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Balancing growth and sustainability: The long-run impact of financial and technological innovations on India's ecological footprint

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Abstract

This study examines the effects of financial and technological innovations on India's ecological footprint—a comprehensive indicator of environmental degradation. Although previous research has addressed the individual impacts of these innovations, their collective influence has not been thoroughly investigated. Using data from 1973 to 2018 and employing ARDL Bounds and Bayer-Hanck cointegration tests, we find a long-run relationship between innovations, economic growth, energy consumption, and the ecological footprint. Notably, while the short-term impact of innovations appears detrimental, both financial and technological innovations demonstrate a long-term beneficial effect on the environment, which suggests that initial investments in innovation may have short-term environmental costs, but ultimately contribute to environmental improvement. Additionally, this study confirms the harmful long-term effects of energy consumption and economic growth on the environment. These findings underscore the importance of transitioning to cleaner energy sources, improving energy efficiency, and implementing robust environmental policies to foster sustainable development in India.

KEYWORDS
ecological footprint, India, innovation

1 | INTRODUCTION

Global warming is a complex phenomenon that affects the entire planet. Increasing human activities have contributed to global warming through greenhouse gas (GHG) emissions. Human-caused climate change has significantly negatively impacted human health, food and water security, the economy, and society (IPCC, 2023). Therefore, global warming has become an important issue for researchers, scholars, and policymakers over the past few decades. Therefore, numerous studies have analyzed the factors affecting environmental degradation, such as institutional quality (e.g., Amegavi et al., 2022), climate policy uncertainty (e.g., Yilanci & Ursavaş, 2023), tourism (e.g., Kongbuamai et al., 2020), urban population (e.g., Yang et al., 2021), globalization (e.g., Bektaş & Ursavaş, 2023), and digital financial inclusion (e.g., Mukalayi & Inglesi-Lotz, 2023), and democracy (e.g., Ursavaş & Apaydın, 2024).

The problem of environmental degradation also threatens developing countries. Developing economies try to achieve a higher level of economic growth, which causes more environmental damage. One of these developing countries is India. India was a closed economy in the pre-1991 period, with US$ 19.35 billion in imports and US$ 13.87 billion in exports in 1988. With globalization, liberalization, privatization, and globalization measures adopted in 1991, several trade reforms have been implemented, including the abolition of the import licensing system, a phased reduction in customs duty, a devaluation of the domestic currency, a cut in tariff rates, and a phased removal of quantitative import restrictions. These measures have boosted trade in India. In addition, efforts have been made to increase capital inflows and foreign direct investment (FDI) and to liberalize the services sector. The Indian economy has extended its borders to other countries, resulting in the globalization of trade. This has resulted in a consistent increase in India's trade in both goods and services (Trade Promotion Council of India, 2021). In other words, India has experienced significant economic growth over the past three decades.

Since the beginning of reforms in the early 1990s, growth rates have accelerated gradually and have become steadier. The economy has become more sophisticated and globally integrated, and macroeconomic stability has increased (Ahmad et al., 2018; Trade Promotion Council of India, 2021). However, economic growth (i.e., economic activities) is closely linked to the environment. Many sectors rely on natural resources as inputs, whereas production and consumption contribute to environmental pollution and other adverse environmental effects. First, as of 2019, India has a substantial ecological deficit of over 150%, with a biocapacity of 0.36 (resource availability), and an ecological footprint (EF) of 1.07 global hectares per capita (resource consumption), and an ecological deficit of an increasing trend (GFN, 2023). India is the third largest energy consumer in the world because of rising incomes and increasing living standards. Energy consumption has doubled since 2000, with coal, oil, and solid biomass meeting 80% of the demand. India's energy consumption has doubled since 2000 but is still less than 40% of the global average per capita (IEA, 2021). According to the United Nations Report (2023), by April 2023, India's population is expected to reach the population of mainland China and overtake China as the world's most populous country, indicating that India will remain at the center of the global energy system because of its size and dynamism, and energy demand in India will substantially increase in the future.

Within this context, this study investigates the impact of different types of innovations, namely technological innovation and financial innovation, on the EF in India by using the autoregressive distributive lag (ARDL) methodology and the Bayer-Hanck cointegration test. The dataset covers the period 1973–2018. New technologies are becoming more widely accepted as prerequisites for significant progress toward mitigating environmental damage.

