



Green innovation and green growth: Evidence from Indian economy

 **Mduduzi Biyase**¹⁺
 **Gurpreet Kaur**²

¹*School of Economics, University of Johannesburg, South Africa.*

¹*Email: mbiyase@uj.ac.za*

²*University School of Business, Chandigarh University, India.*

²*Email: drgurpreet.938@gmail.com*



(+ Corresponding author)

ABSTRACT

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The present study focuses on the major research questions: What kind of relationship exists between green innovation and green growth in India? And how far are the structural as well as the financial factors helpful in empowering this relationship? The study investigates the connection between green innovation and green growth in India using annual time series data from the period 1990 to 2022, collected from multiple sources that include World Development Indicators, Organisation for Economic Co-operation and Development for environment-related technologies, and globalization (LKOF) from the KOF Swiss Economic Institute. The Auto-Regressive Distributed Lag (ARDL) approach has been utilized to analyze short-run and long-run impacts, complemented by FMOLS, DOLS, and CCR estimators. The major findings confirm that green innovation, financial development, and income growth have a significant impact on green growth, but energy consumption and capital formation have a negative impact on green growth. The results demonstrate that a 1 percent rise in technological innovations promotes nearly 0.8 percent green growth. Further, the analysis also supports the positive effect on financial development (0.906) and per-capita income (4.518), but ICT expansion exerts a negative impact of (-0.399), implying the transitional environmental cost connected with digital expansion. The results offer actionable policy insights for India. To promote green growth, it is required to encourage green finance, facilitate the ICT infrastructure and green R & D ecosystem, foster renewable energy investments, and promote innovation-led strategies to achieve long-term environmental and economic resilience.

Contribution/Originality: This study provides India-specific time-series evidence on the link between green innovation and growth, filling a gap left by cross-country research. Using ARDL and robust estimators, it shows that green innovation, income, and financial development drive sustainability. These findings offer actionable policy insights for integrating green finance.

1. INTRODUCTION

The industrial revolution has been continuously supported by Research and Development activities. Advancements in technology promote industrialization around the globe (OECD, 2015). National Academy of Science and Engineering, Acatech (2013) identified four phases of industries based on the growth of technology. Starting from the first revolution that was based on water and steam-powered manufacturing units, then turns to the second revolution, where electricity-powered production units came into existence, subsequently, the third revolution promotes the collaboration of electric and IT, and in the fourth revolution, the trend of IoT and Cyber-Physical systems (Schwab, 2016) came. With the rapid growth of industrialization, certain kinds of challenges were observed

that include ecological damage, environmental degradation, pollution, and climate change (Intergovernmental Panel on Climate Change, 2021). Industrial activities have contributed significantly to global warming through increased carbon dioxide emissions and rising levels of plastic pollution. This may further negatively impact the environment and sustainability (United Nations Environment Programme, 2022) of Mother Earth. The economies need to be reshaped to retain the environment by focusing on sustainable consumption and production patterns (OECD, 2019). To meet the agenda of economic growth and environmental protection, several programmes, including the agenda of 17 sustainable development goals, were launched by the United Nations in 2015 (United Nations, 2015), and also to promote a pollution-free economy, a treaty under the Paris Agreement was signed by 196 countries to achieve zero emissions by 2050.

Green Innovation leads to new opportunities, new processes and techniques, which further encourage the sustainability of the different sectors, increase the efficiency of the resources, and reduce the environmental risk (Takalo, Tooranloo, & Parizi, 2021). Like traditional innovation, the objectives of green innovation are not to focus on increasing production and earning profits. Sanz-Torro, Calafat-Marzal, Guaita-Martinez, and Marti (2025) play a vital role in transforming the economy into a low-carbon economy, diverting investment to renewable sources and encouraging eco-friendly manufacturing practices (Ju & Jin, 2024; Sun, Gao, Tian, & Guan, 2023). Green Innovation is a step to handle the threat of climate change and environmental pollution. With the help of green products, environmental and social sustainability can be achieved, thereby promoting economic growth and development of economies (Rupasinghe, Pushpakumari, & Perera, 2024).

In the context of India becoming self-reliant, uplifting its status, expansion of business, the SMEs are focusing on the production of green products. For economic expansion and environmental sustainability, the industries are investing in green innovation (Hu & Kee, 2022; Ziaei & Roshani, 2024). The adoption of green innovation in India exemplifies a dialectic situation, as it experiences both breakthrough opportunities and difficulties in the implementation process and utilization of renewable sources. Through government initiatives like liberalized policies, offering incentives for stimulating green practices in India, it ensures inclusive growth in the country (Nosheen, Abid, & Zhang, 2021). Green innovation is a positive transformation of the economic framework that supports ecological sustainability (World Economic Forum, 2016).

In India, the government has sought to facilitate entrepreneurship through liberalised policies and targeted incentives. In this regard, initiatives such as the National Green Hydrogen Mission, National Solar Mission, wind and bioenergy programmes, Green Energy Corridors (India Brand Equity Foundation (IBEF), 2025), and green financial initiatives collectively promote green innovation while supporting both environmental and economic sustainability (Aggarwal, 2025). Although many researchers have contributed to the literature on green innovation and green growth, there are still some research gaps in the literature. Prior studies commonly use cross-sectional and panel-data approaches, but very few studies utilized time-series analysis and employed ARDL, FMOLS techniques to examine both long-run and short-run impact for India. In the context of India, existing studies tend to concentrate on whether the ICT expansion promotes or hinders environmental sustainability. While other studies devote attention to green finance, renewable energy, or the adoption of green technology. Very few studies focus on the joint influence of these factors on green growth. The present study utilizes an ARDL model to understand the impact of financial development, globalization, ICT development, and renewable energy on green growth, which has not been used in the context of India.

The present study is structured in five different sections. Through section 2, an overview of theoretical literature has been given based on the contribution given by different researchers.

Section 3 presents the research methodology consisting of data sources, variable definitions, and econometric techniques. Section 4 and Section 5 display empirical results and also summarize the major findings, along with key policy implications related to sustainable growth patterns through green innovation in India, respectively.

