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Unveiling the synergistic impact of fintech and green finance for indian bank sustainable economic growth using SEM–neural network modelling

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Abstract
This study aims to investigate the impact of FinTech adoption and green finance investments on sustainable economic growth within India's banking sector. Employing a two-staged structural equation modeling-artificial neural network (SEM-ANN) approach, this study integrates both linear and non-linear relationships to offer deeper insights. Data were collected from 404 respondents using a convenience sampling method between December 2023 and May 2024. The findings reveal a significant positive impact of FinTech adoption and green finance investments on the sustainable economic development of banking firms. Furthermore, financial inclusion is identified as a key mediator, while the regulatory environment plays a moderating role in shaping these relationships. The study highlights the necessity of aligning FinTech and green finance strategies with future sustainability trends in finance, making a valuable contribution to both academia and policy development. By integrating TAM, RBV, and Institutional Theory, this study contributes to a unified understanding of FinTech–Green Finance synergy and offers insights transferable to other emerging markets. The findings provide actionable insights for policymakers, banking institutions, and researchers, emphasizing the pivotal role of financial technology in driving sustainable economic development in India and beyond.

Keywords FinTech adoption, Green finance investments, Financial inclusion, Regulatory environment, Sustainable economic growth

1 Introduction

In recent decades, India, like many other developing countries, has witnessed substantial economic growth, largely driven by the adoption of new economic policies by banking firms aimed at harnessing the nation's abundant environmental resources [31]. However, this rapid expansion has come with significant environmental consequences, as the excessive exploitation of resources has led to environmental degradation and pollution [41], posing threats not only to ecosystems but also to human health [57]. Recognizing

the urgency of the situation, Indian banking firms are increasingly directing resources towards building a green ecosystem, particularly in rural areas where local populations heavily rely on these resources for their livelihoods [60]. Moreover, India's growing energy demands have resulted in significant dependence on fossil fuels, which currently account for about 60% of the nation's energy consumption [17]. However, this heavy reliance on fossil fuels has contributed to environmental toxins, exacerbating damage to the ecosystem [58]. As India aims to sustain its economic growth, the imperative to balance growth with environmental protection remains a critical concern.

Researchers are actively exploring various innovative methods and strategies to mitigate ongoing environmental degradation [33]. Simultaneously, the Indian government has taken proactive steps towards setting sustainable goals for the nation, implementing measures to promote high-quality economic growth and environmentally friendly practices [32]. A pivotal aspect of these efforts is the adoption of a green finance strategy, designed to finance projects aligned with sustainability objectives [44]. This approach not only supports India's sustainable development but also contributes to global sustainability efforts, highlighting the intricate interplay between economic prosperity and environmental responsibility [24].

Green finance, a multifaceted concept merging finance and environmental concerns, has been widely acknowledged globally for promoting high-quality development [26]. In alignment with this trend, India has made significant strides by issuing substantial amounts of green bonds in recent years, demonstrating a firm commitment to transitioning to a low-carbon economy [7, 64]. Green finance offers numerous advantages, supporting industry operations, investments, financing, and complementary financial services [4]. Despite its prominence, the precise contribution of green finance to high-quality economic growth in emerging economies like India remains a subject of ongoing exploration [55].

The FinTech sector in India has experienced remarkable growth, with widespread adoption by consumers and businesses alike [45]. FinTech provides opportunities for retail investors to engage in environmentally sustainable products aligned with economic development objectives [25]. However, bridging the gap between the supply and demand of funds in renewable sectors remains a challenge. FinTech partnerships are seen as crucial catalysts for advancing green finance, facilitating information dissemination, enhancing efficiency, appraising the value of natural assets, and promoting sustainable economic growth [63].

Financial inclusion, defined by the World Bank, refers to the access of individuals and businesses to essential financial products and services delivered in a responsible and sustainable manner [56]. A robust financial inclusion ecosystem is crucial for economic growth, empowering marginalized populations to participate in formal financial systems, make productive investments, and build financial resilience [16]. The regulatory environment, encompassing laws, policies, and oversight mechanisms, plays a pivotal role in shaping the financial inclusion landscape by creating an enabling environment for innovation, consumer protection, and financial stability [19].

Despite the growing recognition of FinTech innovation and green finance as drivers of economic transformation, most existing studies have investigated these domains in isolation. While FinTech adoption has been linked to improved financial efficiency, accessibility, and inclusion, green finance has primarily been associated with environmental

sustainability and responsible investment. However, limited attention has been given to how these two domains interact synergistically to influence sustainable economic growth (SEG), particularly in emerging economies like India. Furthermore, the mediating role of Financial Inclusion (FI) and the moderating influence of the Regulatory Environment (RE) within this relationship remain underexplored. The absence of an integrated framework that captures both technological and sustainability dimensions restricts a deeper understanding of how digital finance and green investments jointly shape long-term economic resilience. Addressing this gap, the present study adopts a dual-stage Structural Equation Modeling–Artificial Neural Network (SEM–ANN) hybrid framework to examine the linear and non-linear effects of FinTech adoption and green finance investment on SEG. Specifically, the study investigates their direct impacts on SEG, assesses the mediating effect of FI, evaluates the moderating role of RE, and offers theoretical, managerial, and policy-oriented insights to foster a more sustainable, inclusive, and digitally enabled financial ecosystem. Methodologically, the study contributes by being among the first to apply an SEM–ANN hybrid approach in this context, enhancing both explanatory and predictive capabilities. Theoretically, it integrates the Technology Acceptance Model (TAM), Resource-Based View (RBV), and Institutional Theory to explain the interplay between innovation, institutional structures, and sustainable development [9, 22, 59]. Although grounded in the Indian banking sector, the findings offer broader relevance to other emerging economies facing similar regulatory, financial, and environmental challenges. In the next sections, this paper proceeds with a literature review and hypotheses development, SEM-ANN-based research methodology, results and discussion, and conclusions.

2 Literature review and development of hypotheses

This section provides a comprehensive overview of existing literature and hypotheses based on gaps or inconsistencies identified in the literature.

2.1 FinTech adoption (FA) and sustainable economic growth (SEG)

FinTech, characterized by the integration of financial services and technology, has emerged as a transformative force in the financial sector [3]. In India, FinTech has experienced rapid expansion, fostering innovation, financial inclusion, and efficiency [20]. The adoption of FinTech solutions streamlines operations, enhances access to financial services, and stimulates economic growth [2]. Studies suggest that FinTech adoption positively impacts economic development by increasing production efficiency, reducing costs for enterprises, and breaking down financial barriers [6, 12, 52].

