, residual strengths and trends, and typical mode of failure. Considering the specifically designed use in UHI applications, this thermal stability matters more for durability from continued cyclical, passive solar heating than direct fire safety: pavement and surface envelope materials that daily experience 50–70+ °C after exposure to solar irradiance have less opportunity to undergo deleterious microstructural damage than a OPC counterpart would and remain thermally and mechanically stable and resilient after many more cycles of this thermal and environmental regime (Wasim et al., 2021).

6. Solar Reflectance, Albedo, and Surface Finish

Solar reflectance (albedo) largely controls diurnal surface temperatures of pavements and roofs by determining how much shortwave radiation is absorbed versus reflected (Levinson & Akbari, 2002; Santamouris, 2013). Field and lab studies show raising pavement albedo from asphalt's ~0.05–0.10 to >0.30 (reflective coatings or light concrete) can lower peak surface temperatures by ~10 °C or more, with smaller cooling of near-surface air (Middel et al., 2020; Kyriakodis & Santamouris, 2018; Mohegh et al., 2017).

Geopolymer concretes can achieve higher surface reflectance than typical grey OPC in multiple ways, including: choice of precursor, using reflective fine aggregates, surface treatments, and reflective coatings (Zhu, S., & Mai, X., 2019). The lower density and porosity of geopolymers' binder impact nearby reflectance and emissivity, thus enabling mix designs to concurrently satisfy thermal and mechanical requirements (Przybek et al., 2025). Additionally, studies on geopolymer pavement solar reflectance and long term albedo stability are limited compared to work on thermal conductivity and fire performance (Vujovic et al., 2021; Levinson & Akbari, 2002). Much UHI

literature using measured albedos for OPC, asphalt, and coatings, extrapolates such findings to geopolymers, but direct validation is still sparse.

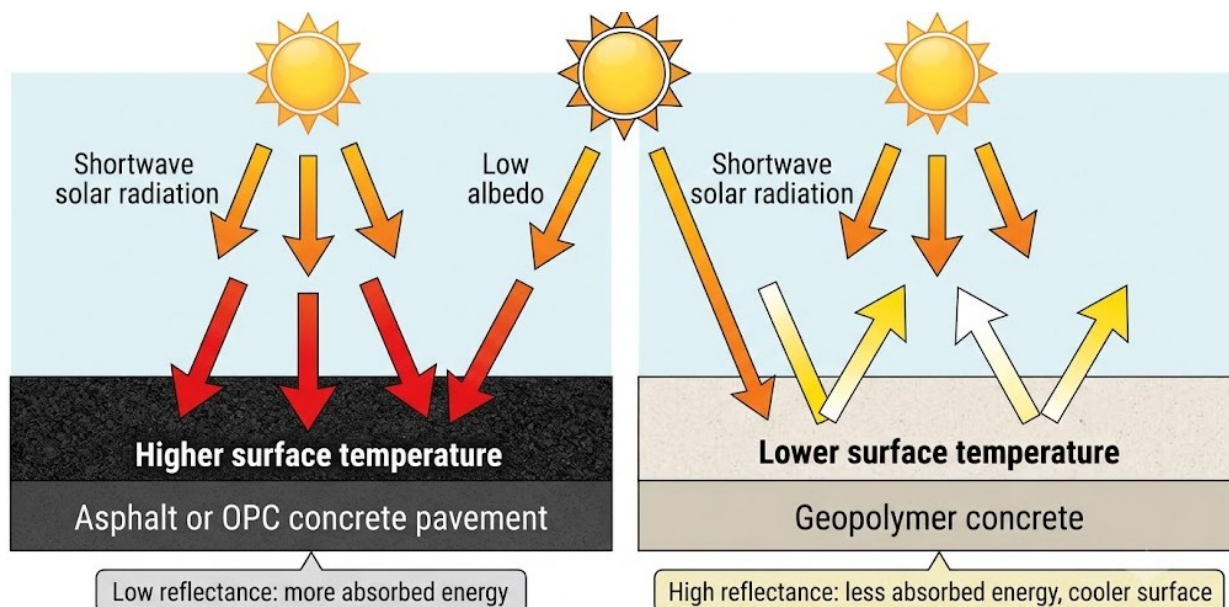


Fig 3: Impact of surface texture and solar reflectance of pavement

Dark low-albedo surfaces that absorb more energy will heat up, while light, reflective geopolymer pavement remains cool (Fig. 3). Still, little research exists on geopolymer pavement solar reflectance and the long term persistence of albedo relative to studies on geopolymer thermal conductivity and fire performance. Many UHI papers rely on measured albedos for OPC, asphalt, and coating materials and draw their own conclusions on the applicability of geopolymers, but validation in this context is inconsistent (Pomerantz et al., 1997; Kyriakodis & Santamouris, 2018).

7. Effect of Curing Strategy on the Thermo-Mechanical Behavior

Optimal curing conditions allow geopolymerization to occur to an extent that optimises density, porosity, and mechanical and thermal properties essential to UHI reduction performance. Metakaolin – based geopolymers have higher solubility under high curing temperature and shorter curing times which lead to higher strength and density up to an optimum point, while excessive time and temperature cause moisture extraction, shrinkage and microcracking and thus lower strength (Rovnaník, 2010). Fly ash and fly ash-GGBS geopolymers achieve curing strength at 60 – 90 °C for a few hours to a day while 90–120°C affects strength adversely. Curing temperature and NaOH molarity modulate strength development and durability: either excessive molarity, long cure time, or very high temperature will be harmful (Gorhan & Kurklu, 2014). For UHI, curing time/temp drive the final porosity/density, which controls the heat transfer property of thermal conductivity and volumetric heat capacity, while specific heat capacity is nearly density independent. Ambient curing and GGBS accelerated systems are being considered for high temperature oven curing not being practical for in situ pavement and building envelopes to attain sufficient strength without external heating (Deb et al., 2014; Paruthi et al., 2024). It is important to consider the compromise between curing practicality and extent of geopolymerization when relating laboratory thermal data and mix optimisation to field scale.

Table 4: Influence of curing regime on geopolymer concrete performance

Curing regime	Main microstructural effect	Strength outcome	Thermal-property implication	Practical relevance	References
Low-temperature / short curing	Incomplete geo-polymerization	Lower early strength	More porous, less predictable conductivity	Easy to apply, but may underperform	(Rovnaník, 2010; Görhan&Kürklü, 2014)
Moderate oven curing	Faster dissolution and polycondensation	Highest strength in many systems	Denser matrix, more stable thermal transport	Good for lab-optimized products	(Rovnaník, 2010; Görhan&Kürklü, 2014)
Excessive curing temperature	Moisture loss, shrinkage cracking, pore disruption	Strength decline	Unstable porosity and thermal response	Can damage performance	(Rovnaník, 2010; Görhan&Kürklü, 2014)
Ambient curing with slag/GGBS	Accelerated hardening without external heat	Moderate to high strength if mix is optimized	Practical thermal performance for field use	Best for real infrastructure use	(Deb et al., 2014; Paruthi et al., 2024)

Table 4 show the effects of different curing regimes on the microstructure, strength, the heat of the geopolymer concrete, as well as, its application in practice and the explanatory literature is specified (parentheses are literature sources in the last column).

8. Applications in Pavement and Building-Envelope Systems

8.1 Pavement applications

Pavement quality geopolymer concrete attracts interest as a pavement material with higher early strength, lower permeability, and enhanced chemical/thermal loading performance versus OPC pavements (Ikotun et al., 2024; Nanda & Priya, 2024). Published values for compressive, flexural, and split tensile strengths equal or higher than standard pavement concrete cement concrete demonstrate that they can withstand repeated loads of traffic and day/night, and annual temperature variations (Ikotun et al., 2024). Beyond load-bearing layers, fly ash- and GGBS-based geopolymers, frequently in combination with ground glass waste powder, have been employed in unbound road base and sub-base stabilization, reducing bulk use of raw materials and lowering embodied emissions while maintaining support strength (Xiao et al., 2020; Sofri et al., 2022; Migunthanna et al., 2022). To reduce UHI, pavement grade geopolymers can be engineered to balance strength, thermal properties, and light/reflective finishing to increase their reflective surface albedo (Zhu, S., & Mai, X. , 2019); however, the high focus on strength, durability, and costs and inconsistent reporting of thermal/UHI metrics signals the need for more field-centric applications studies.

8.2 Building-envelope applications

Porous or expanded aggregate-based lightweight geopolymer concretes can reach low enough thermal conductivities for use as insulation components in envelope wall, roof, and façade construction systems, in both hot-arid and hot-humid climates (Przybek et al., 2025; Zhang et al., 2024; Tayeh et al., 2021). Considering the large urban coverage of envelopes and roofs and their relationship to UHI and cooling energy demand, cool-roof and insulative-envelope design strategies developed for conventional materials can, in principle, be translated to geopolymers if similar level of reflectance, emittance and durability can be obtained (Kyriakodis & Santamouris, 2018). Its demonstrated fire resistant behavior makes geopolymer a viable solution for a not only structural but also skin exterior component where fire safety is integral (Amran et al., 2022; Razak et al., 2022).

9. Environmental and Life-Cycle Considerations

9.1 Carbon savings of geopolymers

The principal appeal of geopolymers to date has been their potential for large reductions in embodied carbon relative to OPC, achieved in part through avoiding the carbon- and energy-intensive calcination of limestone. Turner and Collins (2013) initially estimated CO₂-equivalent savings at 54–71% for geopolymer concrete, but noted these

results are sensitive to the embodied impacts of the alkali activator. Subsequent meta-analyses and LCAs show a large net savings in carbon overall, but dependent on source of precursor, transportation, amount of activator, and boundaries of assessment (Shobeiri et al., 2021). These system-wide results are supported by context-specific case studies. Kiruthika et al. (2024) demonstrated the use of geopolymer concrete to replace OPC in high-rise residential construction reduces embodied energy and CO₂ while maintaining structural performance and reducing costs, however slightly, thus Mechanical and Environmental benefits need not be mutually exclusive. In addition to embodied carbon, replacing fly ash, GGBS and other industrial by-products as precursors also contributes to circular-economy via the recycling of landfill wastes and the decreased use of virgin raw materials as demonstrated by the ongoing assessment by Almutairi et al (2021); Nanda & Priya, 2024). Nonetheless, the environmental argument for geopolymer as a UHI-reducing material is relevant to, but should not be conflated with its embodied-carbon justification. A material can have minimal embodied-carbon but insufficient operational-thermal efficacy, or the other way round. The optimal strategy is a co-optimisation of the mix design (low embodied-carbon, high operational-thermal efficacy), which has yet to be studied in detail (Wasim et al., 2021; Ikotun et al., 2024).