2. LITERATURE REVIEW

Our investigation rests on three principal theoretical concepts, with detailed discussions available in Gharbi, Zarrad, Kalai, and Helali (2025). This derives from the endogenous growth theory (Romer, 1990), which considers R&D and new technologies as the main source of economic growth, hence putting green innovations at the centre of the picture as the main factors driving both productivity and environmental sustainability. Secondly, the Porter hypothesis (Porter & van der Linde, 1995) is used, which asserts that proper environmental regulations are not barriers but rather strategic advantages, thus motivating firms to bring about innovations and improve their market position (Gharbi et al., 2025; Porter & Linde, 1995).

Elucidating the importance of innovation (Porter & van der Linde, 1995; Romer, 1990) observed a significant rate of regulation and requirement of sustainability (Goodland & Daly, 1996) has shed light on the factors that are equally important for fostering green economic growth, notably in developing economies around the globe. Some of the studies confirm that the green innovation stimulates economic growth, but its effectiveness is linked with policy frameworks and the findings by the nodal agencies. Fernandes, Ferreira, and Raposo (2021), using panel data analysis, validate that drivers like technology transfer and innovation have a long-term tendency to promote green growth in developed economies. Nosheen et al. (2021), taking evidence from the European Union, concluded that continuous investment in R&D, providing incentives, and focusing on renewable energy sources encourage more green growth, and also Pachiyappan and Rao (2022) observed that investment in green innovation reduces carbon emissions.

While going through the literature review, an effort has been made to throw light on the positive and negative aspects of the relationship between green growth and green innovation (see Table 1). For example, Javed, Fuinhas, and Rapposelli (2023) and Alola and Adebayo (2023) demonstrate that the increase and decrease in investments in green innovation have positive and negative impacts. Further, by applying the advanced econometric tools, the study observed an asymmetric and non-linear relationship between investment and green growth. The study reveals that the impact of green innovation and the environment is heterogeneous by nature. More investment reduces the CO₂, increases the efficiency of the firms, and firms use cleaner technologies; on the other hand, less or no investment has a negative impact on the environment.

This complexity is mirrored in the synergistic role of co-drivers. Digitalization is recognized as a significant co-driver in the process of the green economy by contributing to the efficiency of resource use and the development of eco-friendly technologies (Hao, Li, Ren, Wu, & Hao, 2023). Besides, the green innovation's contribution goes as far as playing a part in the energy transition through the relationship between our dependent and independent variables and the uptake of sustainable energy, which further corroborates the belief that innovation is the driving force behind the changeover to renewables (Moghadam & Karami, 2024).

As shown in Table 1, recent studies have further fine-tuned the connection by underlining the importance of financial mechanisms and the quality of institutions. Studies conducted in the context of China revealed that the twin policy of R&D investment and green finance acts as a major force in encouraging green innovation, especially in the case of well-established small and medium-sized enterprises (SMEs) (Lui, 2025). The delivery of this financial support is further reinforced by evidence from India, where research on macro-level data has confirmed that green finance, together with renewable energy consumption, has a positive impact on environmental sustainability and CO₂ emissions (Aggarwal, 2025). The necessity for institutional rigor is also identified in the literature since it was found that more stringent government environmental regulations, through empirical research, lead to the improvement of green innovation quality and thus to the reduction of carbon emissions in Chinese firms (Peng, Song, & Li, 2025; Song, Gao, & Lee, 2025). Finally, empirical studies highlighted the necessary conditions for successful firm-level implementation, particularly in emerging markets. Research on Indian SMEs revealed that not all innovation types are equally effective, suggesting that eco-process and eco-organizational innovation are more impactful on sustainable performance than eco-product innovation Singh and Chakraborty (2021); see also Mehmood, Ali, and Shah (2025) and Zhang (2025). Paulmoni, Singh, and Kaur (2024) and Song et al. (2025) demonstrate that green innovation

enhances competitive advantage and generates market credibility for Indian firms. Moreover, the utilization of sustainable manufacturing models is more economical and advocates ecological restoration. Shah, Alnori, Su, and Deng (2021) laid more emphasis on the government support for endorsing green innovation among the SMEs of the country. This may encourage better management of resources, more investment in technology, and generate productivity. Navaneet (2024) & Liu, Wang, and Li (2024) highlight the role of GDP through the Green Growth Index (GGI) and predict that developing countries like India and China, with high GDP, consistently promote green investment and achieve more environmental sustainability. Beyond the initial summary of empirical findings, the diverse body of literature discussed throughout this section reveals a complex and often non-linear relationship between technological advancement and sustainable development. Table 1 provides a neat summary of the selected studies concerning the impact of green innovation. What stands out is the fact that the impact of green innovation is quite sensitive to the method used and the country under study. For example, a recent study by Gharbi et al. (2025) employed PMG-NARDL and found evidence to suggest that positive innovation shocks have a substantial impact on growth compared to negative shocks. Moreover, a study by Singh and Chakraborty (2021) reveals that the impact depends on the type of innovation. More specifically, they found that eco-process changes bring about a more substantial impact on sustainable performance in India than eco-product innovation. What also stands out from the table is that there is a clear collaborative impact of co-determinants, including green finance and digitalization, which are important instruments for converting technological potential into measurable green growth.

Table 1. Summary of selected empirical findings on green innovation and green growth.