The rate of technological innovation is directly correlated with the level of economic growth and environmental quality (Ashford, 1993; World Bank, 2012). Technological innovations boost economic development, while enhancing energy efficiency and improving environmental quality by reducing carbon emissions. A high level of technological innovation may help the country to increase output while decreasing energy consumption (Balsalobre-Lorente et al., 2022; He et al., 2018; Jahanger, Usman, et al., 2022; Song et al., 2019; Yasmeen et al., 2022; Zameer et al., 2020). This may also decrease the consumption of natural energy and increase energy efficiency (Abban et al., 2022; Cui, Aziz, et al., 2023; Deng et al., 2019; Fei et al., 2016; Rafei et al., 2022). In recent years, technological innovation has become a primary driver of sustainable development, combining environmental sustainability and economic growth. Climate change control requires technological advancements. Technological innovation is the primary source for reducing carbon emissions. Innovation-driven green development is vital for achieving industrial transformation, modernization, and improvements in quality and efficiency (Dong et al., 2022). Therefore, green growth strategies have become crucial for countries to achieve sustainable development.

This paper also tests the link between financial innovation and environmental degradation. In recent years, the connection between financial innovations and the environment has been analyzed in several studies. Banks, investors, and other financial actors play a crucial role in the global economy and are major drivers of ecological change. Changes in financial markets are generating new global connections, making financial instruments crucial to global environmental changes (Galaz et al., 2015). There is no consensus on the impact of financial development and innovation on environmental quality (Kirikkaleli, 2023). One can argue that financial development enables a country to expand banking and stock market activities as well as attract foreign direct investment, thereby increasing the economic performance of a nation's financial system, which might impact economic activity and energy demand, thereby increasing environmental degradation (Le & Ozturk, 2020; Mahalik et al., 2017). However, on the contrary, financial development may provide developing countries with an incentive and opportunity to adopt advanced and new technologies and environmentally friendly production methods, which increases energy efficiency and reduces energy consumption (Akinsola et al., 2022; Chishti & Sinha, 2022; Tamazian et al., 2009). Based on the above assessments, the main objective of this study is to test the impact of financial and technological innovations on EF in India. The research questions in this study are as follows: (1) Is there a significant long-run relationship between financial and technological innovations and environmental degradation in India? (2) Does financial innovation affect the EF in India? (3) Does technological innovation reduce the EF in India? (4) Based on the results, what kind of policies can be developed to reduce environmental pollution in India?

The contributions of this study to the literature are threefold. First, to the best of our knowledge, this study represents the pioneering effort in analyzing the relationship between ecological degradation and different types of innovation, mainly financial and technological innovations, within the context of India. While previous research has acknowledged the importance of innovation in addressing environmental challenges, there remains a significant gap in understanding how specific forms of innovation affect ecological EF levels, especially in the Indian context. Therefore, this study aims to bridge this critical gap by examining the impact of both financial and technological innovations on the EF levels in India, thereby shedding light on the mechanisms through which innovation can contribute to environmental sustainability. Second, in addition to exploring the role of innovation, this study comprehensively considers other significant factors that may influence environmental degradation. Specifically, variables such as gross domestic product (GDP) and energy consumption per capita are incorporated into the analysis. By accounting for these crucial determinants, this study provides a holistic understanding of the complex interplay between innovation and environmental sustainability. Third, this study employs the EF per capita as a proxy to measure environmental degradation. The EF offers a comprehensive assessment of the environmental impact by encompassing six key components: the footprints of fishing ground, carbon, forest land, cropland, grazing land, and built-up land. Unlike more conventional proxies, such as carbon dioxide (CO_2) emissions alone, the EF provides a multi-dimensional perspective on environmental degradation. By employing EF per capita as the primary indicator, this study enhances the robustness and accuracy of its analysis and offers valuable insights into the holistic dimensions of environmental sustainability in the Indian context. Finally, this study employs two powerful cointegration tests to analyze the effects of innovation on ecological degradation. The first is the ARDL Bounds cointegration test, which allows the use of regressors with mixed integration levels, and the second is the Bayer-Hanck cointegration test, which combines several cointegration test statistics to produce a powerful test.

The remaining sections of this study are structured as follows: The second part briefly summarizes the related empirical literature. Section 3 presents the dataset. Section 4 discusses the econometric methodology and presents the empirical results and finally, section 6 concludes the paper.

2 | LITERATURE REVIEW

The literature is briefly presented in two subsections: (i) the relationship between technological innovation and the environment, and (ii) the relationship between financial innovation and the environment.