10. Critical Research Gaps and Future Directions

Despite progress in understanding GPC's mechanical properties, durability, fire performance and embodied-carbon advantages, three knowledge gaps hinder its use as a UHI-mitigation strategy. First, no standardized GPC-specific thermal test methods exist for pavement and envelope systems; published thermal conductivity and specific heat tests all come from small-scale steady-state laboratory studies that do not fully reflect transient, diurnal field loading (Przybek et al., 2025). Second, we lack adequate measurements of the solar reflectance, albedo and thermal emittance of GPC compared to OPC, cool pavements and reflective coatings for critical UHI-performance benchmark comparisons (Kyriakodis & Santamouris, 2018; Middel et al., 2020). Third, and most importantly, comprehensive field demonstration on a large scale, and multi-year monitoring of UHI mitigating geopolymer pavements and envelopes under real weather and traffic conditions, is essentially absent in literature. Standard cool-pavement studies already encompass a large number of field cases, but geopolymer studies continue to be largely laboratory-driven. Fourth, durability is under-examined under conditions of combined urban exposure—cyclic thermal loading, ultraviolet (UV) radiation, atmospheric weathering and (where applicable) freeze–thaw exposure. Existing GPC durability investigations are largely concerned with chemical (sulfate, acid and chloride) attack, whilst ignoring the temporal effects of environmental weathering on reflectance and thermal properties. Lastly, the optimization of GPC mix design should be multidimensional, where the impact of every mix parameter on the composite mechanical and thermal performance, embodied carbon, and costs is weighed against one another instead of multi-objective optimization of various parameters (Shobeiri et al., 2021; Ikotun et al., 2024). Filling the research gaps calls for laboratory studies, pilot-scale demonstrations, and long-term field monitoring.

11. Conclusion

Geopolymer concrete exhibits several properties that are of interest from the perspective of UHI mitigation: specific heat capacity and thermal conductivity can be tuned via control of precursors and aggregates. It exhibits improved high-temperature and fire performance relative to traditional concrete and boasts enhanced reflectance via control over mix-design and finishing. Behind these properties lies a binder chemistry which produces a significantly lower embodied carbon footprint compared to conventional concrete; therefore, it is one of few candidates in urban construction capable of delivering simultaneously with respect to the thermal operating performance and the embodied-carbon footprint. The literature demonstrates however, that the UHI mitigation performance is not an inherent property of geopolymer concrete – a characteristic inherent to any class of materials – but relies instead upon the design choices that made for, and include precursor choice, curing regimen, porosity/density management and surfacing.

In order to leverage the full potential of geopolymer for UHI mitigation, there is a need for the integration of testing standards for the assessment of concrete thermal and reflectance properties with outdoor studies reflecting realistic

urban exposure conditions including, durability assessment and combined optimisation frameworks for mixed behaviour modelling. In this way, the contribution to low-carbon, resilient pavement, housing and workplace surfaces will result in significant benefits for increasingly urbanised climates.

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AI-Enabled Sustainable Personalized Language Learning: An Empirical Study of Learners' Experiences

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ABSTRACT

Artificial Intelligence (AI) is increasingly shaping language education by enabling personalized, adoptive and learner centered learning experiences. AI – powered tools like GenAI as conversational chatbots have enhanced language learning through feedbacks, customized pathways for learning and improved learner engagement. Despite these advancements, the existing studies have predominantly focused on conceptual discussions, technology adoption and the effectiveness of specific language learning AI tools, with limited empirical evidence of examining learner's overall experience of AI enabled sustainable personalized language learning. This research addresses the gap by examining learner's perceptions and experiences of AI- enabled personalized language learning within context of sustainable education. A statistical research design was applied and primary responses was collected from 201 respondents through a structured questionnaire. The collected data was used to analyze descriptive statistics to summarize the respondent's demographics and perceptions, Correlation analysis was used to analyse the relationship among the study variables and simple linear regression model analysis was used to understand the influence of AI- enabled personalized language learning on learner engagement, perceived learning effectiveness, learner autonomy and sustainable experience while learning. The findings of the paper indicated that AI-enabled personalized language learning positively contributed on learner's overall experiences by improving engagement, encouraging learner autonomy and enhancing perceived learning effectiveness. The study addressed the identified research gap by providing empirical evidence on learner's experiences with AI-enabled sustainable personalized language learning. The analysis also offers valuable insights to educators, education institutions, policymakers and EdTech developers to create more effective and sustainable language learning practices.

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1. Introduction

Artificial Intelligence is becoming increasingly influential in education, reshaping the ways in which learners engage with, receive and experience learning. The use of Artificial Intelligence such as GenAI, AI Chatbots, intelligent tutoring platforms, adaptive learning applications and automated feedback tools is a new development that provides a new chance for the learners to access the educational content tailored to their individual requirements. This technological advancement is slowly shifting the focus of learning from traditional classroom- based and standardised methods towards more flexible and personalised learnings.

Personalised learning has become significantly important since learners differ in their learning methods, knowledge, abilities, interests and preferred learning modes. A similar learning methods may not necessarily offer the same level of assistance or flexibility to each learner. AI- enable learning platforms can address some of these gaps by personalising learning contents, activities, suggestions and difficulty levels based on individual needs. This allows learners more control over their learning methods and allows them to learn at their own pace of learning. By

integrating the use of AI with personalised learning has the ability to create a more personalised learning environment.

AI-enabled personalisation plays the major role in one of the key areas that is language learning. Language learning largely requires consistent practice, engagement, feedback and constant growth. In traditional classroom learnings, time constraints, class size and individual focus might limit learners' opportunities to success. AI powered language learnings provides various features such as vocabulary development, grammar, translations, writing assistance, conversation and pronunciation practice and quick feedback tools. These technological tools can also allow learners to practice outside the classroom and learn based on their individual needs. Hence AI makes language learning more adaptable, interactive, flexible and personalised. The growing requirement for flexible and continuous learning has led to discussions about sustainability. Sustainable learning involves developing accessible, diverse and adaptable learning experiences that can be moved beyond traditional classroom learning. AI-enabled personalised language learning is helpful by enabling learners to access contents and learn at their own convenience and pace. This adaptability is essential for learners who are increasingly need to develop their skills along with their academic, professional and personal responsibilities.

However, incorporating AI into education creates a several challenges such as inadequate access to technology, privacy concerns, algorithmic bias, inaccurate AI generated contents and over reliance on technology, highlighting the importance of teachers and human connections. As a result, integrating AI in language learning requires balanced consideration between technological skills and learners' actual requirements and experiences. The increasing integration of AI, personalised language learnings and sustainable learning is an essential part of educational transformation as AI provides more personalised and flexible learning opportunities while supporting continued access to traditional classroom learnings. Therefore, it is very much important to understand learners' experiences to determine whether AI-enabled personalised language learning can produce learning environments that are significant, efficient, engaging, personalised and sustainable.

2. Review of Literature

2.1 AI - Enabled Personalised Learning

The growing adoption of AI within the educational sector has led to a change from standardized learning and toward techniques that are more capable of fulfilling the requirements of individual learners. AI technologies can analyse learner patterns and provide adaptive content, feedback, and learning pathways, making personalized learning more practical across different learning environments (Aprilla Fortuna, 2025). Personalised learning has also been associated with adoptable learning pathways that respond to learner's progress, preferences and specific needs (Arani, 2024). The development of GenAI has increased these possibilities by allowing learning materials and feedback to be tailored to individual learning paths (Baskara, 2024). These developments indicate that AI-enabled personalisation can make learning more flexible and learner-centred, while the learners get more control of their learning experiences.

The relationship between AI and personalised learning has also been linked to sustainable education. AI-powered personalised learning can provide learners with adaptable learning opportunities while also promoting long term educational development (Dandachi, 2023). Adaptive AI systems have additionally been associated with resilient and sustainable learning through implementing personalized learning systems and continuous assistance (Manjunath Munenakoppa, 2026). As a result of the rapid development of adaptive learning, there is currently a substantial relationship between personalization and educational sustainability (Wadim Strielkowski, 2024). However, these developments highlight the importance of understanding if the personalization provided by AI can actually be perceived positively by learners.

2.2 Language Learning and Artificial Intelligence

Using AI for language learning provided more opportunities for learners to receive support that is tailored to their language skill and progress. Natural language processing, speech recognition, automated writing evaluation, tutoring

systems, and bots are some examples of AI technologies that are becoming increasingly significant in language learning (Jeong-Bae Son, 2023). AI-powered personalized language learning can also generate adaptive content, feedback from the learner, and learning pathways personalised to every learner's requirement (Arani, 2024). Personalized English language learning has also been linked to adaptive platforms, data-driven learning, and continuous feedback, which can result in more personalized learning experiences (Bhargav H Chohla, 2025). This means that AI is slowly but steadily becoming an integral for the learning process rather than another learning tool.

The application of AI in English Language learning could also enable learners to receive personalized learning materials. Instant feedback and the opportunity for practice at their own pace (Uskanovich, 2025). AI-based adaptive systems have also been known to allow flexible learning, instant feedback and increase language learning opportunities (Wah, 2025). According to other researches done on AI tools for personalized language learning, adaptive systems can affect the engagement, motivation and autonomy of the students (Kazi Bushra Orpy, 2026). This growing body of evidence is causing the emphasis to shift from the capabilities of AI to the learner experiences in using AI.

2.3 Learner Engagement and Perceived Learning Effectiveness

Learner engagement is an essential component of these experiences since personalized content and immediate feedback can motivate learners to become more engaged in language-learning activities. AI-enabled English language learning has been associated to enhanced engagement, motivation, and self-directed learning. Personalized AI systems can also boost learner motivation by lowering language fear and offering learning support tailored to individual needs (Wah, 2025). AI-supported multimodal language activities can enhance learner engagement and motivation by linking language learning to sustainability-related subjects (Aydın Yıldız, 2025). These findings indicate that personalization can make language learning more relevant and interesting for learners.

The significance of AI-generated learning content can also have an impact on how learners evaluate their learning effectiveness. Learners and instructors have indicated positive perceptions of AI-based personalized learning, demonstrating that adaptive learning approaches are acceptable (Ali Al-Badia, 2022). AI-generated location-based vocabulary resources have also received favourable feedback with regard to relevance, accuracy, motivation, and learning efficiency (Liuyi Yang, 2025). However, learning outcomes from AI-supported language learning are influenced not just by technology, but also by instructional design, learning activities, and trainer engagement (Yan Li, 2025). This suggests that perceived learning efficiency should be understood through the learner's experience rather than determined based on the availability of AI technologies.

2.4 AI and Learner Autonomy

Personalized learning can also provide learners more control over their learning experience. AI-driven personalized learning enables learners to choose learning resources, learn at their own pace, and continue studying outside traditional learning environments (K. Bayly-Castaneda, 2024). AI-supported language learning has also been linked to individual learning, which allows learner to take charge for better proficiency. Based on to the empirical evidence on personalized language learning, learner autonomy is one of the most significant outcomes related with AI powered learning (Kazi Bushra Orpy, 2026). These findings suggest that AI personalization may help learners become more independent in managing their learning.