Study (Year)	Model/Method	Key Finding and Coefficient
Gharbi et al. (2025)	PMG-NARDL (Asymmetric)	Positive Shock (Green Innovation): Positive shocks increase green growth. Negative Shock (Green Innovation): Negative shocks reduce green growth.
Javed et al. (2023)	ARDL/NARDL	Asymmetric Effects (Green Technological Innovation): Positive shocks significantly mitigate; negative shocks exacerbate environmental degradation.
Su and Gao (2022)	NARDL	Asymmetric (Green Technological Progress): the impact of a positive shock outweighs the negative impact.
Smol, Kulczycka, and Avdiushchenko (2017)	Empirical	Positive (Green Innovation): GI positively impacts circular economy indicators.
Hao et al. (2023)	Econometric	Positive (Digitalization): Underscores digitalization's role in promoting green growth through resource-efficient processes.
Nosheen et al. (2021)	Co-Integration, FMOLS	Positive (R&D, Financial Incentives, REC): Promoting these factors promotes green growth.
Lui (2025)	DID Analysis	Positive (Green Finance Policy): The green finance policy promotes green innovation, especially in SMEs and experienced enterprises.
Shah et al. (2021)	Fuzzy AHP and TOPSIS	Obstructive/Negative (Adoption of Green Practices): Managerial, technical, and economic barriers hinder adoption in SMEs; requires active government involvement.
Singh and Chakraborty (2021)	SEM	Contextual (Eco-Process/Organizational Innovation): These innovations are more impactful than eco-product innovation for sustainable performance in India.
Pachiyappan and Rao (2022)	BARDL	Positive (Green Innovation): Promoting GI is an effective long-run measure to reduce carbon emissions.
Alola and Adebayo (2023)	NARDL	Negative (Raw Material Productivity Decline): a decrease in productivity brings about a long-run increase in GHG emissions.
Bergougui and Aldawsari (2024)	Empirical	Paradoxical/Nuanced (Green Patents): there is a negative relationship between patenting and the ecological footprint.
Peng et al. (2025) and Song et al. (2025)	DID Technique	Positive (Regulations/GI Quality): Strict government environmental regulations and improved GI quality reduce carbon emissions.
Navaneet (2024) & Liu et al. (2024)	GGI Analysis	Contextual/Positive (GDP): States/cities with high GDP performed better on the Green Growth Index (GGI).
Paulmoni et al. (2024) and Song et al. (2025)	Empirical	Positive (GI Performance): Promotes competitive advantage and market credibility for firms.
Bapat and Patil (2023)	Empirical	Positive (Sustainable Manufacturing Techniques): Encourages environmental sustainability and cost-efficiency.

3. METHODOLOGY

3.1. Data

We use the annual time series from 1990 to 2022. The data for the variables used consists of green growth (adjusted savings: net national savings, current US\$), financial development (domestic credit to the private sector by banks, % of GDP), urbanization (urban population growth, annual %), per capita income (GDP per capita, PPP, constant 2021 international \$), renewable energy (renewable energy consumption, % of total final energy consumption), and ICT development (INDEX: fixed telephone subscriptions per 100 people, individuals using the internet percentage of their population, and mobile cellular subscriptions per 100 people) have been extracted from the World Development Indicators (World Bank, 2022). Data for green innovation (environment-related technologies) have been obtained from the Organisation for Economic Co-Operation and Development (2022), whereas globalization (LKOF) was taken from the KOF Swiss Economic Institute. The underlying variables are all transformed into natural logarithmic form to lessen magnitude and variability, reduce heteroscedasticity, and make the estimated coefficients interpretable as elasticities. A full description of variables, including their measurements and sources, appears in Table 2.

Table 2. Variables, measurement, and data sources.

Variables	Measurement/Proxy	Source
Green Growth (GG)	Adjusted savings: net national savings (current US\$)	World Bank (World Development Indicators)
Green Innovation (GREENI)	environment-related technologies patents	Organisation for Economic Co-Operation and Development (2022)
Globalization (KOF)	Globalization Index	KOF Swiss Economic Institute
Financial Development (LFD)	Domestic credit to private sector by banks (% of GDP)	World Bank (2022)
Urbanization (URBANGROWTH)	Urban population growth (annual %)	World Bank (2022)
Per Capita Income (GDPPCPPP)	GDP per capita, PPP (constant 2021 international \$)	World Bank (2022)
Renewable Energy (REN)	Renewable energy consumption (% of total final energy consumption)	World Bank (2022)
ICT Development (INDEX)	Composite index based on fixed telephone subscriptions (per 100 people), individuals using the internet (% of population), and mobile cellular subscriptions (per 100 people)	World Bank (2022)

3.2. Functional Form of the Model

The present study examines the relationship between green growth, measured by adjusted net savings, and its key determinants, with a particular focus on green innovation, while accounting for globalization, financial development, ICT development, renewable energy consumption, urbanization, and per capita income. Following the modeling approaches employed in prior studies in environmental economics and sustainability (Mensah et al., 2019; Ulucak, İlkay, Özcan, & Gedikli, 2020), the model is expressed in a linear functional form as:

$$GG = f(GI, ICT, FD, RE, URB, GDPpc, KOF) \quad (1)$$

Here, green innovation (GI) includes environment-related technologies, ICT development (ICT) stands for technological connectivity and access, and financial development (FD) measures the domestic credit provided to the private sector by banks. Renewable energy consumption (RE) indicates the share of renewables in total final energy use, while urbanization (URB) denotes the annual rate of growth of the urban population. Per capita income (GDPpc) signals GDP per capita at PPP levels, and globalization (KOF) denotes the degree to which economic, social, and political factors.

The theoretical expectation of the direction of the independent variables comes from the prior empirical and theoretical literature in the related fields. Generally, green innovation (GI) is expected to generate a positive effect on green growth because investments in environmentally-related technologies improve resource efficiency, lessen environmental degradation, and provide for sustainable economic outcomes. An opposite expectation obtains for ICT development (ICT), which may also hamper green growth, as efficient communication and knowledge diffusion may free the adaptation of green technologies. Financial development (FD) is expected to exert a positive influence on green growth in the sense that enhanced access to credit and financial services would enable investments into green projects and renewable energy initiatives. RE is similarly expected to bring about a positive impact by displacing fossil fuel-related activities and corresponding ecological pressures. Urbanization (URB), measured by annual growth of urban population, may exert either positive or negative effects under different socio-economic conditions: on the one hand, urbanization through enhanced economic activities helps in the diffusion of innovation towards green growth; on the other hand, this obviously adds pressure on the environment by increasing energy consumption and pollution levels. Per capita income (GDPpc) is expected to positively affect green growth, uplifted by the presence of the Environmental Kuznets Curve: the higher the income levels, the more the investments in sustainability and environmental protection. On the other hand, globalization (KOF) might positively contribute to green growth through knowledge transfer, foreign investment, and higher awareness of international environmental standards, though in some instances, it could increase resource exploitation, creating a somewhat mixed picture.