2.1 | Technological innovation and the environment

Technological innovation is an essential driver of economic growth. Thus, technological innovations are directly related to environmental externalities, which could be positive or negative according to policymakers' perspectives and measures. In this context, numerous studies have shown that technological innovations improve environmental quality. For example, Churchill et al. (2019) investigated the impact of R&D intensity on carbon emissions for G7 countries between 1870 and 2014, using a non-parametric panel data model. The results reveal a negative relationship between R&D intensity and carbon emissions during the three-quarters of the examined period. Ahmad et al. (2020) tested the relationship between technological innovations and environmental degradation in emerging countries from 1984 to 2016, and showed that technological innovations decrease EF in these countries. Zameer et al. (2020) examined the relationship between technological innovation and CO_2 emissions in India for the period 1985–2017 using the ARDL Bounds test methodology. These results indicate that an increase in technological innovation decreases CO_2 emissions. Using bootstrapping autoregressive distributed lag modeling, Shahbaz et al. (2020) found a negative relationship between technological innovations and carbon emissions in China. According to Yang et al. (2021), an increase in technological innovations decreases the EF level in Brazil, India, China, and South Africa (BICS) countries for the period 1990–2016. Using the STIRPAT methodology, Kihombo et al. (2021) showed a negative relationship between technological innovation and EF in the West and Middle Eastern countries. Koseoglu et al. (2022) investigated the impact of green innovation on the EF for the top 20 green innovator countries over the period 1993–2016. They showed that an increase in green innovation reduces EF. Rout et al. (2022) tested the impact of technological innovation on the EF level in Brazil, Russia, India, China, and South Africa (BRICS countries) for the 1990–2018 period, and the results reveal that technological innovation reduces the EF in BRICS countries. Wenlong et al. (2023) revealed that technological innovation reduces GHG emissions in 10 Asian economies. Udeagha and Muchapondwa (2023) showed a statistically significant and negative relationship between green innovation and CO_2 emissions in South Africa. Javed et al. (2023) tested the relationship between green technologies innovation and EF using a dynamic simulated ARDL (DYARDL) approach. The results indicate that an increase in green innovation decreases the EF level in Italy. Aziz, Sarwar, Hussan, and Saeed (2023) showed a negative correlation between environmental technology and EF in East Asian countries over the period 1999–2019. Cui, Wang, and Zhou (2023) revealed that environmental innovation helps reduce the EF in Gulf Council countries. Aziz, Sarwar, Nawaz, et al. (2023) showed that technology has a significant effect on reducing environmental degradation in Saudi Arabia.

In contrast, some studies have found a positive or insignificant link between technological innovation and environmental degradation. For example, Ganda (2019) demonstrated a significant and positive relationship between the number of patent families and emissions in OECD countries. Erdoğan et al. (2020) tested the impact of innovation on sectoral carbon emissions for the G20 countries over the period 1971–2017. The results indicate that innovation in the construction sector worsens environmental quality, whereas an increase in innovation in the industrial sector decreases carbon emissions. The study by Destek and Manga (2021) revealed that there is no statistically significant relationship between innovations and EF in big emerging markets (BEM) countries.

2.2 | Financial innovations and the environment

Numerous studies have investigated the relationship between financial development/innovation and environmental degradation for different countries (or country groups) using various ecological variables, such as carbon emissions (e.g., Ozturk & Acaravci, 2013), EF (Usman & Hammar, 2021), and econometric approaches, and have reported mixed results.

In this line, the first group of studies uses CO_2 emissions as a proxy for environmental degradation. Tamazian et al. (2009) and Tamazian and Rao (2010) revealed that financial development is significantly related to environmental degradation. Tamazian et al. (2009) also showed that financial development decreases CO_2 emissions in the BRIC countries. However, Tamazian and Rao (2010) showed that financial liberalization, which is not accompanied by a strong institutional structure, may be harmful in transition. Shahbaz et al. (2013) found that financial development reduces carbon emissions for the Indonesian economy, and the results also confirm the inverted U-shaped relationship between financial development and emissions. Cetin and Ecevit (2017) showed that financial development positively affects carbon emissions in the long run in Türkiye. The study by Chien et al. (2021) indicates that financial innovation negatively and significantly affects carbon emissions and PM2.5 in Asian economies. Chishti and Sinha (2022) showed that while positive shocks from financial innovation substantially reduce CO_2 emissions and negative shocks from financial innovation increase emissions in BRICS countries. Moreover, positive technological innovation shocks are crucial for lowering carbon emissions, whereas negative shocks have no effect. Çetin et al. (2022) showed that financial development decreases emissions in upper-middle-income countries. Kirikkaleli (2023) analyzed the impact of financial innovation on the environment for India over the period 2000Q1-2018Q4 using Fourier-based econometric models. These results indicate that financial innovation and renewable energy consumption can reduce environmental degradation in India.