However, having greater access to AI does not always result in increased learner autonomy. Excessive reliance on AI could encourage dependency and diminish learners' motivation to engage in independent learning tasks (Wah, 2025). The efficiency of AI-supported in learning the language is also determined by how teachers and students engage with AI in the learning environment (Yan Li, 2025). Hence, the key issue is not whether AI enables personalized learning, but if that personalization genuinely increases learners' independence and autonomy.

2.5 Sustainable Learning Experiences

The backbone of continuous and flexible learning leads to inclusion of sustainability as a component of personalized learning using artificial intelligence. Generative AI can assist learners build skills in more flexible educational

environments while also providing personalized learning experiences (Baskara, 2024). AI-enabled personalized learning has also been related to learner empowerment, meaningful learning, and skill development (Dandachi, 2023). Adaptive AI can contribute to more sustainable and resilient education by providing flexible learning methods and personalized learning assistance (Manjunath Munenakoppa, 2026). AI-supported language learning can also assist learners acquire language skills based on their unique needs, hence contributing to long-term growth (Omar Ali Al-Smadi, 2024). This shows that sustainability can include not only environmental challenges but also flexible and adaptable learning.

When AI is used to personalize language learning, the relationship becomes critical. The use of location-based vocabularies enables learners to get personalized language content in real-world circumstances outside of the classroom. AI-driven multi-modal language learning promotes sustainability, reflection, and engagement (Aydin Yıldız, 2025). AI-powered adaptive systems can provide learners with instant feedback and personalized learning opportunities while also increasing engagement and proficiency in languages (Vo, 2025). Similarly, AI-based personalized learning can help to ensure long-term learning by adapting learning content to learners' pace, preferences, and performance while also enabling ongoing assessment and feedback (Fatima Rahioui, 2025). Learners that adopt AI-generated content have more positive perceptions of long-term tailored learning (Zhileng Xiong, 2026). These findings confirm the relationship between AI, personalization, and sustainable learning, but they also demonstrate that sustainability is frequently considered within specific purposes rather than as part of the overall learner experience.

3. Research Gap

The review of the existing literature indicates a comprehensive discussion of AI-enabled personalized learning, language learning, learner engagement, learning effectiveness, learner autonomy, and sustainable education. These studies provide important insights into AI's ability to personalize learning and improve learner experiences. However, there has been little empirical research on the relationship between AI enabled personalized language learning and long-term learning experiences from the perspective of learners. Sustainability is frequently considered at a higher conceptual or educational level, whereas research on AI enabled language learning has primarily focused on engagement, motivation, language performance, and autonomy. The most recent studies has started to connect AI-generated content to long-term personalized learning, but the combined impact of AI- enabled personalization on learner engagement, perceived learning effectiveness, learner autonomy, and long-term learning experiences is still unexplored (Xiong & Huang, 2026). Considering all of these gaps, this paper aims to address them by empirically examining these four characteristics from the learners' perspective, particularly examining how AI enabled personalized language learning to long-term learning experiences.

4. Research Objectives

- To examine learner's perception of AI-enabled personalized language learning within the sustainable education.
- To analyse the relationship between AI-enabled personalized language learning, learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences.
- To evaluate the influence of AI-enabled personalised language learning on learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences.

5. Research Methodology

5.1 Research Design

This study uses a quantitative research approach to study learner's experiences with AI-enabled personalized language learning and its influence on learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences.

5.2 Research Variables

Independent Variables: AI- Enabled Personalized Language Learning
Dependent Variables: Learner Engagement, Perceived Learning Effectiveness, Learner Autonomy, Sustainable Learning Experiences.

5.3 Population

The population of the study consist of learners who have experience using AI-powered tools for language learning.

5.4 Sample Design

- A total of 239 responses were collected through structured questionnaire. After screening the collected responses, 201 valid responses were considered for statistical analysis.
- The sampling unit includes learners who have participated in the survey and have used AI Tools for language learning.
- The study has used convenience sampling method. Respondents was selected as per their availability and their willful participation in filling their response.

5.5 Data Collection

- Primary Data was obtained through a structured questionnaire with close ended questions. The questionnaire was distributed digitally through Google Forms.
- The questionnaire included demographic questions and their experiences with AI-enabled personalized language learning questions followed by statements related to research variables were measured using Likert Points Scale where Strongly Disagree was 1 and Strongly Agree was 5.
- The questionnaires was prepared based as per the research objectives and hypothesis.

5.6 Formulation of Hypothesis

Hypothesis 1: The relationship between AI-enabled personalized language learning and learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences.

Null Hypothesis (H01): There is no statistically significant relationship between AI-enabled personalized language learning and learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences.

Alternative Hypothesis (H11): There is significant positive relationship between AI-enabled personalized language learning and learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences.

Hypothesis 2: The impact of Artificial Intelligence enabled personalized language learning on learner engagement, perceived effectiveness of learning, Learner Autonomy and Sustainable Learning Experience. **Null Hypothesis (H02):** AI- enabled personalized language learning does not have significant influence on learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences. **Alternative Hypothesis (H12):** AI- enabled personalized language learning have significant positive influence on learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences.

5.7 Data Analysis Tools & Techniques

The data that was collected were analyzed using descriptive statistics, correlation and simple linear regression.

- Descriptive Statistics: was used to understand the summary of the data and understand the overall response patterns.
- Pearson Correlation: was for examining the relationship of AI-enabled personalized language learning and learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences.

- Simple Linear Regression (SLR): were used to understand the influence of AI-enabled personalized learning with learner engagement, perceived effectiveness, learner autonomy and sustainable learning experiences.

6. Data Analysis and Interpretation

The data analysis part of the paper is conducted to assess the role of AI-enabled personalized language learning influencing learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences. For the analysis, composite scores were calculated for five variables: AI-enabled personalized language learning, learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences. The analysis begins with demographic analysis of the respondents and their patterns of AI usage in language learning followed by Cronbach's Alpha Reliability Analysis; Descriptive Statistics, which provides an overall understanding of the data; Correlation Analysis, which examines the relationship between the research variables and tests the correlation hypothesis (H01/ H11) and regression analysis, which evaluates the influence of AI-enabled personalized language learning on learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences and tests the regression hypothesis (H02/ H12).

6.1 Demographic Analysis

6.1.1 Gender

Gender Distribution (N=239)

Gender	Frequency	Percentage (%)
Female	127	53.14%
Male	108	45.19%
Prefer not to say	4	1.67%
Total	239	100.00 %

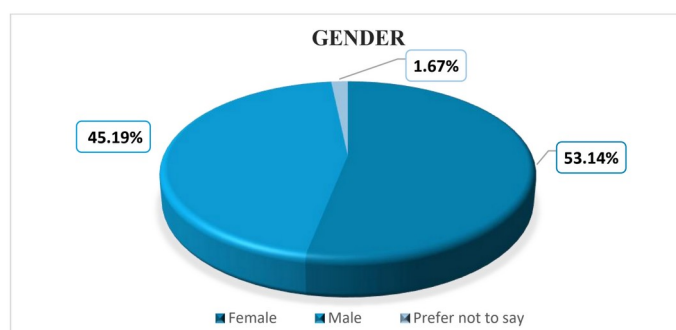


Figure 1: Gender distribution of respondents

The sample consists of 239 respondents with a relatively even representation across gender categories. Female respondents are of 53.14% (127 females), while male respondents are of 45.19% (108 males). A small portion of 1.67% (4 responders), preferred not to disclose their gender. The distribution indicates that responses obtained were from both male and female participants in fairly comparable proportions, providing representation from both groups for the study.

6.1.2 Age

Age Group (N=239)

Age group	Frequency	Percentage (%)
18-25	202	84.52%
26-30	27	11.30%
31-40	5	2.09%
Above 40	5	2.09%
Total	239	100.00%

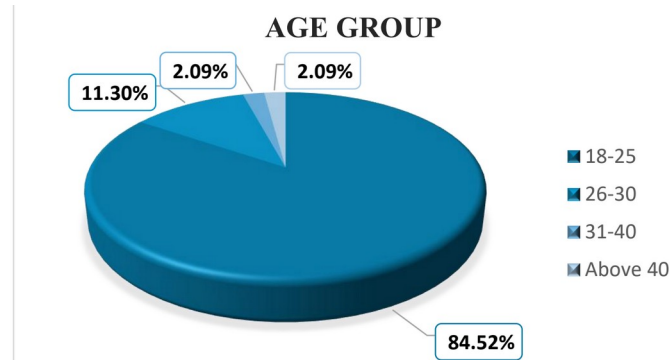


Figure 2: Age group of respondents

The age distribution shows that the respondents in the study are of different age groups. Respondents aged 18-25 years were 84.52% (202 respondents), followed by those aged 26-30 years at 11.30% (27 respondents). The 31-40 years and above 40 age categories both had 2.09% (5 respondents). Overall, the sample includes respondents across all four age categories, with a larger representation of younger participants.

6.1.3 Occupation

Occupation (N=239)

Current Occupation	Frequency	Percentage (%)
Student	197	82.43%
Working Professional	32	13.39%
Others	10	4.18%
Total	239	100.00%

Note: Others category includes doctors, teachers, research scholars and job seekers.

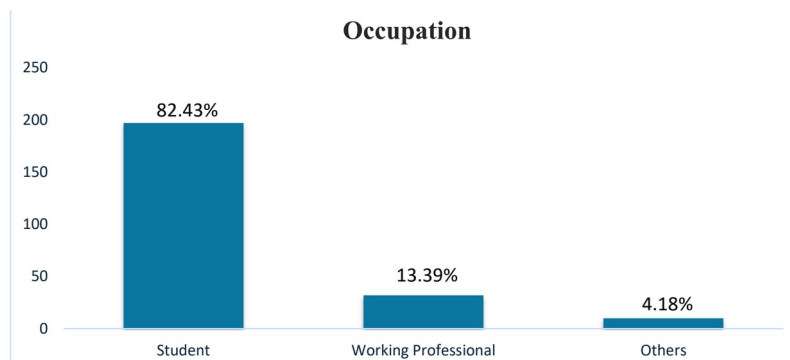


Figure 3: Occupation of respondents

The respondents are divided into various occupational groups, with 197 respondents (82.43%) are students and 32 respondents (13.9%) are working professionals. The remaining 10 respondents (4.18%) fall under other categories which includes doctors, teachers, research scholars and job seekers. This shows that the study includes participants from both student and professional backgrounds, with some representation from other occupational groups as well.