Recent studies further emphasize the role of digital technologies in promoting financial inclusion, particularly in emerging economies. Salari et al., [50] argue that digital innovations significantly enhance financial access, improving economic resilience and reducing inequality. Similarly, [49] employ the Technology Acceptance Model (TAM) to demonstrate that FinTech adoption in the Italian banking industry accelerates economic efficiency and customer engagement. These studies underscore the growing importance of FinTech in driving sustainable economic growth. However, the complex interplay between technological advancements, financial stability, and environmental considerations requires further empirical investigation.

Hypothesis 1 (H1). There is a significant positive impact of FinTech adoption on Sustainable Economic Growth.

2.2 Green finance investment (GFI) and sustainable economic growth (SEG)

Green finance directs financial resources toward environmentally sustainable projects, fostering economic and ecological sustainability [18]. Banking institutions are increasingly integrating environmental considerations into their investment decisions, supporting green industries [40]. This shift reflects a broader recognition of the need to balance resource exploitation with sustainability goals [28].

Empirical studies suggest that green finance promotes sustainable economic growth by optimizing economic structures, improving energy efficiency, and reducing carbon footprints [34]. Investments in energy conservation and environmental protection encourage firms to adopt innovative and sustainable production processes [11, 31]. (Mumtaz Ali, Mehdi Seraj, Fatma Türüç 2023) analyze South Asian economies and find that banking sector development, clean energy consumption, and green finance investments collectively contribute to environmental sustainability. Similarly, [47] highlight that sustainability-driven financial policies enhance both financial performance and ecological outcomes in the banking industry of the United Arab Emirates. Despite these insights, the precise mechanisms through which green finance influences sustainable economic growth require further empirical validation.

Hypothesis 2 (H2). There exists a significant positive impact of Green Finance Investments on Sustainable Economic Growth.

2.3 Financial inclusion (FI) and regulatory environment (RE)

Financial inclusion, defined as access to essential financial services, is fundamental to fostering economic growth and reducing inequality [56]. A well-developed financial inclusion ecosystem enables marginalized populations to participate in formal financial systems, facilitating productive investments and financial resilience [41]. Furthermore, an enabling regulatory environment plays a crucial role in shaping financial inclusion policies and ensuring financial stability [57].

Recent research highlights the interconnectedness of financial inclusion, education, and economic growth. Raza et al., [48] examine the moderating role of education in financial inclusion and healthcare access, underscoring its importance in socio-economic development. Geddes et al., [17], Wang, [58] argue that financial inclusion mediates the relationship between financial innovations (such as FinTech and green finance) and economic development. Similarly, regulatory environments determine the effectiveness of financial policies, ensuring innovation, consumer protection, and market stability [15, 33].

Recent works in BRICS nations and India highlight their potential but often overlook mediators (like financial inclusion) and moderators (such as regulation) (A. A. Syed et al., [53]; Aamir Aijaz [54]). Given these dynamics, this study emphasizes the mediating role of financial inclusion and the moderating role of the regulatory environment in shaping the relationships between FinTech adoption, green finance investments, and sustainable economic growth [8, 27, 30, 43]. Addressing these relationships will help fill the existing research gap.

Hypothesis 3 (H3). Financial Inclusion mediates the relationship between FA and SEG.

Hypothesis 4 (H4). Financial Inclusion mediates the relationship between GFI and SEG.

Hypothesis 5 (H5). Regulatory Environment moderates the relationship between FA and SEG.

Hypothesis 6 (H6). Regulatory Environment moderates the relationship between GFI and SEG.

These hypotheses form the foundation for analyzing the relationships among FA, GFI, FI, RE, and SEG within the Indian banking sector. Through empirical investigation, this study aims to provide insights into the mechanisms driving sustainable economic growth in the context of financial innovation and environmental sustainability. Figure 1 presents the conceptual framework of the study, visually mapping the direct, mediating, and moderating relationships among the core constructs to guide the subsequent structural and predictive analyses.

2.4 Theoretical foundation

To support the conceptual model, this study integrates three theoretical frameworks: the Technology Acceptance Model (TAM), the Resource-Based View (RBV), and Institutional Theory. TAM explains how users adopt financial technologies based on perceived usefulness and ease of use, thus providing a behavioral basis for understanding FinTech adoption and its economic effects. RBV views FinTech capabilities and green finance initiatives as strategic organizational assets that can enhance competitiveness, sustainability, and long-term value creation. Institutional Theory offers a complementary lens by emphasizing the influence of formal regulations, norms, and institutional pressures particularly useful in understanding how the regulatory environment and financial inclusion shape innovation outcomes. Together, these theories provide a robust multi-dimensional foundation for analyzing how technological, strategic, and institutional forces interact to drive sustainable economic growth in the Indian banking context.

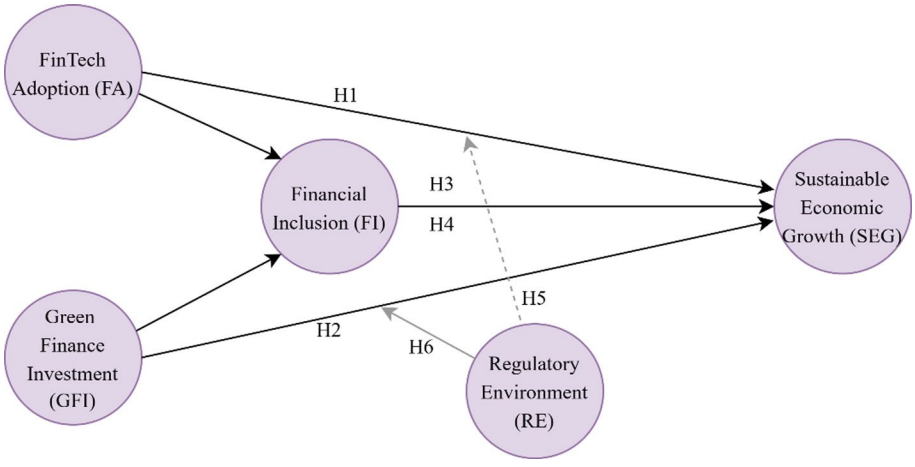

Fig. 1 Conceptual Framework of Study

3 Research methodology

3.1 Questionnaire development and validation

First, based on the literature review, the dependent, independent, mediator, and moderating variables are identified for the study. Table 1 provides a list of these variables, along with relevant references and explanations.