Having established the functional form of the model, the next step involves the use of an econometric approach capable of describing both long-run equilibrium relationships, if these exist, and short-run dynamics between green growth and its potential determinants. This is necessary because variables, such as green innovation, ICT development, financial development, renewable energy consumption, urbanization, per capita income, and globalization, are drawn from macroeconomic and development indicators that tend to exhibit mixed orders of integration. Standard cointegration techniques such as Engle and Granger (1987) and Johansen (1991) require that all series be integrated of the same order and are thus not applicable in this particular case.

The ARDL methodology offers various advantages, rendering it very much appropriate for applied work within environmental and sustainability economics. First, unlike the traditional cointegration techniques, ARDL can be run regardless of whether the regressors are $I(0)$ or $I(1)$, hence avoiding the pre-testing bias inherent to unit-root testing. Second, the short-run and long-run coefficients are estimated simultaneously in a single reduced-form equation, which is appropriate for dynamic adjustment. Third, the approach is suitable for small and finite sample sizes, which are often the case for time series spanning only a limited number of years of developing and emerging economies. Fourth, ARDL models include an error-correction representation, which enables one to measure the speed of adjustment back to long-run equilibrium after experiencing a short-run shock. This series of advantages has contributed to the widespread use of ARDL in empirical studies relating to growth, energy, and environmental sustainability.

The ARDL specification-form model for this study is given by:

$$\Delta LGG_t = \alpha_0 + \sum_{i=1}^n \vartheta_1 \Delta LGG_{it-j} + \sum_{i=1}^n \vartheta_2 \Delta LICT_{it-j} + \sum_{i=1}^n \vartheta_3 \Delta LFD_{it-j} + \sum_{i=1}^n \vartheta_4 \Delta LRE_{it-j} + \sum_{i=1}^n \vartheta_5 \Delta LURB_{it-j} + \sum_{i=1}^n \vartheta_6 \Delta LGDPpc_{it-j} + \sum_{i=1}^n \vartheta_7 \Delta LKOF_{it-j} + \sum_{i=1}^n \vartheta_8 \Delta LGI_{it-j} + \phi_1 LGG_{it-1} + \phi_2 LICT_{it-1} + \phi_3 LFD_{it-1} + \phi_4 LRE_{it-1} + \phi_5 LURB_{it-1} + \phi_6 LGDPpc_{it-1} + \phi_7 LKOF_{it-1} + \phi_8 LGI_{it-1} + u_{it} \quad (2)$$

Where α_0 denotes the intercept term, Δ represents the first-difference operator, and $\vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4, \vartheta_5, \vartheta_6, \vartheta_7$ and ϑ_8 capture the short-run coefficients associated with the explanatory variables. The long-run coefficients are derived from $\phi_1, \phi_2, \phi_3, \phi_4, \phi_5, \phi_6, \phi_7$ and ϕ_8 , which reflect the long-run elasticities of green growth with respect to its determinants. Once the long-run relationship of variables is established through the bounds-testing procedure, the model is further adjusted into the error-correction representation (ECM), which can be formally written as:

$$\Delta LGG_{it} = \alpha_0 + \sum_{i=1}^n \vartheta_1 \Delta LGG_{it-j} + \sum_{i=1}^n \vartheta_2 \Delta LICT_{it-j} + \sum_{i=1}^n \vartheta_3 \Delta LFD_{it-j} + \sum_{i=1}^n \vartheta_4 \Delta LRE_{it-j} + \sum_{i=1}^n \vartheta_5 \Delta LURB_{it-j} + \sum_{i=1}^n \vartheta_6 \Delta LGDPpc_{it-j} + \sum_{i=1}^n \vartheta_7 \Delta LKOF_{it-j} + \sum_{i=1}^n \vartheta_8 \Delta LGI_{it-j} + \rho_1 ECM_{t-1} \quad (3)$$

Equation 3 is quite similar to Equation 2, except that it contains ρ_1 , which measures the rate of adjustment toward the long-run equilibrium after short-run shocks. Since there is always the risk of an econometric estimator being very sensitive to the specification of the model, we thus complement the results of ARDL with three other long-run estimators: Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR), so that the results may be tested for robustness and consistency.

Each of the three estimators has its unique feature. The FMOLS, developed by Phillips and Hansen (1990), implements appropriate non-parametric correction for problems of serial correlation that arise from the endogenous regressors, thus providing efficient and unbiased estimates of long-run parameters. DOLS, proposed by Stock and Watson (1993), addresses similar issues by augmenting the cointegrating regression with leads and lags of differenced regressors such that simultaneity bias and small-sample problems can be controlled for. The CCR, due to Park (1992), is a method by which the cointegrating regression is transformed such that the long-run correlation between the regressors and the error term is removed, resulting in asymptotically efficient estimators without the need for prewhitening or additional correction terms.

FMOLS, DOLS, and CCR, when used in tandem with ARDL, are especially advantageous because they provide the analysis with the triple robustness of an estimation that might otherwise not have been considered. Consistent results independently derived through these methods thus give considerable weight to the long-run relationships between green growth and its determinants. Therefore, this triangulation of methods serves to lessen any concerns about estimator sensitivity and further reinforces the alleged empirical evidence.

3.3. Empirical Analysis

This section presents the empirical analysis, including trend analysis, descriptive statistics, unit root tests, and ARDL results. We begin with the trend analysis to provide a visual overview of the behavior of the variables over time.