6.2 Patterns of AI Usage in Language Learning

6.2.1 How many have used AI tools for language learning?

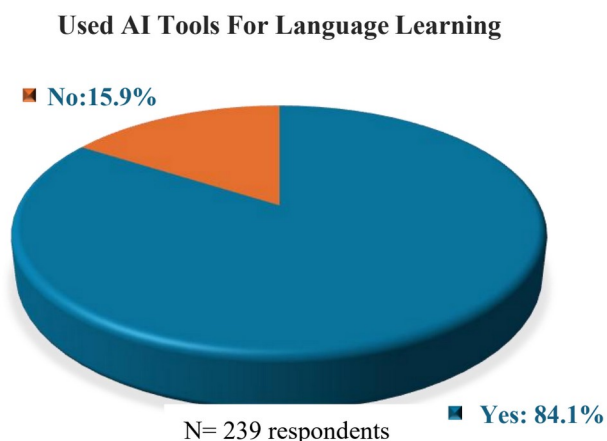


Figure 4: Respondents who have used AI tools for language learning

The above analysis shows that out of 239 total respondents, 201 (84.1%) respondents have use AI- powered tools language learning while 38 (15.9%) respondents have not used any AI tools for language learning. This indicates that AI tools are already being used by a large number of respondents as part of their language learning activities, The remaining respondents who have not used AI tools also indicates that there remains scope for further adoption. Based on these results, the 201 respondents who have used these tools for learning are considered as respondents in the analysis of this paper.

6.2.2 AI Tools Used for Language Learning

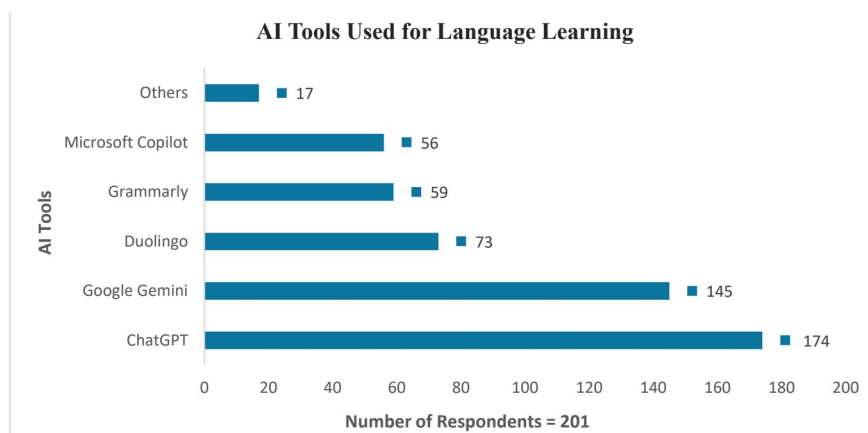


Figure 5: AI tools used for language learning

Among 201 respondents who reported using AI-based tools for language learning ChatGPT was the most frequently used tool with 174 (86.6%) respondents followed by Google Gemini with 145 (72.1%) respondents, Duolingo was used by 73 respondents (36.3%), while Grammarly and Copilot were used by 59 (29.4%) and 56 (27.9%) respondents respectively. The remaining 17 (8.5%) respondents reported using other tools such as Claude, DeepL Write, Perplexity, Grok and Google Translate. This analysis indicates that the respondents use a mix of general-

purpose AI tools and specified language learning applications. The relatively high use of ChatGPT and Google Gemini shows that general - purpose GenAI tools are also being used for language learnings alongside platforms specifically designed for language learning.

6.2.3 Frequency of Users Using AI for Language Learning

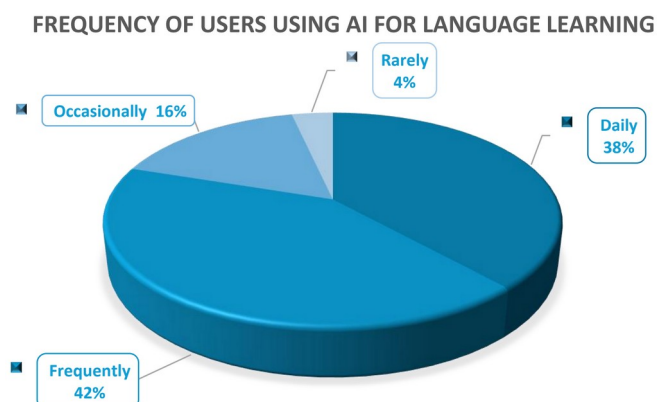


Figure 6: Frequency of using AI for language learning

The above analysis shows that among the 201 respondents who use AI tools for language learning, 84 (41.8%) reported using them frequently, and 77 (38.3%) reported using them daily. A further 33 respondents (16.4%) use AI tools occasionally, while only 7 respondents (3.5%) indicate they use them rarely. Overall, the analysis indicates that a significant majority of respondents use AI products on a regular basis, with 80.1% indicating daily or frequent use. This shows how Artificial Intelligence has become an major part of many respondents' for language learning experience.

6.2.4 Duration for Language Learning with AI Tools

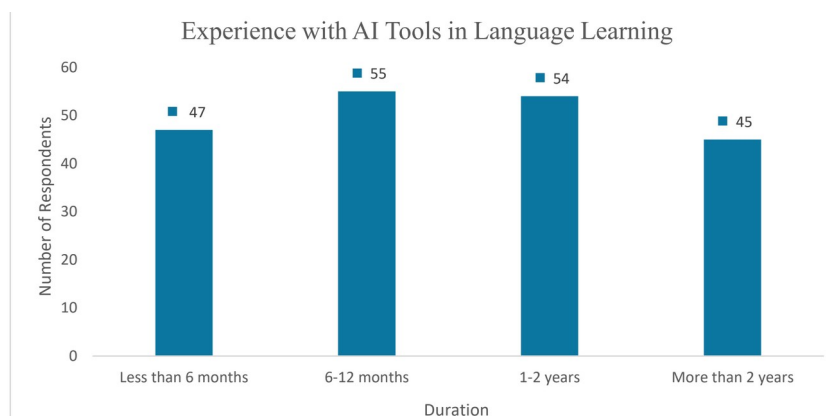


Figure 7: Experience with AI tools in language learning

The analysis show that 55 respondents (27.4%) have been using AI tools for 6-12 months, which was closely followed by 54 respondents (26.9%) with 1-2 years of experience. 47 (23.4%) of respondents have used AI tools. Some 45 (22.4%) have been using them for over 2 years, while less than 6 months put in by others. Overall, respondents' attitudes are generally. The duration groups were distributed evenly across the new users and experienced ones.

6.3 Cronbach's Alpha Reliability Analysis

Reliability Analysis of Research Variables

Variables	Cronbach's Alpha (α) Value	Reliability Level
AI-Enabled Personalized Learning	0.9166	Excellent
Learner Engagement	0.8907	Good
Learning Effectiveness	0.9001	Excellent
Learner Autonomy	0.9090	Excellent
Sustainability Learning	0.9192	Excellent
Overall	0.9715	Excellent

The reliability analysis indicates that the Cronbach's Alpha values for the research variables are within the range of good to excellent levels, 0.8907 to 0.9192. The Cronbach's alpha value of 0.9715 shows high level of reliability across the variables. The results indicate that the measurements applied in the study are consistent, and are suitable for subsequent statistical analysis.

6.4 Descriptive Statistics

Descriptive Statistics of Research Variables

Statistic	AI-Enabled Personalized Learning	Learner Engagement	Perceived Learning Effectiveness	Learner Autonomy	Sustainable Learning Experiences
Mean	3.753	3.738	3.753	3.779	3.843
Standard Deviation	0.985	0.914	0.972	1.010	0.987
Standard Error	0.069	0.064	0.069	0.071	0.070
Kurtosis	1.073	0.977	0.707	0.779	1.292
Skewness	-1.247	-1.071	-1.106	-1.150	-1.327

The analysis shows that mean values for all five variables are higher than the midpoint of five-point scale, ranging from 3.738 to 3.843. Sustainable Learning Experiences has the highest mean, followed by Learner Autonomy. AI-Enable Personalised Language Learning and Learning Effectiveness have similar mean values, while Learner Engagement has the lowest mean. Overall, the analysis indicates that respondents had generally positive views across the different aspects of AI-Enabled Personalised Language Learning.

The standard deviation values range between 0.914 to 1.010 indicating some variation in the responses. The negative skewness values for all five variables ranges from -1.071 to -1.327, indicating that respondents were generally towards higher end of the scale. The kurtosis values range from 0.707 to 1.292, indicating relatively greater concentration of responses around the centre. The Skewness & Kurtosis values fall within the commonly accepted range ± 2 , indicating that the distribution do not show substantial departures from normality. Therefore, the data are considered reasonably reliable for the Pearson Correlation and Simple Linear Regression analysis.

6.5 Correlation Analysis

Pearson's Correlation was conducted to analyze the relationship between the research variables, which includes AI-enabled personalized learning, learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences.

Pearson Correlation Matrix

	AI-Enabled Personalized Learning	Learner Engagement	Perceived Learning Effectiveness	Learner Autonomy	Sustainable Learning Experiences
AI-Enabled Personalized Learning	1.000	0.770	0.741	0.738	0.725
Learner Engagement	0.770	1.000	0.767	0.709	0.752
Perceived Learning Effectiveness	0.741	0.767	1.000	0.839	0.842
Learner Autonomy	0.738	0.709	0.839	1.000	0.839
Sustainable Learning Experiences	0.725	0.752	0.842	0.839	1.000

The analysis shows that AI-enabled personalized language learning has strong positive relationship among all four dependent variables. AI-enabled personalized language learning has strong positive correlation with learner engagement ($r=0.770$), followed by perceived learning effectiveness ($r=0.741$), learner autonomy ($r=0.738$) and sustainable learning experiences ($r=0.725$). This indicates that respondents who experienced higher levels of AI-enabled personalized language learning reported more positive learning experiences. Among the four variables, learner engagement has the strongest relationship with AI-enabled personalized learning.

The dependent variables also indicate strong positive relationships among the dependent variables. Perceived learning effectiveness is strongly correlated with learner autonomy ($r=0.839$) and substantial learning experiences ($r=0.842$) while learner autonomy is strongly correlated with sustainable experiences ($r=0.839$). These relationships indicate that the different dimensions of learning experiences are closely interconnected.

Since the relationships between AI-enabled personalized language learning and four dependent variables are significant at $p < 0.001$. Therefore, we reject null hypothesis (H01) and accept alternative hypothesis (H11). The result indicate there is significant positive relationship between AI-enabled personalized learning, learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences. Overall, the correlation analysis supports the relationship between the research variables and provide a basis for the further regression analysis.

6.6 Regression Analysis

To test Hypothesis, four separate simple linear regression models were estimated, with AI-enabled personalized language learning as independent variable and learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences as dependent variables.

6.7 Hypothesis 1: AI-Enabled Personalized Language Learning → Learner Engagement

Regression Statistics	Value
Multiple R	0.770
R Square	0.593
Adjusted R Square	0.591
Standard Error	0.584
Observations	201

	df	SS	MS	F	Significance F
Regression	1	98.951	98.951	289.730	1.09×10^{-40}
Residual	199	67.964	0.342		
Total	200	166.915			

Regression Coefficients — AI-Enabled Personalized Language Learning Predicting Learner Engagement

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	1.058	0.163	6.503	6.22×10^{-10}	0.737	1.379
AI-Enabled Language Learning	0.714	0.042	17.021	1.09×10^{-40}	0.631	0.797

6.7.1 Regression Equation

$$\text{Learner Engagement} = 1.058 + 0.714 \times (\text{AI-Enabled Personalized Language Learning})$$

Interpretation

The model is significant statistically, $F(1, 199) = 289.730$, $p < 0.001$, shows that AI-enabled personalized learning significantly predicts learner engagement. The R^2 value of 0.593 shows that AI-enabled personalized learning explains 59.3% of the variation in learner engagement, while the Adjusted R^2 of 0.591 indicates a similar level of explanatory power after adjustment. The Value of Multiple R was 0.770 which indicates a strong linear relationship of these variables.