To offer greater specificity and contextual clarity, the FinTech tools considered in this study include mobile banking applications, blockchain-based KYC systems, AI-driven credit scoring models, digital wallets, and Robo-advisors. Similarly, Green Finance Investments were represented through tools such as green bonds, ESG-linked loans, solar energy financing, and green mutual funds. These specific tools formed the operational basis for item construction under the broader constructs of FinTech Adoption (FA) and Green Finance Investments (GFI).

The process of questionnaire development and validation was critical to ensuring both the reliability and validity of the data collected [1]. Drawing from the literature, a structured questionnaire was designed with sections for personal demographics and constructs related to the study variables: FA, GFI, Financial Inclusion (FI), Regulatory Environment (RE), and Sustainable Economic Growth (SEG). Each construct was represented by 10 items, grounded in literature and designed to comprehensively capture its conceptual breadth. To validate the instrument, a pilot study involving 60 banking professionals was conducted. The questionnaire's psychometric properties were assessed using Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA), which

Table 1 Variables of the study

Sr. No.	Variable Name	Type of Variable	Explanation	References
1.	Sustainable Economic Growth (SEG)	Dependent	Sustainable economic development represents the long-term, balanced, and environmentally responsible expansion of an economy. This is often measured in terms of increased GDP, improved living standards, and reduced negative environmental impacts over time.	Gu et al., [19], Qiu, [45]
2.	FinTech Adoption (FA)	Independent	FinTech refers to the use of technology to provide innovative financial services, and in this study, it presumably represents the level of technological innovation and adoption in the financial sector.	Anshari et al., [6], Muganyi, [34], Zhou, [63]
3.	Green Finance Investments (GFI)	Independent	Green finance investment refers to financial resources allocated to environmentally friendly and sustainable projects or initiatives. In this context, the GFI can represent the level of investment in green and sustainable initiatives within the economy.	Akomea-Frimpong et al., [3], Zhou, [64]
4.	Financial Inclusion (FI)	Mediating	In this study, it potentially plays a role in explaining how FinTech and green finance investments affect sustainable economic growth. Financial inclusion represents access to and availability of financial services for all sections of society, including those who were previously disadvantaged or excluded.	Muganyi et al., [34], Pushp, [44]
5.	Regulatory Environment (RE)	Moderating	In this study, RE likely affects how FinTech and green finance investments affect sustainable economic development. The regulatory environment includes government policies, regulations and legal frameworks that shape the financial sector and its ability to foster sustainable economic growth. This may facilitate or hinder the impact of FinTech and GFIs on SEGs, depending on their nature and severity.	(Muganyi et al., [34]; OECD, [39]; "Policies to Enhance Sustainable Development," 2001)

confirmed item reliability, factor loadings, and construct validity thereby enhancing the instrument's robustness and relevance [1].

3.2 Sampling and data collection

The sampling and data collection process is meticulously conducted to ensure a representative sample. A convenience sampling method is used, and Cochran's formula is applied to determine the minimum required sample size, considering a 95% confidence level and a 5% margin of error [13] (Eq. 1).

$$n_o = \frac{z^2 pq}{e^2} \tag{1}$$

This formula accounts for a 95% confidence level, with a standard normal deviation (z) of 1.96, a 5% margin of error (e = 0.05), and a population variability (p) of 0.5 to maximize variability. The complementary probability (q) is calculated as 0.5 (1-p). Using these values, the study determined the minimum required sample size to be 384.

Data collection is carried out using a Google form distributed to bank professionals in India, where respondents indicate their level of agreement on items related to the study variables via a 7-point Likert scale. Out of 500 forms sent, 457 responses were received, and after verification, 404 responses are considered suitable for analysis. Demographic information, including age group, gender, and education level, is collected to provide context and insights into the respondents' characteristics. Although the convenience sampling method facilitated efficient data collection, it introduces potential bias, which is addressed in the limitations section of the manuscript. Future research is encouraged to employ stratified or random sampling techniques to enhance generalizability and representativeness. Table 2 offers a detailed overview of the demographic profile of the participants, aiding in a deeper understanding of the survey or research study's respondents. Regarding age, the largest portion falls within the 40–50 years range (40.6%), followed closely by those over 50 years (29.7%). In terms of gender, most respondents are male (59.9%). With regard to education, undergraduates make up the largest group (74.0%), while postgraduates and PhD holders account for the smallest percentages at 20.0% and 6.0%, respectively.

3.3 Data analysis

For data analysis, a two-stage SEM-ANN approach is used to thoroughly examine the relationships between variables. Structural Equation Modeling (SEM) is first applied to evaluate the effect of FinTech adoption and green finance investments on sustainable

Table 2 General Information of Respondents

Demographic Variable	Category	Frequency	Percent
1. Age group	18–30 Years	40	9.9
	30–40 Years	80	19.8
	40–50 Years	164	40.6
	More than 50 Years	120	29.7
2. Gender	Male	242	59.9
	Female	162	40.1
3. Education Level	Undergraduate	299	74.0
	Postgraduate	81	20.0
	PhD	24	6.0

economic growth, mediated by financial inclusion and moderated by the regulatory environment. SmartPLS 4 software is used for SEM analysis, providing statistical insights into the direct and indirect effects of variables (Bharadwaj, Patwardhan, Kumar, et al., 2025). In the second stage, an Artificial Neural Network (ANN) model was developed to capture complex nonlinear relationships that SEM may not fully uncover. IBM SPSS's neural network module was used to build a multilayer perceptron (MLP) model with a sigmoid activation function and backpropagation training algorithm. The dataset was split into 70% training and 30% testing subsets to validate model performance. Input variables included FinTech adoption, green finance, financial inclusion, and regulatory environment, while sustainable economic growth was the output node. The ANN analysis provided normalized importance values, revealing the relative predictive power of each input. This hybrid SEM–ANN methodology offers both causal inference and predictive robustness, making it particularly suitable for modeling the dynamic and nonlinear interactions prevalent in the Indian financial ecosystem. Figure 2 depicts the research methodology workflow, illustrating key stages: theoretical model development, construct measurement, pilot validation, SEM-based hypothesis testing, and ANN-based predictor ranking.

4 Results and discussion

4.1 Descriptive statistics and common method bias (CMB)

The analysis of descriptive statistics (see Table 3) reveals that the mean scores of the measured items range between 3.36 and 6.61, indicating that respondents generally exhibit a tendency toward agreement across the constructs under investigation. The standard deviation values range from 0.949 to 1.905, signifying a moderate level of variability in responses, suggesting that while there is some degree of dispersion, responses remain relatively consistent.