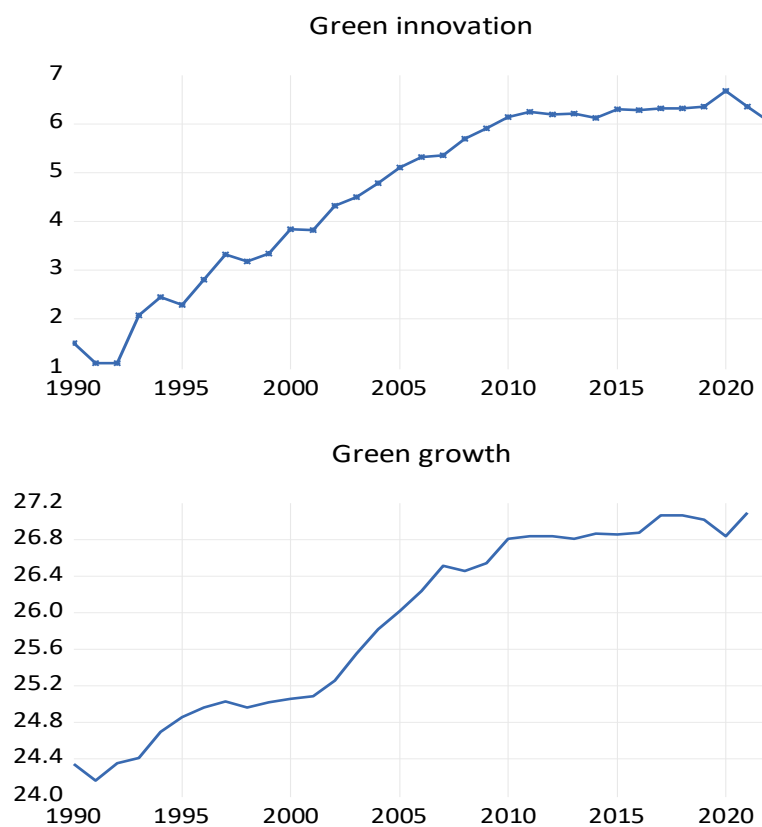


Figure 1. Trends in green innovation and growth in India.

Figure 1 illustrates how the dependent and independent variables of interest changed over time. What seems to stand out almost immediately from the diagram is the gradual rise in both variables, though with diverse patterns. The independent variable suggests an upswing phase, implying some embracing of sectors that are technologically inclined. The dependent variable resembles the trend of the independent variable, implying the fact that the Indian economy has experienced a significant degree of structural change during this period. The joint or shared movements in these variables may imply that an increase in green innovation is associated with an increase in green growth. Also noticeable are episodes of wider gaps in the lines, perhaps reflecting the fact that increases in innovation are constrained by various binding economic and institutional constraints.

That divergence draws attention toward issues of absorption capacity, regulatory quality, and the complementary roles of infrastructure and finance in ensuring that innovation translates to developmental dividends in the long run.

The descriptive statistics, as shown in Table 3, illustrate preliminary insights into the series employed while investigating the relationship between green innovation and green growth in India. Green growth (LGG1A) exhibits stability in nature, with a large mean value (25.95) and a standard deviation of 0.93, suggesting that this property has just a slow, steady upward path over time. However, green innovation (LGREENI) shows a much higher degree of variation, with $\sigma = 1.62$, depicting uneven advancement of India in the development of environmentally friendly technology, which routinely correlates with the varying levels of policy incentives and technology diffusion internationally. Financial development (LFD1) and globalization (LKOF) show significant levels of variation. The trade openness variable (proxied by globalization) is clearly skewed (-0.97) to the left, signifying a certain degree of trade restriction during the global financial shocks. The ICT index has an average of -0.03 , showing that India's substantial increase in ICT has been somewhat characterized by non-uniform patterns. The other variables, such as renewable energy and urbanization, seem to have reduced dispersion, while economic growth unsurprisingly displays an upward swing during this period.

Skewness and kurtosis statistics suggest that the majority of variables are slightly negatively skewed and platykurtic (with kurtosis < 3), implying lighter tails and, hence, fewer extreme fluctuations. In terms of econometric modeling, this favors the objective as it decreases the probability of estimation distortion owing to outliers.

Table 3. Descriptive stats.

Measure	GG	GI	FD1	KOF	ICT index	REN	URB	GDPpc
Mean	25.954	4.769	3.618	3.509	0.028	3.716	2.639	8.333
Median	26.233	5.313	3.775	3.688	0.134	3.765	2.655	8.325
Maximum	27.063	6.674	3.998	3.819	1.514	3.941	2.972	8.978
Minimum	24.358	1.093	3.113	2.775	-1.997	3.481	2.281	7.718
Std. Dev.	0.934	1.615	0.335	0.343	0.937	0.163	0.195	0.400
Skewness	-0.285	-0.639	-0.353	-0.966	-0.725	-0.128	-0.107	0.107
Kurtosis	1.477	2.152	1.396	2.382	2.647	1.405	1.887	1.730

Table 4 presents the results of the unit root tests (ADF and PP). The table shows that the variables are mixed, either at level $[I(0)]$ or at first difference $[I(1)]$. In particular, globalization (KOF) somehow displays evidence of weak level stationarity under some specifications, and so it may be treated as an $I(0)$ variable. By contrast, green growth (GG), green innovation (GI), financial development (FD1), (ICT INDEX), renewable energy (REN), urbanization (URB), and per capita income (GDPpc) are non-stationary at levels but stationary at first difference and, hence, are classified as $I(1)$. This mixture of $I(0)$ and $I(1)$ variables and the absence of $I(2)$ variables allows us to go for the ARDL bounds testing procedure (Pesaran, Shin, & Smith, 2001). The ARDL approach is considered very apt in this context because it can handle regressors of mixed integration orders while providing consistent estimates for the short-run dynamics and long-run relationship.

Table 4. Unit root test.