The regression coefficient for AI-enabled personalized learning is positive and statistically significant ($B = 0.714$, $t = 17.021$, $p < 0.001$). That means that a increase in AI-enabled personalized learning is associated with an estimated 0.714-unit increase in learner engagement. The regression coefficient has a 95% confidence interval ranging from 0.631 to 0.797, meaning the estimated coefficient is still positive within this interval. Since p-value falls below the 0.05 level of significance, the correlation between the use of AI enabled personalized learning and the level of engagement of learners is statistically significant. Thus, the Null hypothesis (H_0) is rejected, while Alternative hypothesis (H_1) is accepted. The results suggest a strong relationship between personalized learning based on AI and student engagement, namely a positive predictive relationship.

6.8 Hypothesis 2: AI-Enabled Personalized Language Learning → Learner Effectiveness

Regression Statistics	Value
Multiple R	0.741
R Square	0.548
Adjusted R Square	0.546
Standard Error	0.655
Observations	201

	df	SS	MS	F	Significance F
Regression	1	103.662	103.662	241.614	3.41×10^{-36}
Residual	199	85.379	0.429		
Total	200	189.040			

Regression Coefficients — AI-Enabled Personalized Language Learning Predicting Perceived Learning Effectiveness

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	1.010	0.182	5.538	9.59×10^{-8}	0.651	1.370
AI-Enabled Language Learning	0.731	0.047	15.544	3.41×10^{-36}	0.638	0.824

6.8.1 Regression Equation

$$\text{Effectiveness Score} = 1.010 + 0.731 \times (\text{AI-Enabled Personalized Language Learning})$$

Interpretation

The model is significant statistically, $F(1, 199) = 241.614$, $p < 0.001$, indicating that AI-enabled personalized language learning significantly predicts perceived learning effectiveness. The R^2 value of 0.548 shows that AI-enabled personalized language learning explains 54.8% of the variation in perceived learning effectiveness, while the Adjusted R^2 of 0.546 indicates a similar level of explanatory power after adjustment. The value of Multiple R was 0.741 which shows a strong linear relationship between the variables.

The estimated regression coefficient for AI-enabled personalized language learning is positive ($B = 0.731$, $t = 15.544$, $p < 0.001$). This means that increase in AI-enabled personalized language learning is associated with an estimated 0.731-unit increase in perceived learning effectiveness. The regression coefficient has a 95% confidence interval ranging from 0.638 to 0.824, shows that the estimated coefficient remains positive across the interval.

Since p-value is less than the 0.05 level of significance, the relationship between AI-enabled personalized language learning and perceived learning effectiveness is significant. Thus, the Null hypothesis (H_0) is rejected, while Alternative hypothesis (H_1) is accepted. The result shows that AI-enabled personalized language learning has a significant positive predictive relationship with perceived learning effectiveness.

6.9 Hypothesis 3: AI-Enabled Personalized Language Learning → Learner Autonomy

Regression Statistics	Value
Multiple R	0.738
R Square	0.545
Adjusted R Square	0.542
Standard Error	0.683
Observations	201

	df	SS	MS	F	Significance F
Regression	1	111.142	111.142	238.124	7.55×10^{-36}
Residual	199	92.881	0.467		
Total	200	204.023			

Regression Coefficients — AI-Enabled Personalized Language Learning Predicting Learner Autonomy

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.938	0.190	4.932	1.71×10^{-6}	0.563	1.314
AI-Enabled Language Learning	0.757	0.049	15.431	7.55×10^{-36}	0.660	0.853

6.9.1 Regression Equation

$$\text{Learner Autonomy} = 0.938 + 0.757 \times (\text{AI-Enabled Personalized Language Learning})$$

Interpretation: The model is significant statistically, $F(1, 199) = 238.124$, $p < 0.001$, which suggests that the model is predictive of learner autonomy and that AI-enabled personalized language learning has a significant impact. The R^2 value of 0.545 reveals that the AI-based personalized language learning model accounts for 54.5% of the variance in learner autonomy, and the Adjusted R^2 value was 0.542, nearly the same. The multiple correlation coefficient is 0.738, which means that the two variables are indicating a strong relationship between the two variables.

The estimated regression coefficient for AI-enabled personalized language learning is positive ($B = 0.757$, $t = 15.431$, $p < 0.001$). This means that increase in AI-enabled personalized language learning is associated with an

estimated 0.757-unit increase in learner autonomy. The regression coefficient has a 95% confidence interval ranging from 0.660 to 0.853, indicating that the estimated coefficient remains positive across the interval.

Since p-value is less than the 0.05 level of significance, the relationship between AI-enabled personalized language learning and learner autonomy is significant. Thus, the Null hypothesis (H02) is rejected while Alternative hypothesis (H12) is accepted. The findings show that AI-enabled personalised language learning has a significant positive predictive relationship with learner autonomy.

6.10 Hypothesis 4: AI-Enabled Personalized Language Learning → Sustainable Learning Experience

Regression Statistics	Value
Multiple R	0.725
R Square	0.526
Adjusted R Square	0.524
Standard Error	0.681
Observations	201

	df	SS	MS	F	Significance F
Regression	1	102.556	102.556	221.075	4.02×10^{-34}
Residual	199	92.316	0.464		
Total	200	194.872			

Regression Coefficients — AI-Enabled Personalized Language Learning Predicting Sustainable Learning Experiences

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	1.114	0.190	5.875	1.75×10^{-8}	0.740	1.489
AI-Enabled Language Learning	0.727	0.049	14.869	4.02×10^{-34}	0.631	0.823

6.10.1 Regression Equation

$$\text{Sustainability Learning Experience} = 1.114 + 0.727 \times (\text{AI-Enabled Personalized Language Learning})$$

Interpretation

The model is significant statistically, with $F(1, 199) = 221.075$, $p < 0.001$, as AI-enhanced personalized language learning is a significant predictor for sustainable learning experiences. The R^2 value of 0.526 means that AI-based personalized language learning is able to account for 52.6% of the variation in the sustainable learning experiences, and the Adjusted R^2 value (0.524) indicates a similar explanatory power after adjustment. The Multiple R is 0.725 an indication of a strong linear relationship between both variables.

The regression coefficient of AI enabled personalized language learning is statistically significant ($B = 0.727$, $t=14.869$, $p < 0.001$) and positive. This implies that the estimated increase in sustainable learning experiences is 0.727-unit for every one-unit increase in AI-enabled personalized language learning. The regression coefficient has a 95% confidence interval ranging from 0.631 to 0.823, which shows that estimated regression coefficient is positive in this interval.

Since p-value is less than the 0.05 level of significance, the relationship between AI-based personalized language learning and sustainable learning experiences is statistically significant. So, the Null hypothesis (H02) is rejected, while alternative hypothesis (H12) is accepted. The findings show that personalized language learning using AI has good positive predictive effects on sustainable learning experience.

6.11 Summary of Testing Hypothesis

Hypothesis	Test Performed	Value	Analysis
H01 / H11 — Correlation	Pearson r (AI-enabled personalized language learning with Engagement, Effectiveness, Autonomy and Sustainability)	$r = .725$ to $.770$, all $p < .001$	H01 rejected; H11 accepted
H02 / H12 — Regression (Engagement)	Simple linear regression	$R^2 = .593$, $F(1,199) = 289.730$, $p < .001$	H02 rejected; H12 accepted
H02 / H12 — Regression (Effectiveness)	Simple linear regression	$R^2 = .548$, $F(1,199) = 241.614$, $p < .001$	H02 rejected; H12 accepted
H02 / H12 — Regression (Autonomy)	Simple linear regression	$R^2 = .545$, $F(1,199) = 238.124$, $p < .001$	H02 rejected; H12 accepted
H02 / H12 — Regression (Sustainability)	Simple linear regression	$R^2 = .526$, $F(1,199) = 221.075$, $p < .001$	H02 rejected; H12 accepted

7. Findings

The results obtained from the correlation and regression analysis shows a significant positive relationship between AI-assisted personalized language learning and engagement, learning effectiveness and sustainable learning experiences. The correlation values fall within the range of 0.725 to 0.770. The regression results further show that AI-enabled personalization significantly contributes to each outcome, with the models explaining between 52.6% and 59.3% of the variation in the respective outcomes.

Among the four outcomes, learner engagement shows the strongest relationship with AI-enabled personalization ($r = 0.770$; $R^2 = 0.593$). This suggests that when learners experience more personalized and adaptive support through AI tools, remain involved in their learning activities. The results for perceived learning effectiveness, learner autonomy and sustainable learning experiences also show strong positive relationships, suggesting that personalized AI support may help learners feel more effective in their learning, take greater control of their learning process and maintain a more flexible and continuous learning experience.

Overall, the findings suggest that AI-enabled personalization can play an important role in supporting learner-centered and sustainable language learning. Rather than being used only as a technological assistant, AI-based personalization appears to be connected with learners' engagement, learning effectiveness, learner autonomy and sustainability of their learning experience.

8. Recommendations

The findings suggest that AI-enabled personalized language learning has scope for wider adoption, particularly among groups that have not yet used these tools. Working professionals and respondents in the 26-30 age group indicates relatively higher non-adoption rates, although these results should be interpreted with caution because some groups had fewer respondents.

Future AI-enabled personalized language learning platforms could provide flexible learning schedules, short learning modules and career-oriented language content to suit working professionals and young adults. For older users, simple interfaces, guided onboarding and voice-based features may make these tools easier to use. Overall, greater attention to needs of different learner groups can help make AI-enabled personalized language learning more accessible, flexible and sustainable.

9. Limitations

- The study included 201 respondents who have using AI based tools for personalized language learning. Since a number of participants is limited, the findings may not be fully represent the wider population of language learners.
- The study mainly focusses on primary data gathered using a structured questionnaire. Since the responses are based on participants personal experiences and perceptions, the findings may be affected by response bias.
- The study follows cross-sectional research design where data were gathered at one point in time. As a result, it doesn't show how learning experiences with AI- enabled personalized language learning might change over a long period of time.
- The study examined only few factors such as learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences. Other factors such as learning performance, digital skills and institutional support were not considered.
- The respondents used different variety of AI tools for language learning. The difference between specific AI-tools were not examined separately, which may influence learners' experiences.