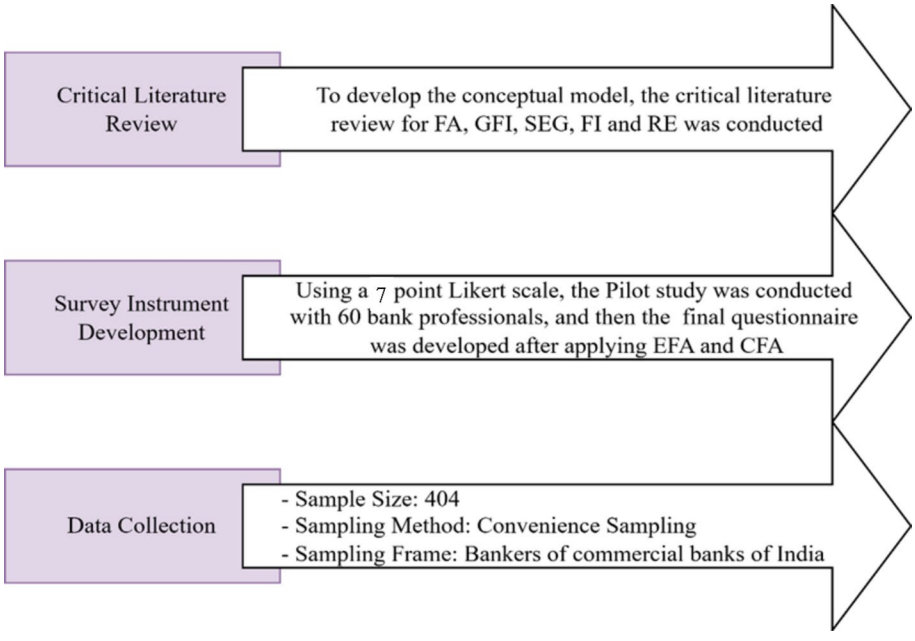

Fig. 2 Flow chart for Research Methodology

Table 3 Descriptive Statistics

Variables		Items	Mean	Std. Deviation	Skewness	Kurtosis	Factor Loading	VIF
Sustainable Economic Growth (SEG)	Dependent Variable (DV)	SEG1	5.04	1.365	-1.358	0.848	0.782	1.693
		SEG2	5.57	0.975	-2.769	8.027	0.724	1.588
		SEG3	3.36	1.384	-0.224	-1.143	0.794	1.471
		SEG4	3.53	1.905	0.296	-1.07	0.66	1.300
FinTech Adoption (FA)	Independent Variables (IV)	FA1	6.61	0.854	-2.985	11.238	0.81	2.093
		FA2	6.53	0.949	-2.716	9.062	0.855	2.491
		FA3	6.48	0.956	-2.458	7.48	0.885	2.982
		FA4	6.42	1.004	-2.387	7.094	0.874	2.802
		FA5	6.53	0.872	-2.551	8.425	0.859	2.533
Green Finance Investment (GFI)		GFI1	6.04	1.25	-1.472	2.05	0.767	1.754
		GFI2	5.62	1.373	-1.197	1.477	0.825	2.099
		GFI3	5.88	1.174	-0.991	0.7	0.864	2.405
		GFI4	5.86	1.217	-1.238	1.69	0.801	1.937
		GFI5	5.91	1.236	-1.338	1.991	0.793	1.851
Financial Inclusion (FI)		FI1	6.23	1.14	-1.877	4.124	0.844	1.609
		FI2	5.56	1.497	-1.147	1.029	0.839	1.998
		FI3	5.95	1.315	-1.487	2.183	0.888	2.167
Regulatory Environment (RE)	Moderator	RE1	6.06	1.066	-1.465	2.761	0.929	1.932
		RE2	6.30	1.006	-1.97	4.727	0.911	1.932

An assessment of skewness and kurtosis indicates that skewness values range from – 2.985 to 0.296, while kurtosis values span from – 1.143 to 11.238. The relatively high kurtosis values observed in certain variables, particularly those associated with FinTech Adoption (FA), suggest that these distributions are more peaked than a normal distribution. Nevertheless, the majority of the skewness and kurtosis values fall within the acceptable range for normality assumptions [21].

Furthermore, an examination of multicollinearity was conducted using the Variance Inflation Factor (VIF). The results indicate that all VIF values are below the recommended threshold of 3.0 [38], confirming that multicollinearity is not a significant concern in this study.

To assess potential Common Method Bias (CMB), Harman's single-factor test was performed. The results (see Table 4) reveal that the first extracted factor accounts for 35.682% of the total variance, which is well below the 50% threshold commonly used to determine the presence of CMB [23]. This finding suggests that common method variance does not pose a significant threat to the validity of the study's results.

The statistical findings demonstrate that the dataset meets the fundamental assumptions of reliability and validity. The absence of significant multicollinearity and the minimal influence of CMB enhance the robustness of the analysis (Mumtaz Ali, Mehdi Seraj, Fatma Türüç, 2023). These results provide confidence in the subsequent multivariate analyses, ensuring that the findings drawn from this dataset are methodologically sound and interpretable within the context of the study.

4.2 General linear model (GLM) analysis

The General Linear Model (GLM) analysis presented in Table 5 highlights the significant impact of various predictor variables on SEG. The corrected model exhibits strong statistical significance ($F = 2.695$, $p < 0.001$), indicating its effectiveness in explaining

Table 4 Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
FA1	6.780	35.682	35.682	6.780	35.682	35.682
FA2	2.085	10.974	46.657	2.085	10.974	46.657
FA3	1.920	10.103	56.760	1.920	10.103	56.760
FA4	1.279	6.734	63.494	1.279	6.734	63.494
FA5	1.151	6.059	69.552	1.151	6.059	69.552
GFI1	0.864	4.548	74.101			
GFI2	0.572	3.010	77.111			
GFI3	0.524	2.759	79.870			
GFI4	0.483	2.544	82.415			
GFI5	0.463	2.437	84.852			
FI1	0.415	2.185	87.037			
FI2	0.387	2.038	89.075			
FI3	0.375	1.972	91.047			
RE1	0.325	1.713	92.760			
RE2	0.310	1.631	94.391			
SEG1	0.290	1.528	95.919			
SEG2	0.275	1.446	97.366			
SEG3	0.267	1.403	98.768			
SEG4	0.234	1.232	100.000			

Extraction Method: Principal Component Analysis

Table 5 General Linear Model Analysis (Tests of Between-Subjects Effects)