Unit Root Test Table (PP)									
At Level									
		GG	GI	FD1	KOF	ICT Index	REN	URB	LGDPpc
With Constant	t-Statistic	-1.004	-1.992	-0.778	-2.993	-2.217	-1.030	-0.960	0.905
	Prob.	0.739	0.289	0.812	0.046	0.205	0.738	0.755	0.994
		No	No	No	**	No	No	No	No
With Constant & Trend	t-Statistic	-1.217	0.6970	-1.422	-0.788	-1.340	-1.233	-2.392	-3.318
	Prob.	0.889	0.999	0.834	0.956	0.856	0.884	0.376	0.081
		No	No	No	No	No	No	No	*
At First Difference									
With Constant	t-Statistic	-4.793	-5.2253	-5.086	-3.266	-2.973	-3.882	-3.943	-6.263
	Prob.	0.001	0.000	0.000	0.025	0.050	0.006	0.005	0.000
		***	***	***	**	*	***	***	***
With Constant & Trend	t-Statistic	-5.061	-6.9241	-4.991	-3.643	-3.505	-3.863	-3.860	-6.215
	Prob.	0.002	0.000	0.002	0.042	0.059	0.027	0.026	0.000
		***	***	***	**	*	**	**	***
Unit Root Test Table (ADF)									
At Level									
		GG	GI	FD	KOF	ICT index	RE	URB	GDPpc
With Constant	t-Statistic	-1.016	-1.965	-0.688	-3.366	-2.373	-1.079	-0.869	0.651
	Prob.	0.735	0.299	0.835	0.020	0.158	0.711	0.785	0.989
		No	No	No	**	No	No	No	No
With Constant & Trend	t-Statistic	-0.948	-0.129	-0.835	-0.700	-1.299	-4.018	-2.749	-3.293
	Prob.	0.937	0.992	0.951	0.965	0.867	0.022	0.225	0.086
		No	No	No	No	No	**	No	*
At First Difference									
With Constant	t-Statistic	-4.763	-5.189	-1.937	-3.212	-3.009	-3.848	-4.021	-5.615
	Prob.	0.001	0.000	0.311	0.029	0.047	0.006	0.004	0.000
		***	***	No	**	**	***	***	***
With Constant & Trend	t-Statistic	-5.059	-6.565	-4.787	-3.784	-3.504	-3.826	-3.953	-5.529
	Prob.	0.002	0.000	0.003	0.031	0.059	0.029	0.022	0.001
		***	***	***	**	*	**	**	***

Note: *** shows 1% level of significance, **shows 5% level of significance, *shows 10% level of significance

Table 5 presents bounds test results about the cointegration between the variables, thus providing substantial evidence for the existence of a stable long-run relationship among green growth, innovation, financial development, ICT, globalization, renewable energy, urbanization, and income for that matter in India.

Table 5. Bounds test results.

Test Statistic	Value
F-statistic	4.272

The determinants of green growth are analyzed using the ARDL approach (Table 6), which captures the dynamics of the short-term and long-run relationships while taking into consideration mixed integration orders (I(0) and I(1)) and the speed of adjustment from within the error-correction term. To further provide robustness to the model, the ARDL estimations are complemented with the FMOLS, DOLS, and CCR estimators (Table 7), which address endogeneity and serial-correlation problems and small-sample biases. Hence, the combined effects of green innovation, financial development, ICT, GDP growth, and other structural factors in the study will be comprehensively assessed for their temporal influence on green growth.

In the long term, with a coefficient of 0.791 (and a p-value of 0.0047), green innovation drives green growth, implying that a unit increase in green innovation would almost correspond to a rise of 0.8 units in green growth. This implies that the technological advances and adoption of an environmentally benign set of practices occupy center stage, since various studies have concluded that developing and using clean technology-based innovation helps speed up environmental and economic performance (Khan, Zhong, Khan, Dong, & Nuță, 2024; Meirun, Mihardjo, Haseeb,

Khan, & Jermisittiparsert, 2021). In addition, financial development (0.906, $p = 0.0189$) advances green growth by enhancing the accessibility of credit to investors and the efficient working of financial markets with regard to investment in green technologies and infrastructure (Murshed, 2024). GDP per capita (GDP, 4.518, $p = 0.0361$) is positive, supporting evidence that higher income levels assist in green consumption and investment (Tawiah, Zakari, & Adedoyin, 2021). ICT development (INDEX, -0.399, $p = 0.0099$), instead, depicts a counteractive role in green growth; it may imply that the ICT infrastructure as presently instituted would not support environmental objectives, a situation observed in some other developing economies. Renewable energy adoption (REN, 2.585, $p = 0.139$) and urbanization (URB, 1.333, $p = 0.0711$) have marginal positive effects on sustainable outcomes.

In the short term, the error-correction term (COINTEQ = -0.693, $p < 0.001$) provides evidence that short-run fluctuations are quickly corrected within a single period, accounting for almost 70% of disequilibria. This observation of fast short-term convergence mechanisms, above all, proves the stability of the long-run relationship. An immediate rise in green growth is generated from the changes in green innovation, financial development, and economic growth; meanwhile, other factors, namely globalization, renewable energy, and urbanization, are in their budding stages with smaller influences. The set of observations intensifies the statement that policy interventions that pertain to green innovation and financial development can bring about instant and concrete enhancements in green growth along with the long-term path itself.

Table 6. ARDL results.

Variables	Coefficient	Std. Error	t-Statistic	Prob.
GI	0.791	0.249	3.1789	0.005
FD	0.906	0.355	2.554	0.019
KOF	0.337	0.760	0.444	0.662
ICT index	-0.399	0.140	-2.849	0.009
RE	2.585	1.679	1.539	0.139
URB	1.333	0.699	1.906	0.071
GDPpc	4.518	2.011	2.246	0.036
TREND	-0.197	0.105	-1.879	0.075
Variable	Coefficient	Std. Error	t-Statistic	Prob.
COINTEQ	-0.693	0.0850	-8.149	0.000
D(GI)	0.277	0.045	6.204	0.000
D(FD)	0.748	0.197	3.792	0.001
D(KOF)	0.435	0.213	2.0456	0.055
D(ICT index)	-0.069	0.041	-1.706	0.104
D(RE)	1.0185	0.532	1.916	0.071
D(URB)	0.371	0.202	1.838	0.082
D(LGDPpc)	3.621	0.477	7.591	0.000
C	-20.741	2.533	-8.189	0.000
R-squared	0.905	Mean dependent var.		0.088
Adjusted R-squared	0.865	S.D. dependent var.		0.125
S.E. of regression	0.046	Akaike info criterion		-3.062
Sum squared resid.	0.0403	Schwarz criterion		-2.634
Log likelihood	51.872	Hannan-Quinn criter.		-2.931
F-statistic	22.601	Durbin-Watson stat.		2.465
Prob(F-statistic)	0.000			
Diagnostic test				
Normality	0.209			0.900
Breusch-Godfrey Serial Correlation	2.212			0.168
Heteroskedasticity Breusch-Pagan-Godfrey	0.818			0.653