10. Future Scope of the Study

- Future research could consider broader and more varied groups of learners including people from different age groups and educational backgrounds. This would help make the findings more representative and applicable to a wider population.
- Long-term studies could be carried out to understand how learners' experiences with AI-enabled personalized language learning develop and change over the period of time instead of at single point of time.
- Further studies can compare different AI based learning tools to identify whether learner engagement, perceived effectiveness, learner autonomy and views on sustainable learning differ depending on the platform they use.
- Further research could combine learners' perceptions with measurable learning outcomes such as improvements in vocabulary, grammar, speaking ability and writing skills. This would provide a clear picture of the actual learning benefits.
- Future research could also take a broader view of sustainable factors such as accessibility, digital inclusion, responsible use of AI, data privacy and whether AI – supported learning can be maintained effectively over the long-term.

11. Conclusion

This study examined how AI-enabled personalized learning of languages influences learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences. The respondents showed positive perceptions across all four areas with sustainable learning experiences having the highest mean score. The correlation analysis also revealed strong positive relationship between AI-enabled personalization and each of the four outcomes. The regression findings further confirmed that personalization through AI significantly contributes to learner engagement, perceived learning effectiveness, learner autonomy and sustainable learning experiences. Among these outcomes, Learner engagement demonstrated strongest relationship.

Taken together, these findings suggest that AI based personalization can offer more than just convenience in language learning. By adopting learning assistance to individual needs, it can encourage learners to participate more actively perceived greater learning value and take greater responsibility for their own learning.

Overall, the paper highlights the potential of AI-enabled personalization as a learner-centered approach. However, its wider adoption should be accompanied by responsible use of AI, privacy and the diverse need of learners. This

research thus adds to the increasing debate on the application of AI Technology in the creation of engaging, effective, autonomous and sustainable language learning environments.

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Intelligent Technologies for Sustainable Development: Integrating AI, Analytics, and Automation for Future-Ready Systems

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ABSTRACT

With the evolution of Analytics, Artificial Intelligence, and also Intelligent Automation is transforming the way organizations and governments address complex sustainability challenges. Data-driven decision-making, predictive analytics, intelligent resource allocation, and automated operations are authorised by smart technologies that provide to achieve the SDGs. This paper presents the context illustrating the analytics that are Artificial Intelligence (AI-driven) and automation can accelerate sustainable development across critical domains, including smart cities, healthcare, agriculture, energy management, transportation, manufacturing, environmental monitoring, and public governance. The study synthesizes recent research on cloud computing, ML DL, IoT, digital twins, and intelligent decision support systems to identify emerging trends, opportunities, and implementation challenges. The findings indicate that integrating analytics with AI enhances operational efficiency, minimizes resource consumption, improves predictive maintenance, optimizes energy utilization, and supports real-time monitoring of environmental and social indicators. Furthermore, intelligent automation reduces operational costs while improving service quality, transparency, and productivity across public and private sectors. Despite these there are various challenges depending on cybersecurity and data privacy, algorithmic bias, interoperability, high implementation costs, and the Artificial Intelligence systems that impacts the environment. This proposed framework emphasizes responsible AI governance, sustainable digital infrastructure, and collaborative innovation among academia, industry, and policymakers to maximize societal benefits. The paper concludes that the union of analytics, and AI, inclusive sustainability.

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1. Introduction

The twenty-first century has witnessed unprecedented technological advancements alongside growing environmental and socio-economic challenges. Population growth, rapid urbanization, depletion of natural resources, biodiversity loss, climate change, and increasing energy demands have intensified the need for strategies of sustainable development. Achieving the goals requires innovative technological solutions capable of supporting efficient resource management, intelligent decision-making, and resilient infrastructures.

Artificial Intelligence (AI), advanced data analytics, and automation have emerged as transformative technologies that can significantly contribute to sustainable development. The Artificial Intelligence capabilities across multiple domains, including healthcare, agriculture, environmental monitoring, transportation, manufacturing, and smart governance.

Data analytics complements AI by converting raw data into actionable knowledge. The increasing availability of big data generated from IoT devices, satellite imagery, social media, industrial sensors, healthcare systems, and public infrastructure provides unprecedented opportunities to assist organizations in understanding current conditions,

forecasting future scenarios, and optimizing operational performance. These capabilities are particularly valuable for sustainability initiatives, where real-time information is essential for effective resource allocation and environmental management.

Automation technologies further enhance sustainability by reducing repetitive manual tasks, improving operational efficiency, minimizing human error, and enabling continuous monitoring of critical systems. Industrial automation, robotic process automation (RPA), autonomous vehicles, intelligent manufacturing systems, and smart energy management solutions are increasingly adopted to improve productivity while reducing environmental impact. Combined with AI and analytics, automation forms the foundation of Industry 4.0, enabling interconnected cyber-physical systems that optimize industrial and societal processes.

The connected devices continuously collect environmental, industrial, healthcare, and transportation data, creating opportunities. To monitor air quality, predict equipment failures, and improve agricultural productivity. Cloud computing and edge computing provide scalable computational infrastructure for processing massive volumes of data while supporting decentralized intelligence.

The integration of intelligent technologies has already demonstrated substantial benefits across numerous sustainability domains. Smart irrigation systems reduce water consumption while maintaining agricultural productivity. Computer vision technologies enable automated disease detection, allowing farmers to implement targeted interventions and minimize pesticide usage.

Healthcare systems increasingly utilize AI for disease diagnosis, medical imaging analysis, predictive healthcare analytics, and personalized treatment planning. During public health emergencies, AI-assisted epidemiological modeling has supported disease surveillance, outbreak prediction, and healthcare resource allocation.

Smart cities represent another major application area for intelligent technologies. Urban populations continue to grow rapidly, increasing pressure on transportation systems, energy infrastructure, waste management, water resources, and public services. AI-enabled traffic management systems optimize vehicle movement, reducing congestion and emissions. Intelligent waste management systems utilize sensor networks and predictive analytics to improve waste collection efficiency. Smart grids integrate renewable energy sources while maintaining grid stability through predictive demand forecasting and automated energy distribution.

Environmental sustainability has also benefited from intelligent technologies. Predictive analytics assists governments in climate adaptation planning, disaster risk reduction, and ecosystem conservation. Automated environmental monitoring systems continuously measure pollution levels, water quality, and atmospheric conditions, enabling timely interventions.

Despite these significant advancements, widespread adoption of intelligent technologies presents several challenges. Data privacy concerns, cybersecurity threats, algorithmic bias, lack of transparency, interoperability limitations, high implementation costs, digital inequality, and increasing computational energy requirements remain major obstacles.

Existing research often investigates AI, analytics, or automation independently, whereas practical sustainable systems increasingly rely on their integrated application. There remains a need for comprehensive frameworks that combine these technologies into unified architectures capable of supporting cross-sector sustainability objectives. Such integrated approaches can facilitate intelligent decision-making, improve operational efficiency, enhance environmental monitoring, and strengthen resilience against emerging global challenges.

This paper addresses this need by presenting an integrated perspective on intelligent technologies for sustainable development. The recent developments in AI, analytics, and automation, identifies research gaps, proposes a conceptual framework for future-ready sustainable systems, discusses real-world applications across multiple sectors, examines implementation challenges, and outlines promising directions for future research. The proposed framework emphasizes collaboration among governments, industries, academia, and society to create intelligent ecosystems capable of accelerating progress toward sustainable development goals while ensuring ethical, transparent, and inclusive technological innovation.

1.1 The research objectives

1. To review Artificial Intelligence role, analytics, and automation in achieving sustainable development.
2. To review recent advancements in intelligent technologies supporting environmental, economic, and social sustainability.
3. To suggest an integrated conceptual framework for future-ready sustainable development.
4. To recommend future research directions for responsible and scalable intelligent technologies.

2. The literature review

2.1 Introduction

The technologies such as AI, DL, ML, IoT, Data analytics, automation facilitate evidence-based decision-making, optimize resource utilization, improve operational efficiency, and support resilient infrastructures. Recent research has explored their applications in environmental protection, renewable energy, healthcare, agriculture, manufacturing, transportation, and smart cities. Despite these developments, the literature reveals fragmentation in technological adoption, limited interdisciplinary integration, and several implementation challenges. This section critically reviews recent studies relevant to intelligent technologies and sustainable development.

2.2 AI for Sustainable Development

The Artificial Intelligence capabilities enable governments, industries, and organizations to improve efficiency while minimizing environmental impacts.

Machine learning algorithms support accurate forecasting of energy demand, optimization of renewable energy generation, intelligent transportation management, environmental monitoring, and precision agriculture.

Deep learning techniques have further expanded AI applications through image recognition, satellite image interpretation, medical diagnostics, and automated surveillance systems. Reinforcement learning enables autonomous systems to optimize dynamic decision-making in energy management and industrial automation.

However, researchers also emphasize concerns regarding algorithmic transparency, explainability, fairness, and computational energy consumption. The increasing environmental cost of training large AI models has motivated the development of Green AI approaches that prioritize computational efficiency alongside predictive accuracy.

2.3 Data Analytics for Sustainable Decision-Making

Data analytics has become an essential component of digital transformation and sustainable governance. Organizations now generate enormous quantities of data from IoT sensors, smart devices, industrial equipment, healthcare systems, transportation networks, and environmental monitoring stations.

The analytics such as descriptive summarizes historical information to understand existing conditions, while diagnostic analytics investigates the causes behind observed events.

Several studies indicate that combining AI with predictive analytics significantly improves resource allocation and sustainability planning. Governments increasingly utilize analytics platforms to optimize water management, monitor air pollution, forecast natural disasters, and evaluate climate policies.

Business organizations employ advanced analytics to reduce waste, improve supply chain efficiency, optimize logistics, and enhance manufacturing productivity. Healthcare institutions leverage predictive analytics for disease surveillance, hospital resource planning, and patient risk assessment.

Despite these advantages, researchers identify challenges associated with data quality, interoperability, privacy protection, heterogeneous data integration, and real-time processing of large-scale datasets.

2.4 Automation and Industry 4.0 Technologies

Automation represents another critical pillar of sustainable digital transformation. Industrial automation has evolved from simple programmable logic controllers to intelligent cyber-physical systems capable of autonomous operation.

Industry 4.0 integrates several advanced technologies, including:

- Digital Twins
- Cloud Computing
- Edge Computing
- Additive Manufacturing
- Blockchain

These technologies enable smart factories where machines communicate autonomously, predict equipment failures, optimize production schedules, and minimize resource wastage.

Automated manufacturing systems significantly improve productivity while reducing energy consumption and operational costs. Predictive maintenance algorithms decrease machine downtime by detecting anomalies before equipment failures occur.

Several researchers emphasize that Industry 4.0 technologies also contribute to the Circular Economy by enabling efficient recycling, remanufacturing, lifecycle monitoring, and sustainable supply chain management.

Nevertheless, successful implementation requires considerable investments, workforce training, cybersecurity measures, and standardized communication protocols.

2.5 IoT and Sustainable Smart Systems

IoT provides the digital infrastructure necessary for intelligent sustainability systems. Billions of interconnected sensors continuously collect environmental, industrial, agricultural, healthcare, and transportation data.