Source	Type III Sum of Squares	Df	Mean Square	F	*P*-Value
Corrected Model	1057.951	345	3.066	2.695	0.000
Intercept	3996.904	1	3996.904	6605.273	0.000
FA	55.685	5	11.137	3.652	0.000
GFI	36.431	5	7.286	2.913	0.000
FI	77.21	5	15.442	3.952	0.000
RE	40.727	4	10.182	4.63	0.000
FA * FI	46.791	17	2.752	3.859	0.000
FA * RE	40.119	9	4.457	3.935	0.000
GFI * FI	120.771	29	4.164	4.115	0.000
GFI * RE	38.945	29	1.344	3.218	0.000
FI * RE	42.199	9	4.689	4.986	0.000
Error	52.897	58	0.912	-	-
Total	11,094	404	-	-	-
Corrected Total	1110.848	403	-	-	-

R-Squared = 0.926 (Adjusted R-Squared = 0.473) **Dependent Variable** = SEG

the observed variability in SEG. The intercept demonstrates a highly significant effect ($F = 6605.273$, $p < 0.001$), underscoring its foundational role in predicting SEG.

Among the main effects, FA ($F = 3.652$, $p < 0.001$), GFI ($F = 2.913$, $p < 0.001$), FI ($F = 3.952$, $p < 0.001$), and RE ($F = 4.63$, $p < 0.001$) all exhibit statistically significant influences on SEG, emphasizing their independent contributions. Additionally, interaction effects such as FA * FI ($F = 3.859$, $p < 0.001$), FA * RE ($F = 3.935$, $p < 0.001$), GFI * FI

Table 6 Internal Consistency, Reliability and Convergent Validity of Constructs

FA	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
	0.909	**0.911**	**0.933**	**0.735**
FI	0.821	0.832	0.892	0.735
GFI	0.869	0.874	0.906	0.658
RE	0.82	0.827	0.917	0.847
SEG	0.727	0.741	0.83	0.55

Table 7 Discriminant Validity – HTMT Ratio

FA	FA	FI	GFI	RE	SEG	RE x GFI	RE x FA
FI	0.535						
GFI	0.506	0.667					
RE	0.43	0.358	0.413				
SEG	0.267	0.273	0.354	0.363			
RE x GFI	0.395	0.259	0.391	0.305	0.1		
RE x FA	0.607	0.343	0.338	0.396	0.094	0.673	

(F = 4.115, $p < 0.001$), GFI * RE (F = 3.218, $p < 0.001$), and FI * RE (F = 4.986, $p < 0.001$) further reinforce the complex interplay among these variables.

The R-squared value of 0.926 and an adjusted R-squared of 0.473 indicate that the model explains approximately 92.6% of the total variance, though the adjusted R-squared suggests a more conservative explanatory power. These findings underscore the intricate relationships influencing SEG, offering critical insights for researchers and policymakers seeking to understand the dynamics of the studied constructs.

4.3 Assessment of Measurement Model

Table 6 presents the internal consistency, reliability, and convergent validity of the study's constructs. According to recommended thresholds, Cronbach's alpha values above 0.70, composite reliability (rho_a and rho_c) above 0.70, and an average variance extracted (AVE) above 0.50 indicate acceptable reliability and validity [36]. The Cronbach's alpha values range from 0.727 to 0.909, confirming good internal consistency across constructs. Similarly, composite reliability (rho_a) values range from 0.741 to 0.911, while composite reliability (rho_c) values range from 0.83 to 0.933, further supporting construct reliability. The AVE values, which range from 0.55 to 0.847, indicate adequate convergent validity, suggesting that the constructs explain a substantial proportion of their respective variances.

Table 7 reports the results of the Heterotrait-Monotrait (HTMT) ratio analysis to assess discriminant validity. Generally, HTMT values below 0.85 confirm discriminant validity by ensuring that constructs are more distinct than similar. The highest HTMT value in the Table 7 is 0.673, well below the recommended threshold, thereby affirming the distinctiveness of the study's constructs [36].

Table 8 presents the Fornell-Larcker (F-L) criterion results for further assessment of discriminant validity. The diagonal values in the Table 8 represent the square root of AVE for each construct, while the off-diagonal elements indicate inter-construct correlations [36]. Discriminant validity is confirmed when diagonal values exceed their corresponding off-diagonal correlations. In this study, the diagonal values for FA (0.857),

Table 8 Discriminant Validity - Fornell-Larcker (F-L) criterion

	FA	FI	GFI	RE	SEG
FA	0.857				
FI	0.472	0.857			
GFI	0.45	0.567	0.811		
RE	0.372	0.3	0.351	0.92	
SEG	0.22	0.217	0.29	0.283	0.742

Table 9 Hypotheses of the study

Hypothesis	Path	T-Statistics	*P*- value	Path Coefficients	Decision
Direct Hypotheses					
H1	FA -> SEG	2.486	0.013	0.122	Supported
H2	GFI -> SEG	4.599	0	0.187	Supported
Mediating Hypotheses					
H3	FA -> FI -> SEG	0.739	0	0.035	Not Supported
H4	GFI -> FI -> SEG	13.092	0	0.212	Supported
Moderating Hypotheses					
H5	RE x FA -> SEG	2.737	0.006	0.076	Supported
H6	RE x GFI -> SEG	0.169	0.866	0.005	Not Supported

FI (0.857), GFI (0.811), RE (0.92), and SEG (0.742) are all higher than their respective inter-construct correlations, verifying that each construct maintains sufficient distinction from the others. These findings establish the reliability and validity of the measurement model, ensuring that the constructs used in the study are both internally consistent and conceptually distinct.

4.4 Results of hypothesis testing

The results presented in Table 9 offer critical insights into the roles of FinTech adoption (FA) and Green Finance Investments (GFI) in promoting Sustainable Economic Growth (SEG). While most hypothesized relationships were statistically significant and supported, two hypotheses H3 (the mediating role of Financial Inclusion between FA and SEG) and H6 (the moderating role of Regulatory Environment between GFI and SEG) were not supported by the data.

H3 was not supported, indicating that FinTech adoption does not significantly lead to sustainable economic growth through the mediating mechanism of financial inclusion. This finding suggests that simply introducing FinTech tools is not sufficient to foster inclusion unless accompanied by digital literacy, infrastructure, and trust-building measures. In developing regions, especially in rural or semi-urban areas, barriers such as limited internet access, low smartphone penetration, and lack of user awareness hinder the inclusive impact of FinTech [48, 50]. Therefore, the assumed automatic trickle-down effect of FinTech on inclusion may not manifest unless backed by targeted financial education, access programs, and digital readiness initiatives.