Figure 2 presents the stability of the estimated ARDL model, which is tested using two tests: CUSUM and CUSUMSQ. In both graphs, the computed CUSUM and CUSUMSQ statistics were plotted in blue lines, while the red dashed lines denote the bounds of a 5% level of significance. The CUSUM test reveals that the statistic line remains within those bounds during the whole period, indicating no signs of structural instability over the sample

period. The accompanying CUSUMSQ diagram also resembles the CUSUM graph, as shown by the blue line comfortably located between the two boundary red lines, confirming no signs of structural instability over the sample period.

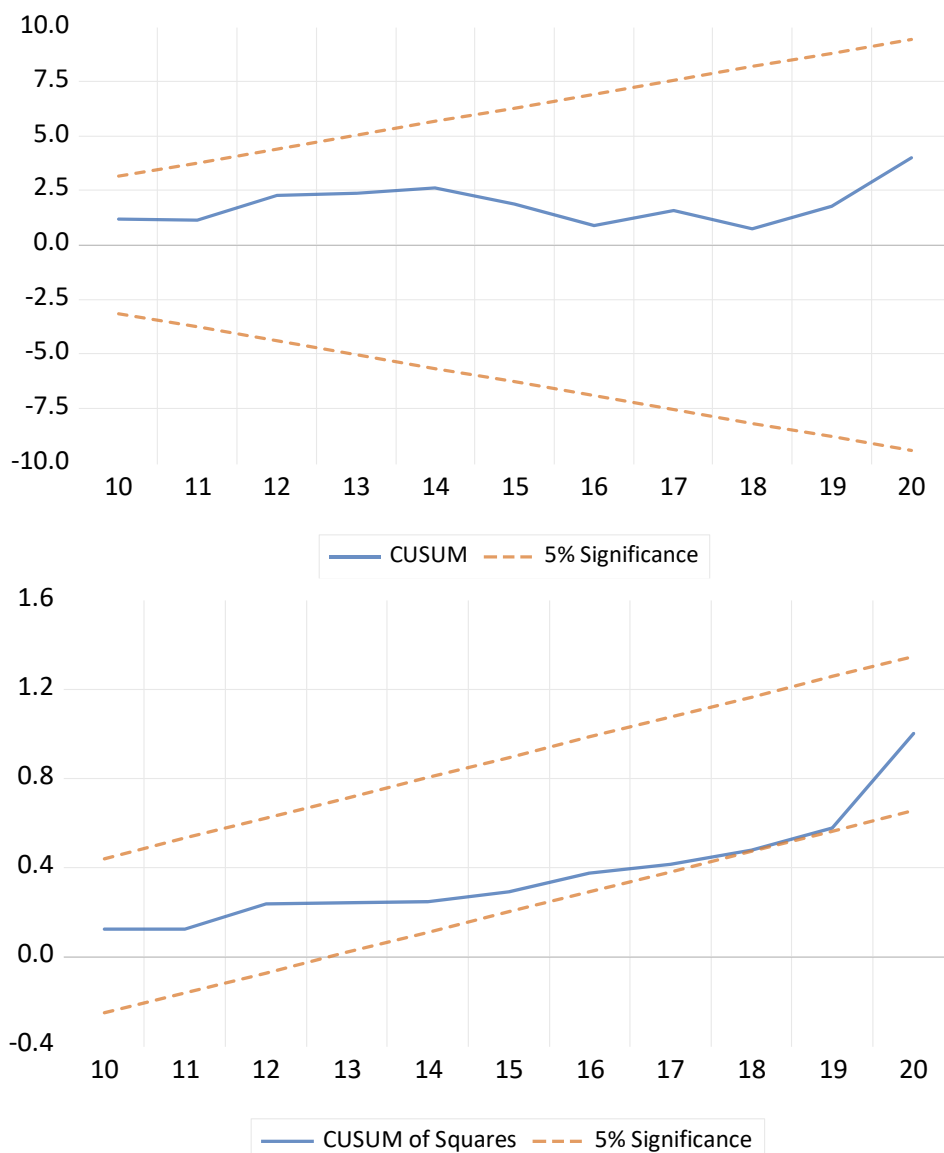


Figure 2. CUSUM and CUSUMSQ stability test of the estimated ARDL model.

As noted in the methodology section, an attempt was made in this study to ensure that the results derived from the ARDL are robust and insensitive to different estimators by employing FMOLS, DOLS, and CCR. Perhaps reassuringly, the estimated coefficient of our variable of interest (Green innovation) still presents a positive and significant impact on growth in all the methods that we used in the study, confirming that it is a dominating determinant for green growth. Similar to the ARDL results, the estimated coefficient of the financial development variable still enters all the models positively and significantly. Similarly, globalization enters all the complementary models positively and significantly. Other control variables (such as renewable energy and urbanization), however, seem to be entering these models in different directions (positive or negative), though they are not significant. Across all robustness checks, R^2 values exceed 0.99, and long-run variance is low, confirming the stability and reliability of the results.

Table 7. Robustness results (FMOLS, DOLS and CCR).