IoT devices support:

- Energy consumption
- Traffic congestion
- Waste collection
- Agricultural soil conditions
- Industrial equipment
- Smart buildings

When integrated with AI and analytics, IoT systems enable autonomous responses to changing environmental conditions. Intelligent street lighting adjusts illumination according to pedestrian movement and ambient conditions. Smart energy grids dynamically balance electricity supply and demand.

Edge computing has recently emerged as an effective solution for reducing latency by processing data closer to IoT devices instead of transmitting all information to centralized cloud servers.

Researchers note that IoT-enabled sustainability systems require strong cybersecurity mechanisms due to increasing risks associated with unauthorized access and data breaches.

2.6 AI Applications Across Sustainable Development Sectors

2.6.1 Healthcare

Artificial Intelligence improves disease diagnosis, medical image analysis, electronic health record management, drug discovery, personalized treatment planning, and telemedicine services.

2.6.2 Agriculture

Precision agriculture utilizes AI, IoT sensors, drones, satellite imagery, and predictive analytics to maximize crop productivity while minimizing resource consumption.

Applications include:

- Smart irrigation
- Crop disease detection
- Yield prediction
- Fertilizer optimization
- Pest monitoring
- Weather forecasting

These technologies improve food security while conserving water and reducing chemical usage.

2.6.3 Smart Cities

Smart cities integrate intelligent technologies to improve urban sustainability.

Major applications include:

- Intelligent traffic management
- Smart parking
- Waste management
- Smart grids
- Water distribution
- Public safety
- Environmental monitoring

AI-supported transportation systems reduce congestion, fuel consumption, and greenhouse gas emissions while improving mobility.

2.6.4 The energy system

Smart grids automatically balance electricity demand and supply while integrating distributed renewable resources.

2.6.5 Manufacturing

Intelligent manufacturing systems improve:

- Production planning
- Predictive maintenance
- Quality inspection
- Energy optimization
- Inventory management
- Supply chain resilience

Industrial robots perform repetitive operations with higher precision while minimizing waste generation.

2.6.6 Environmental Monitoring and Climate Action

Climate change has accelerated interest in AI-assisted environmental monitoring.

Satellite imagery combined with deep learning supports:

- Deforestation detection

- Land-use classification
- Forest fire prediction
- Flood forecasting
- Glacier monitoring
- Biodiversity assessment

Machine learning models also estimate carbon emissions and evaluate the effectiveness of environmental policies. Automated environmental monitoring stations continuously collect pollution data, enabling governments to respond rapidly to hazardous conditions.

2.7 Ethical, Social, and Technical Challenges

Although intelligent technologies offer considerable sustainability benefits, several challenges remain.

2.7.1 Ethical Challenges

- Algorithmic bias
- Lack of transparency
- Explainability issues
- Accountability
- Responsible AI governance

2.7.2 Technical Challenges

- Poor data quality
- Data integration
- System interoperability
- Scalability
- High computational requirements

2.7.3 Security Challenges

- Cybersecurity threats
- Privacy protection
- Unauthorized data access
- Secure IoT communication

2.7.4 Social Challenges

- Digital divide
- Workforce displacement
- Limited digital literacy
- Resistance to technological adoption

2.8 Comparative Analysis of Recent Studies

Table 1: Comparative Review of Selected Studies

Focus Area	Major Contribution	Identified Limitation
AI for Sustainability	AI supports environmental monitoring and intelligent decision-making	Limited explainability
Industry 4.0	Smart manufacturing improves resource efficiency	High implementation cost
Data Analytics	Predictive models improve sustainability planning	Data quality issues
IoT Systems	Real-time monitoring enhances operational efficiency	Security vulnerabilities
Smart Cities	Intelligent infrastructure reduces emissions	Infrastructure interoperability
Climate Analytics	AI improves climate forecasting accuracy	Large computational requirements
Healthcare AI	Better diagnosis and healthcare management	Ethical concerns
Precision Agriculture	Efficient water and fertilizer utilization	Limited adoption in developing regions
Renewable Energy	Improved energy demand forecasting	Renewable variability remains challenging
Automation	Higher productivity with lower waste	Workforce reskilling required

2.9 Summary of Literature Review

The reviewed literature demonstrates that Artificial Intelligence, analytics, automation, IoT, and Industry 4.0 technologies have become powerful enablers of sustainable development. These technologies improve operational efficiency, support environmental conservation, enhance healthcare delivery, optimize agricultural productivity, strengthen renewable energy systems, and facilitate smart city development. However, existing studies generally investigate these technologies independently or within domain-specific contexts. Limited research provides an integrated framework that combines AI, analytics, automation, IoT, cloud computing, and governance mechanisms into a unified sustainability ecosystem. Furthermore, concerns regarding explainability, ethics, cybersecurity, interoperability, digital inclusion, and environmental impacts of AI remain insufficiently addressed. These limitations highlight the need for a holistic, interdisciplinary framework capable of supporting future-ready sustainable systems.

3. Research Gap

The technology of a specific application domain, such as smart agriculture, healthcare, renewable energy, or manufacturing. While these domain-specific contributions provide valuable insights, they often overlook the interconnected nature of sustainability challenges, which require integrated technological solutions.

A significant limitation identified in the literature is the lack of a unified framework that combines AI, analytics, automation, IoT, cloud computing, and edge intelligence into a cohesive ecosystem. Current research tends to evaluate these technologies independently, making it difficult for policymakers and practitioners to develop comprehensive strategies for sustainable development. Furthermore, many studies emphasize technological performance without adequately considering governance, ethical AI, data privacy, cybersecurity, and social inclusion.

Another research gap concerns the explainability and transparency of AI models. Although machine learning algorithms achieve high prediction accuracy, many operate as "black-box" systems, limiting user trust and accountability. This issue is particularly critical in healthcare, environmental monitoring, and public policy, where decisions significantly affect human lives and societal well-being.

The literature also highlights the limited adoption of intelligent technologies in developing countries due to regulatory challenges. Existing frameworks rarely address scalability, affordability, and accessibility for resource-constrained environments.

Additionally, there is insufficient research on measuring the sustainability impact of AI itself. Green AI, energy-efficient computing, and sustainable AI lifecycle management remain emerging research areas requiring further investigation.

Based on these observations, this study proposes an integrated framework that combines AI, analytics, automation, IoT, cloud computing, and responsible governance to support future-ready sustainable systems. The framework emphasizes interdisciplinary collaboration, ethical AI to bridge the identified research gaps.

4. Research Methodology

4.1 Research Design

The research focuses on synthesizing contemporary concepts, technological advancements, and sustainability principles to propose a comprehensive model for future-ready intelligent systems.

The methodology consists of five sequential stages:

1. Identification of the problem.
2. Technology Analysis.
3. Development of an integrated conceptual framework.
4. Application Mapping

It enables the formulation of a holistic model grounded in contemporary research while identifying opportunities for future empirical validation.

4.2 Data Collection

Table 2 : Data Collection Components

Source of data	The collected data	Reason
The sensors of IoT	Temperature, humidity, air quality, water quality	Environmental monitoring
Smart Energy Meters	Electricity generation and consumption	Energy optimization
Healthcare Information Systems	Patient records, diagnostics, treatment information	Healthcare analytics
Smart Transportation Systems	Traffic density, vehicle movement, congestion	Intelligent traffic management
Agricultural Sensors	Soil moisture, nutrient levels, crop health	Precision agriculture
Industrial Automation Systems	Machine performance, energy consumption, production data	Predictive maintenance and manufacturing optimization
Weather Monitoring Systems	Rainfall, wind speed, temperature	Climate forecasting
Satellite Observation Systems	Land use, vegetation, environmental changes	Environmental monitoring

4.3 Literature Selection

The literature reviewed in this study consists of recent peer-reviewed publications focusing on:

- Artificial Intelligence
- Data Analytics
- Automation
- Industry 4.0
- Smart Cities
- Sustainable Development

- Internet of Things (IoT)
- Environmental Sustainability
- Climate Change
- Digital Transformation

The selected articles represent multidisciplinary perspectives from internationally recognized journals and collectively provide a broad understanding of technological innovations supporting sustainable development.

4.4 Conceptual Framework Development

Based on the identified research gaps and literature synthesis, an integrated intelligent sustainability framework is proposed. The framework combines data acquisition, analytics, AI-driven decision support, automation, and continuous monitoring within a closed feedback loop. The model is designed to support diverse sustainability applications while emphasizing ethical governance, scalability, and resilience.

5. Proposed Intelligent Sustainability Framework

5.1 Framework Overview

The proposed **Intelligent Sustainability Framework (ISF)** integrates advanced digital technologies to create an adaptive ecosystem capable of supporting sustainable development across multiple sectors.

The architecture is designed around continuous feedback, ensuring that systems learn from operational outcomes and improve performance over time.

5.2 Layer 1: Data Acquisition

The first layer collects data from multiple heterogeneous sources, including:

- IoT sensors
- Environmental monitoring stations
- Satellite imagery
- Healthcare databases
- Smart transportation systems
- Industrial equipment
- Agricultural sensors
- Renewable energy infrastructure
- Government open-data platforms
- Social media and citizen reports

The diversity of these data sources enables a comprehensive understanding of environmental, economic, and social conditions.

5.3 Layer 2: Data Management and Cloud Infrastructure

Collected data are transmitted to cloud and edge computing platforms where they are securely stored, cleaned, and integrated.

Key functions include:

- Data preprocessing
- Data validation
- Data integration

- Data encryption
- Distributed storage
- Cloud scalability
- Edge computing for low-latency processing

This layer ensures that high-quality, secure, and accessible data are available for analytical processing.

5.4 Layer 3: Advanced Analytics

Advanced analytics transforms raw information into meaningful insights using multiple analytical techniques.

5.4.1 Descriptive Analytics

Provides historical summaries of system performance.

Examples include:

- Energy consumption trends
- Traffic congestion statistics
- Water usage reports

5.4.2 Diagnostic Analytics

Investigates causes behind observed events.

Examples include:

- Identifying causes of pollution spikes
- Determining reasons for equipment failures

5.4.3 Predictive Analytics

Forecasts future events using machine learning models.

Examples include:

- Energy demand forecasting
- Disease outbreak prediction
- Flood forecasting
- Crop yield estimation

5.4.4 Prescriptive Analytics

Recommends optimal actions.

Examples include:

- Smart irrigation schedules
- Traffic signal optimization
- Resource allocation strategies

5.5 Layer 4: Artificial Intelligence Engine

The AI engine forms the core intelligence of the framework.

Major AI components include:

5.5.1 Machine Learning

Supports predictive modeling and classification.

Applications include:

- Disease diagnosis
- Energy forecasting
- Crop prediction
- Equipment maintenance

5.5.2 Deep Learning

Processes complex image and video data.

Applications include:

- Satellite image analysis
- Medical image diagnosis
- Disaster detection

5.5.3 Natural Language Processing (NLP)

Processes textual information.

Applications include:

- Policy analysis
- Citizen feedback analysis
- Environmental reporting
- Intelligent chatbots

5.5.4 Reinforcement Learning

Optimizes sequential decision-making.