H6 was also not supported, implying that the Regulatory Environment does not significantly moderate the relationship between green finance investments and sustainable economic growth. This may stem from the fragmented policy frameworks, inadequate regulatory enforcement, and the nascent stage of green financial instruments in India and similar emerging economies [28, 34]. Despite the existence of green finance guidelines, their adoption may not be uniform across financial institutions. The lack of comprehensive ESG reporting mandates or centralized monitoring mechanisms could

weaken the influence of regulation on green finance efficacy. Additionally, in markets where environmental sustainability is still a secondary policy priority, regulations may exist more in principle than in effective practice.

The supported hypotheses (H1, H2, H4, and H5) largely align with prior research, confirming the positive influence of FinTech and green finance on economic sustainability [3, 6], and validating the moderating strength of regulation in enhancing FinTech outcomes [15]. The strong mediation of FI in the green finance–SEG relationship is also consistent with the view that green investments often target underserved or decentralized energy sectors, where financial inclusion mechanisms such as microloans and community-based finance are vital [35].

However, the lack of support for H3 and H6 opens up promising avenues for future research. Scholars could investigate alternative mediating factors such as digital financial literacy, trust in technology, or institutional transparency, and moderators like market maturity, policy consistency, or ESG disclosure norms. Additionally, longitudinal studies could help assess how evolving regulatory landscapes and gradual FinTech penetration may influence these relationships over time.

In sum, while the model confirms several theoretical expectations, it also reveals important contextual limitations and policy-practice mismatches that should be addressed to unlock the full potential of FinTech and green finance for sustainable development.

Figure 3 illustrates the structural model depicting the direct, mediating, and moderating relationships among FA, GFI, FI, RE, and SEG. It shows that FA and GFI have significant direct impacts on SEG, while FI significantly mediates the GFI–SEG link but not the FA–SEG path. Additionally, RE significantly moderates the FA–SEG relationship, enhancing its effect, but does not moderate the GFI–SEG link, highlighting contextual limitations in regulatory influence over green finance outcomes.

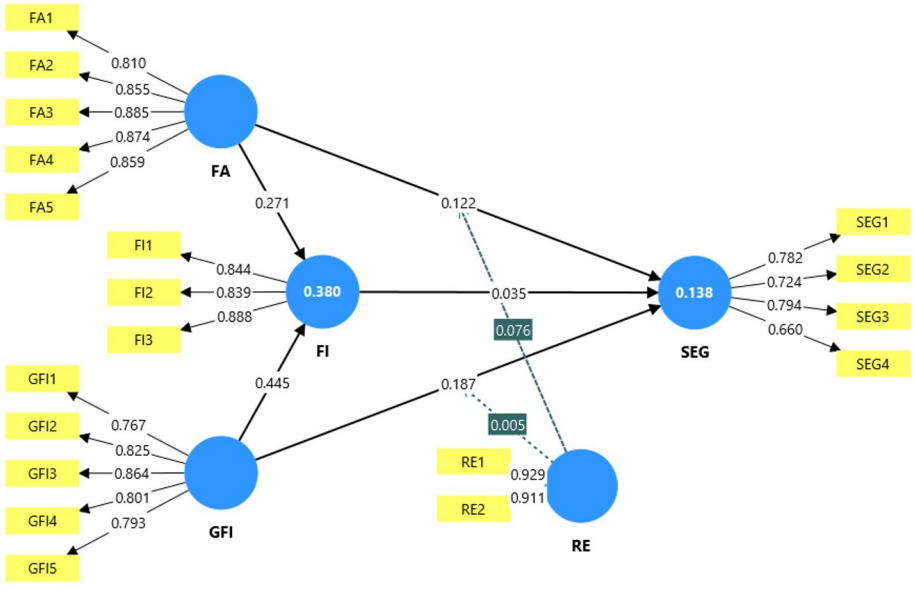

Fig. 3 Proposed Structural Model

Table 10 Values of RMSEA for model A

Network	RMSE (Training)	RMSE (Testing)	Total Sample
ANN1	0.412	0.489	404
ANN2	0.419	0.502	404
ANN3	0.471	0.481	404
ANN4	0.503	0.641	404
ANN5	0.478	0.603	404
ANN6	0.458	0.512	404
ANN7	0.434	0.463	404
ANN8	0.490	0.572	404
ANN9	0.411	0.513	404
ANN10	0.403	0.483	404
Mean	0.447	0.525	
Standard Deviation	0.036	0.059	

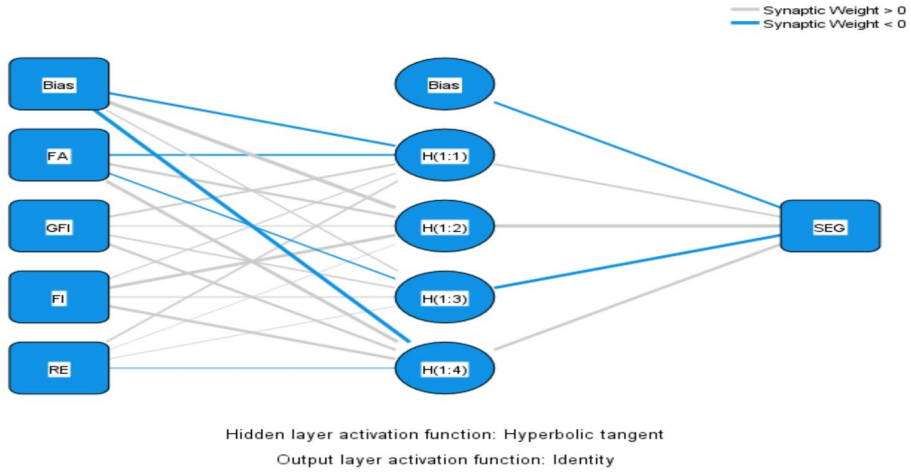

Fig. 4 Developed ANN Model

4.5 ANN analysis

The ANN model architecture includes an input layer, one or more hidden layers, and an output layer. In this study, the input layer comprised four independent factors, and the output layer contained the SEG variable. The model was trained using the input data and known output values to learn the patterns and relationships between the independent and dependent variables. Once trained, the ANN was used to make predictions on new data. The study utilized IBM's SPSS neural network module to conduct the ANN analysis, capturing both linear and non-linear interactions among variables without requiring a normal distribution of data.