Variables	Coeff	SE	
GI	0.371***	0.120	
FD	0.591***	0.254	
KOF	1.154***	0.311	
ICT index	-0.256***	0.061	
RE	0.478	0.583	
URB	-0.150	0.241	
LGDPpc	3.407***	0.721	
C	-9.208	7.261	
TREND	-0.161***	0.033	
R-squared	0.993	Mean dependent var.	26.01
Adjusted R-squared	0.990	S.D. dependent var.	0.898
S.E. of regression	0.089	Sum squared resid.	0.153
Long-run variance	0.005		
Dynamic Least Squares (DOLS)			
GI	0.295***	0.093	
FD	0.699***	0.211	
KOF	1.144***	0.372	
ICT index	-0.230***	0.069	
RE	0.2004	0.645	
URB	-0.142	0.288	
LGDPpc	3.392***	0.849	
C	-8.117	8.488	
TREND	-0.158***	0.039	
R-sq	0.994	Mean dependent var.	25.955
Adj Rs	0.991	S.D. dependent var.	0.934
S.E. of regression	0.089	Sum squared resid.	0.158
Long-run variance	0.007		
Canonical Cointegrating Regression (CCR)			
GI	0.324***	0.132	
FD	0.785***	0.187	
KOF	1.056***	0.477	
ICT index	-0.271***	0.0815	
RE	0.769	0.813	
URB	-0.219	0.375	
GDPpc	2.494*	1.307	
C	-3.478	10.769	
TREND	-0.108	0.068	
R-squared	0.991	Mean dependent var.	26.011
Adjusted R-squared	0.987	S.D. dependent var.	0.898
S.E. of regression	0.103	Sum squared resid.	0.201
Long-run variance	0.005		

Note: *** shows 1% level of significance, *shows 10% level of significance.

4. CONCLUSION

This study explored the dynamic interplay between green innovation and green growth in India over the period 1990–2020, incorporating key macroeconomic determinants such as renewable energy consumption, globalization, financial development, income growth, and urbanization. Using the ARDL bounds-testing framework and validating the results through FMOLS and DOLS estimators, the analysis confirmed that there is indeed a long-run cointegrating relationship among the variables. The findings reveal that green innovation, financial development, and economic growth are major contributors to green growth in India, whereas energy use and capital formation exert adverse effects on environmental quality. These results emphasize that technological innovation and well-developed financial systems are essential for achieving a sustainable growth trajectory.

From a policy perspective, the findings underscore the importance of mainstreaming green innovation into India's economic development agenda. Policymakers should prioritize the mainstreaming of green innovation and the

strengthening of financial mechanisms, given their significant long-run elasticities of 0.791 and 0.906, respectively. Specifically, the government should provide targeted incentives for environment-related technologies, as a 1% increase in green innovation corresponds to a nearly 0.8-unit rise in green growth by improving resource efficiency and accelerating the adoption of environmentally benign practices. Simultaneously, financial institutions must enhance credit accessibility for investors, as a more developed financial sector directly facilitates the funding of green infrastructure and renewable energy initiatives. Because the model indicates a high speed of adjustment, correcting nearly 70% of short-run disequilibria within a single period, integrating these innovation-led strategies with financial reforms will provide a rapid and robust pathway toward a low-carbon, resilient economy.

Overall, this study provides India-specific time-series evidence demonstrating that sustained green growth depends not merely on technological advancement, but on the effective interaction between innovation, finance, and global integration. By addressing these dimensions collectively, India can progress toward a low-carbon, innovation-driven economy that reconciles its developmental ambitions with environmental sustainability.

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Authors' Contributions: Both authors contributed equally to the conception and design of the study. Both authors have read and agreed to the published version of the manuscript

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Appendix

The ICT index is largely driven by the first principal component, explaining 64% of the variance, with strong contributions from internet usage and mobile subscriptions, while the second component adds 28%, mainly through fixed-line subscriptions; together, the three components account for all variance, as shown in the eigenvalues, loadings, and scree plot (see Appendix, Table A1 and Figure A1).

Table A1. ICT index results.

Eigenvalues: (Sum = 3, Average = 1)					
Number	Value	Difference	Proportion	Cumulative Value	Cumulative Proportion
1	1.930	1.088	0.643	1.930	0.643
2	0.842	0.615	0.281	2.772	0.924
3	0.227	---	0.076	3.000	1.000
Eigenvectors (loadings):					
Variable	PC 1	PC 2	PC 3		
Individuals using int.	0.656	0.250	0.711		
Mobile_Cell subs.	0.650902	0.288557	-0.702		
Fixed_Tele sub.	-0.381	0.924	0.026		

Scree Plot (Ordered Eigenvalues)

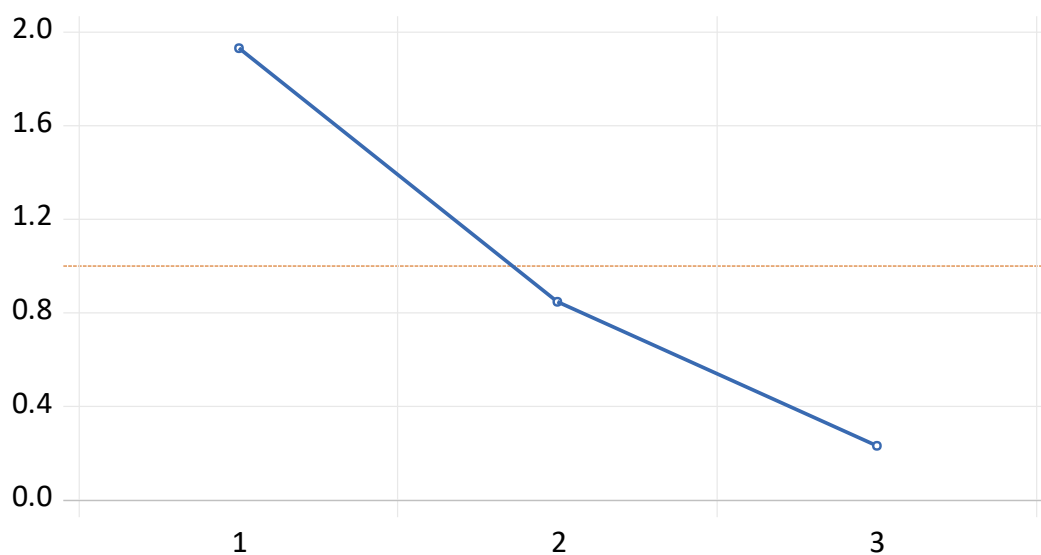


Figure A1. ICT index scree plot.

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