Applications include:

- Smart grid control
- Autonomous transportation
- Industrial robotics

5.6 Layer 5: Intelligent Automation

The framework incorporates automation technologies that execute AI-generated recommendations with minimal human intervention.

Automation components include:

- Robotic Process Automation (RPA)
- Industrial Robotics
- Autonomous Vehicles
- Smart Irrigation Systems
- Automated Energy Management
- Intelligent Waste Collection
- Smart Manufacturing
- Building Automation

Automation increases operational efficiency while reducing resource consumption and human error.

5.7 Layer 6: Decision Support System

This layer presents AI-generated insights to decision-makers through interactive dashboards and visualization platforms.

Decision support functions include:

- Sustainability performance indicators
- Carbon emission monitoring
- Resource utilization analysis
- Climate risk assessment
- Smart city management dashboards
- Healthcare resource allocation
- Disaster preparedness planning

Decision-makers can evaluate multiple scenarios before implementing policies.

5.8 Layer 7: Continuous Monitoring and Feedback

The final layer continuously evaluates system performance.

Key monitoring indicators include:

- Energy efficiency
- Water consumption
- Carbon emissions
- Air quality
- Waste generation
- Equipment reliability
- Healthcare outcomes
- Agricultural productivity

Feedback collected from operational systems is returned to the AI engine, enabling continuous learning and model improvement.

AI-Driven Analytics Pipeline

A unified framework transforming raw data into intelligent decisions – and back into smarter models through continuous learning.

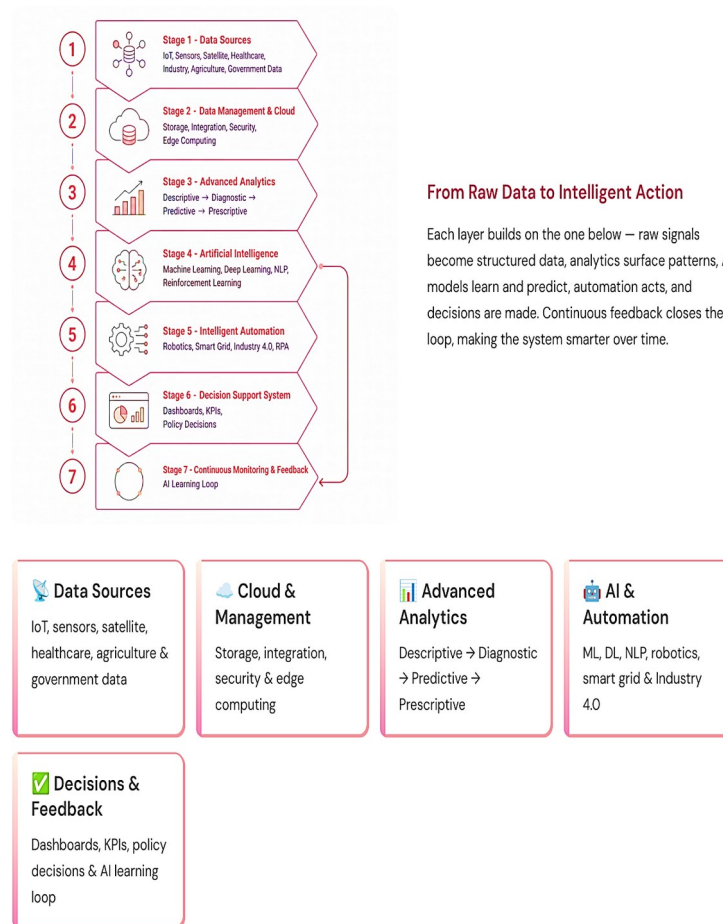


Figure 1. Conceptual Intelligent Sustainability Framework

5.9 The benefits of this context

- Integrates multiple intelligent technologies within a single architecture.
- Supports evidence-based decision-making through real-time analytics.
- Enables adaptive learning using AI feedback mechanisms.
- Improves operational efficiency through intelligent automation.
- Enhances environmental monitoring and resource optimization.
- Facilitates scalability across diverse sectors, including healthcare, agriculture, manufacturing, transportation, and smart cities.
- Promotes responsible AI through governance, transparency, and ethical considerations.

Framework is designed to be flexible and extensible, allowing future incorporation of Explainable AI (XAI), Quantum Computing, and Green AI.

6. Applications of the Intelligent Sustainability context

Intelligent Sustainability context provides a comprehensive architecture for integrating AI, analytics, and automation across multiple domains. The framework enhances operational efficiency while supporting environmental, economic, and social sustainability.

6.1 Smart Cities

Smart cities rely on interconnected digital infrastructure to improve urban management and citizen well-being. Within the proposed framework, IoT sensors continuously collect data on transportation, energy consumption, waste management, public safety, and environmental conditions and support intelligent parking systems. Predictive analytics assists city administrators in forecasting infrastructure demands and identifying maintenance requirements before failures occur.

Automation further contributes through adaptive street lighting, intelligent waste collection, and smart water distribution systems. These technologies reduce energy consumption, lower operational costs, and improve service quality.

6.2 Healthcare

Healthcare systems increasingly generate large volumes of clinical, diagnostic, and patient monitoring data. The proposed framework integrates AI-based diagnostic models, predictive analytics, and intelligent automation to improve healthcare delivery. Machine learning algorithms assist clinicians in disease diagnosis, early risk prediction, and treatment planning. Predictive models identify vulnerable patient populations and forecast disease outbreaks, enabling proactive healthcare interventions.

Automation reduces administrative burdens through electronic health record management, appointment scheduling, and laboratory workflow optimization. Remote patient monitoring supported by IoT devices enables continuous health assessment, particularly for chronic disease management.

6.3 Precision Agriculture

Agriculture remains highly dependent on environmental conditions and efficient resource management. AI-driven analytics to optimize agricultural practices. Precision farming techniques enable intelligent irrigation scheduling, crop disease detection, fertilizer optimization, and yield prediction.

Automation technologies such as autonomous tractors, robotic harvesting systems, and drone-based monitoring further enhance agricultural productivity while reducing water consumption, pesticide usage, and labor requirements.

6.4 Renewable Energy Administration

The present challenges with the intermittent nature. The proposed framework integrates AI forecasting models with smart grid technologies to improve energy generation, storage, and distribution. Predictive analytics estimates future electricity demand and renewable energy production based on weather conditions, while intelligent automation balances grid loads in real time.

Smart grids equipped with IoT devices continuously monitor energy usage and automatically adjust distribution to maximize efficiency.

6.5 Smart Industrialised

The technologies to improve productivity and sustainability. To identify potential failures before they occur. Automated quality inspection systems utilize computer vision to detect manufacturing defects, reducing material waste and improving product quality.

Digital twins simulate manufacturing processes, allowing organizations to evaluate production scenarios and optimize resource utilization without disrupting operations. These technologies enhance operational resilience while supporting SDG 9: Industry, Innovation, and Infrastructure.

6.6 Environmental Monitoring

Environmental sustainability requires continuous observation of ecosystems and climate conditions. The proposed framework combines remote sensing, IoT sensors, and AI-based image analysis, biodiversity, land-use changes, and greenhouse gas emissions. DL for coastal erosion, and natural disasters.

Predictive analytics assists policymakers in evaluating climate risks and planning mitigation strategies. Automated environmental monitoring stations provide real-time alerts when pollution levels exceed acceptable thresholds, enabling rapid intervention.

6.7 Disaster Risk Management

Natural disasters pose significant threats to sustainable development. AI-based predictive models integrated with meteorological data improve forecasting of floods, wildfires, droughts, hurricanes, and earthquakes. IoT sensor networks continuously monitor environmental conditions, while automated emergency response systems disseminate warnings to affected communities. Intelligent resource allocation algorithms support disaster response planning by optimizing emergency logistics and healthcare deployment.

7. Challenges and Ethical Considerations

7.1 The data security and its privacy

Intelligent systems depend on extensive data collection from individuals, organizations, and public infrastructure. Protecting sensitive information requires robust cybersecurity measures, secure communication protocols, data encryption.

7.2 Algorithmic preference

The social or demographic biases, if not carefully managed, AI systems may generate unfair or discriminatory outcomes in healthcare, employment, financial services, or public administration. Organizations must ensure fairness through diverse training datasets, bias detection techniques, and regular model evaluation.

7.3 Clarity and Explainability

Lack of explainability limits user confidence and regulatory acceptance, particularly in high-stakes applications. Explainable AI (XAI) techniques are essential for improving transparency, accountability, and stakeholder trust.

7.4 Cybersecurity Risks

The increasing connectivity of IoT devices expands the attack surface for cyber threats. Intelligent infrastructures supporting energy systems, transportation networks, healthcare, and industrial automation require continuous security monitoring, intrusion detection, and secure software updates to maintain operational resilience.

7.5 Energy Consumption of AI

Green AI approaches seek to improve computational efficiency while maintaining high predictive performance through optimized algorithms, energy-efficient hardware, and sustainable data centers.

7.6 Workforce Transformation

Automation and intelligent systems may replace repetitive tasks previously performed by human workers. Although new employment opportunities emerge in digital technologies, successful workforce transition requires continuous education, reskilling, and lifelong learning programs to prepare employees for evolving technological environments.

7.7 Digital Divide

Unequal access to digital infrastructure limits the adoption of intelligent technologies in developing regions. Investments in broadband connectivity, affordable computing resources, digital literacy, and inclusive innovation policies are essential to ensure equitable access to technological benefits.

8. Upcoming Directions of Research

The emerging technologies that further strengthen intelligent sustainability systems. Several promising directions include:

- **Explainable Artificial Intelligence:** understandable explanations for automated decisions.
- **Green AI:** Designing computationally efficient algorithms
- **Edge AI:** Processing data for the real-time decision making.
- **Human-Centered AI:** Designing intelligent systems that prioritize user needs, accessibility, and ethical considerations.
- **Circular Economy Technologies:** Integrating AI with sustainable production, recycling, remanufacturing, and resource recovery systems.
- **AI Governance Frameworks:** Establishing international standards and regulatory policies for responsible AI deployment.
- **Climate Intelligence:** Combining Earth observation technologies with AI for climate adaptation, biodiversity conservation, and disaster resilience.

These research directions based on inclusive digital ecosystems.

9. Conclusion

Intelligent technologies are transforming sustainable autonomous operations across multiple sectors. This paper presented a comprehensive review of AI, analytics, automation, IoT, and Industry 4.0 technologies and examined their contributions. A novel Intelligent Sustainability Framework was proposed to integrate these technologies into a unified architecture supporting smart cities, healthcare, agriculture, manufacturing, renewable energy, environmental monitoring, and disaster management.

Future research should prioritize Green AI, Explainable AI, Digital Twins, Federated Learning, and human-centered design to ensure sustainable and ethical digital transformation.

The proposed framework demonstrates that integrating AI, analytics, and automation can significantly accelerate progress toward resilient, future-ready societies. By combining technological innovation with ethical governance and inclusive policies, intelligent systems can become powerful enablers of sustainable conservation.

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