To prevent over-fitting, a tenfold cross-validation procedure was implemented, dividing the data into 90% for training and 10% for testing. The root mean square error (RMSE) results for both training and testing phases are shown in Table 10. RMSE, a scale-dependent measure of prediction accuracy, estimates errors in specific datasets [61]. The mean RMSE values for training and testing were 0.447 and 0.525, respectively, indicating the model's ability to accurately identify both linear and nonlinear correlations. The relatively low mean RMSE values and minimal standard deviations observed in both phases further support the ANN model's high precision in recognizing correlations, as depicted in Fig. 4.

Table 11 illustrates the performance of the sensitivity analysis conducted in the study. This analysis aimed to the ranking of variables according to their normalized importance (NI) concerning the dependent variable. By examining the significance of each independent variable, the sensitivity analysis elucidated how variations in these variables influenced the projected values by the network structure.

The findings of the sensitivity analysis revealed that GFI emerged as the most crucial predictor of SEG. Following GFI, the FA, FI, and RE were identified as the next significant predictors. This ranking provides valuable insights into the relative importance of these variables in influencing SEG, thereby informing strategic decision-making processes.

4.6 Discussion over findings

The findings presented in the results section offer significant insights into relationships between various factors and Sustainable Economic Growth (SEG) in the context of banking firms in India. This discussion section interprets these findings, evaluates their alignment with existing literature, and explores their practical implications.

Impact of FinTech Adoption (FA) and Green Finance Investments (GFI) on SEG.

The study's findings support prior research suggesting that advancements in financial technology (FinTech) and sustainable finance practices positively influence economic growth. According to [46] FinTech adoption enhances financial intermediation efficiency, promotes financial inclusion, and fosters innovation in financial services, all of which contribute to economic expansion (Raza, Alavi, et al., 2024; [49]). Similarly, green finance investments are linked with sustainable development goals, environmental conservation, and resource efficiency, leading to long-term economic benefits.

Dey et al., [14], Zheng, [62]. The empirical evidence confirms that both FA and GFI play crucial roles in fostering SEG, aligning with the global push for digital financial inclusion and environmentally responsible investment strategies.

Role of Financial Inclusion (FI) as a Mediator.

The mediation analysis underscores the significance of FI in driving SEG. However, while the mediating role of FI in the relationship between GFI and SEG is statistically significant, its mediation effect between FA and SEG is not supported. This suggests that financial inclusion primarily enhances the impact of green finance investments rather than FinTech adoption on economic growth. Prior research has highlighted the positive correlation between FI and SEG, emphasizing that improved access to financial services empowers marginalized populations, stimulates entrepreneurship, and boosts productivity, leading to poverty reduction and economic advancement [37]. The findings suggest that while FinTech adoption enhances financial services, its direct contribution to SEG may not be significantly dependent on FI as an intermediary factor.

Moderating Effect of Regulatory Environment (RE).

The moderating role of the regulatory environment (RE) highlights the crucial influence of policy frameworks in shaping the impact of FA and GFI on SEG. The findings indicate that RE significantly moderates the relationship between FA and SEG but does not significantly influence the impact of GFI on SEG. Regulatory policies play a vital role in determining market stability, promoting financial innovation, and ensuring investor confidence [29]. Effective financial regulations foster trust in digital financial solutions, safeguard consumer interests, and encourage sustainable finance practices (Shayan et al.,

Table 11 Sensitivity Analysis

Variables	ANN:1	ANN:2	ANN:3	ANN:4	ANN:5	ANN:6	ANN:7	ANN:8	ANN:9	ANN:10	AI	NI (%)
RE	0.512	0.475	0.562	0.514	0.488	0.524	0.562	0.544	0.562	0.581	0.571	0.534
FI	0.521	0.478	0.512	0.571	0.501	0.588	0.671	0.561	0.511	0.599	0.601	0.799
FA	0.602	0.561	0.622	0.561	0.611	0.591	0.701	0.582	0.533	0.606	0.677	0.871
GFI	1.000	0.588	0.650	0.601	0.623	0.611	1.000	1.000	0.604	0.701	0.912	1.000

[61]). The results indicate that a well-structured regulatory framework is necessary for maximizing the benefits of FinTech adoption, while green finance investments may be influenced more by macroeconomic and institutional factors rather than direct regulatory interventions.

Validity and Reliability of the Measurement Model.

A rigorous assessment of the measurement model confirms the reliability and validity of the study's constructs, reinforcing the credibility of the findings. Prior studies emphasize the importance of stringent measurement validation to ensure the accuracy and dependability of empirical research [1]. A robust measurement model enhances the study's contribution by ensuring that the constructs accurately reflect the underlying theoretical dimensions, allowing researchers to derive meaningful conclusions [5]. By establishing the validity and reliability of the constructs, this study provides a solid foundation for future research on FinTech adoption, green finance, and their roles in promoting sustainable economic growth.

The findings reinforce the significance of FinTech adoption and green finance investments as key drivers of sustainable economic growth in the banking sector. While FI serves as a mediator in the GFI-SEG relationship, its role in the FA-SEG link remains inconclusive. Moreover, the regulatory environment plays a crucial moderating role in determining the success of FinTech adoption, but does not significantly influence the impact of green finance investments on SEG [48]. These insights provide valuable implications for policymakers, financial institutions, and researchers seeking to enhance financial inclusion and sustainability-driven economic strategies. These results offer actionable implications for policymakers and financial institutions striving to develop resilient, inclusive, and innovation-driven financial ecosystems. Future research should investigate cross-country, sectoral, and longitudinal dynamics to generalize the model and better understand the institutional and technological interactions shaping sustainable finance in emerging economies.

5 Implications, limitations, and future scope

5.1 Theoretical implications

This study contributes to the growing body of literature on sustainable economic growth by offering empirical evidence on the interplay between FinTech adoption, green finance investments, financial inclusion, regulatory environment, and economic sustainability. It expands existing knowledge by integrating both linear and non-linear modeling approaches, providing a more comprehensive understanding of the determinants of SEG in the banking sector. The findings validate and extend theories related to financial innovation, economic development, and sustainability, demonstrating the significant role of regulatory policies and financial inclusion in shaping economic outcomes.

5.2 Practical implications

The study's findings have substantial implications for policymakers, financial institutions, and investors seeking to enhance financial sustainability. From a regulatory perspective, policymakers can leverage these insights to formulate and implement adaptive regulatory frameworks that strike a balance between financial innovation and consumer protection. Institutions such as the Reserve Bank of India (RBI) and other financial

regulators should promote regulatory sandboxes, enabling the controlled testing of emerging FinTech solutions to ensure their alignment with sustainability goals.

Enhancing financial inclusion is another critical area where financial institutions should expand their digital financial services, mobile banking, and microfinance initiatives to address funding gaps, particularly for underserved entrepreneurs. To support this, digital literacy programs should be encouraged to boost the accessibility and adoption of FinTech services, especially in rural and semi-urban regions.

To scale green finance investments, the government should introduce tax benefits and incentives for financial instruments such as green bonds, sustainable loans, and carbon credit trading, motivating financial institutions to prioritize green investments. Additionally, banks and non-banking financial institutions (NBFCs) should incorporate ESG (Environmental, Social, and Governance) frameworks into their lending strategies to ensure sustainable finance practices that align with global sustainability objectives.

Fostering innovation in the banking sector is essential for achieving financial sustainability. Financial institutions should focus on developing tailored digital banking solutions that align with sustainability goals while addressing diverse consumer needs. Collaborations with FinTech startups and technology firms can further accelerate the adoption of AI, blockchain, and digital payment solutions, driving efficiency and inclusivity in the financial sector.

From an investment perspective, the study highlights the role of FinTech-enabled financial services in supporting green finance instruments, ensuring that sustainability remains a key consideration in financial markets. Investors can utilize these insights to make data-driven investment decisions that align with sustainability objectives, mitigate risks, and enhance long-term value creation. By integrating FinTech adoption, green finance investments, financial inclusion, and regulatory policies, stakeholders can foster a resilient, inclusive, and innovation-driven financial ecosystem that supports sustainable economic growth.

5.3 Limitations of the study

Despite offering valuable insights, this study has several limitations. First, it employs a convenience sampling method, which may introduce selection bias and limit the representativeness of the broader population within the Indian banking sector. Second, the cross-sectional design constrains the ability to infer causal relationships between the studied variables over time. Third, the country-specific focus on India restricts the generalizability of the findings to other emerging or developed economies with different financial and regulatory ecosystems. Lastly, construct specificity in earlier questionnaire iterations was limited, potentially affecting the precision of participant responses and overall measurement reliability.

5.4 Future scope of research

Future studies can address these limitations by adopting stratified or multi-stage random sampling techniques to enhance representativeness across demographic and institutional subgroups. Longitudinal or panel-based designs could uncover temporal trends and causal dynamics in FinTech and green finance adoption. Comparative cross-country analyses, particularly among BRICS or ASEAN economies, can help establish the global applicability of the conceptual framework. Researchers may also explore additional

mediating variables such as trust in digital platforms, technological self-efficacy, or financial literacy, as well as moderating factors like market maturity, institutional strength, or ESG transparency. Further, deeper investigation into emerging FinTech innovations including blockchain-based KYC, AI-driven credit scoring, digital green bonds, and carbon trading platforms could advance understanding of their nuanced impacts on sustainable economic growth.

6 Conclusion and policy recommendation

This study offers comprehensive insights into the determinants of Sustainable Economic Growth (SEG) within the Indian banking sector by integrating FinTech Adoption (FA), Green Finance Investments (GFI), Financial Inclusion (FI), and the Regulatory Environment (RE) into a unified empirical framework. The results affirm that both FA and GFI are pivotal in enhancing SEG. While FinTech adoption contributes through increased operational efficiency, broader access to financial services, and accelerated innovation, green finance drives environmental sustainability and long-term economic stability. The mediating role of FI strengthens these relationships by promoting inclusive growth, fostering entrepreneurship, and reducing socio-economic disparities. Additionally, the moderating role of RE, especially on FA, emphasizes the importance of adaptive regulatory mechanisms in maximizing the impact of technological and sustainable financial innovations.

The methodological integration of Structural Equation Modeling (SEM) and Artificial Neural Networks (ANN) elevates the analytical robustness of the study. SEM facilitates causal inference through linear modeling of direct and indirect relationships, while ANN captures non-linear dependencies and improves predictive performance. This dual-layered approach addresses the complexity of emerging market financial ecosystems, making the study particularly relevant for data-rich but structurally diverse economies like India.

From a policy standpoint, several recommendations emerge. First, enhancing financial inclusion must be prioritized through widespread financial literacy programs, digital banking penetration, and targeted incentives for inclusive financial service delivery. Policymakers should also advance sustainable finance regulations, offering tax incentives, ESG-linked compliance mechanisms, and clear guidelines for green investments to encourage environmentally responsible lending. Promoting FinTech innovation through regulatory sandboxes, R&D subsidies, and support for AI, blockchain, and digital payment platforms can further modernize the sector. However, parallel efforts must be made to reinforce risk management frameworks, addressing concerns related to cybersecurity, digital fraud, and market instability.

Encouraging public-private partnerships (PPP) is also vital. Strategic collaborations between governments, financial institutions, and technology firms can accelerate infrastructure development, scale green finance instruments like green bonds and carbon credit trading, and extend digital financial services to rural and semi-urban areas. Such synergies will enhance the resilience and inclusivity of India's financial ecosystem.

Finally, while the current study lays a strong foundation, future research should explore the granular impacts of specific FinTech tools (e.g., robo-advisors, digital wallets, blockchain KYC) and green finance products (e.g., ESG loans, solar financing) on SEG. Further investigation into cultural, behavioral, and institutional dimensions influencing

financial inclusion, as well as comparative evaluations of regulatory models across economies, can enhance the generalizability and strategic relevance of the findings.

In conclusion, the integration of FinTech, green finance, financial inclusion, and effective regulatory governance is essential for achieving sustainable economic growth in emerging markets like India. By strategically leveraging these drivers, stakeholders can pave the way for a resilient, inclusive, and innovation-led financial ecosystem that supports long-term economic and environmental sustainability.

Author contributions
Authors 1 and 3: Wrote a DraftAuthors 2 and 4: Methodological AnalysisAuthors 5 and 6: Review the Manuscript.

Funding
Open access funding provided by Manipal Academy of Higher Education, Manipal. No funding is received to conduct the research work.

Data availability
The authors declare that data associated with outcomes of this study are available from the corresponding author based on a reasonable request.

Declarations

Ethics approval
This study was conducted under ethical guidelines and regulations. The research protocol was reviewed and approved by the relevant ethics committee of MITS-DU, Gwalior, ensuring compliance with ethical standards.

Consent to participate
All participants provided informed consent before participating in the study.

Consent to publish
Not Applicable.

Clinical trial number
Not Applicable.

Competing interests
The authors declare no competing interests.

Received: 17 August 2025 / Accepted: 11 March 2026
Published online: 26 March 2026

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