The second group of studies uses EF, which is a more comprehensive indicator, as a proxy for environmental degradation. For example, according to Yang et al. (2021), an increase in financial development increases the EF level in BICS countries from 1990 to 2016. Jahanger, Yu, et al. (2022) show that while financial development increases EF levels in Asian countries, an increase in financial development decreases environmental degradation in African, Latin American, and Caribbean countries in the long run. Rout et al. (2022) tested the impact of financial development on the EF in BRICS countries and found a negative and significant relationship between these variables. Chen et al. (2022) showed that financial development has a negative impact on eco-efficiency in the top 10 polluted countries. Huo et al. (2023) investigated the relationship between financial innovations and environmental degradation in China and showed that financial innovations have direct and indirect effects on environmental degradation via economic globalization. Moreover, the results show that environmental technologies positively affect environmental degradation in China. Çetin et al. (2023) showed that financial development increases environmental degradation in emerging economies over the period 1991–2018.

While existing research provides valuable insights into the individual impacts of financial and technological innovations on environmental quality, a comprehensive understanding of their combined effects on India's ecological footprint remains elusive. Studies often focus on specific innovation types or environmental indicators, neglecting the complex interplay between diverse innovations and a holistic measure such as the ecological footprint. This study aims to bridge this gap by examining the long-term relationship between financial innovation, technological innovation, economic growth, energy consumption, and the ecological footprint of India. By employing robust econometric techniques and considering a comprehensive set of variables, this study seeks to provide a more nuanced understanding of the role of innovation in balancing growth and sustainability within the Indian context.

3 | DATA AND MODEL

To test the effect of innovation on the environment, we consider the following function:

$$\mathbf{EF} = \mathbf{f}(\mathbf{FI}, \mathbf{TI}, \mathbf{GDP}, \mathbf{EC}), \tag{1}$$

where EF shows the ecological footprint per capita, FI is financial innovation, TI denotes the technological innovation, GDP indicates the per capita gross domestic product (in constant 2015 US$), and EC shows the per capita aggregated energy consumption (measured in gigajoules). The EF measures the environmental impact of human activities in terms of the area of biologically productive land and water required to produce the resources consumed and assimilate the waste generated. It is measured in global hectares per capita, and we obtain the EF from the Global Footprint Network website.[i] FI is proxied by the ratio of broad money supply (M3) to narrow money supply (M1). This measure captures the development and sophistication of the financial system. Data on money supply are obtained from the OECD data.[ii] The TI is proxied by the total number of patents granted. This measure captures a country's level of inventive activity. Data on patents are obtained from the OECD data service[2]. The GDP measures the economic output of a country per person. It is measured in constant 2015 U.S. dollars and is obtained from the World Bank data service.[iii] The EC measures the total amount of energy consumed by a country per person. It is measured in gigajoules per capita. The data are gathered from the Energy Institute Statistical Review of World Energy.[iv] The data range covers the period from 1973 to 2018 since data are not available outside this period for all variables. We use all data in logarithms for empirical purposes; hence, Equation 1 becomes:

$$\ln \mathrm{EF}_t = \alpha_1 + \alpha_2 \ln \mathrm{FI}_t + \alpha_3 \ln \mathrm{TI}_t + \alpha_4 \ln \mathrm{GDP}_t + \alpha_5 \ln \mathrm{EC}_t + u_t. \tag{2}$$

This model aligns with the ecological modernization theory (EMT). EMT argues that economic development and technological innovation can lead to environmental improvement. This is because economic growth can provide the resources needed to invest in environmental protection, and technological innovation can lead to the development of cleaner and more efficient technologies. The EMT suggests that the relationship between economic development and environmental degradation is not necessarily linear. During the early stages of development, environmental degradation may increase as economic activity increases. However, as countries become wealthier and more technologically advanced, they become better able to invest in environmental protection and adopt cleaner technologies. This can lead to a decline in environmental degradation even as economic growth continues.

The functional form in Equation 2 is appropriate for this study because it can capture non-linear relationships between variables. This is important because the relationship between economic development and environmental degradation is often non-linear, as suggested by EMT. Moreover, the coefficients of a log-linear model can be interpreted as elasticities, and transforming variables into logarithms can help reduce heteroscedasticity and improve the accuracy of the regression estimates.

The primary hypothesis of this study is that financial and technological innovations have a significant and negative impact on India's ecological footprint in the long run, that is;

H1: Financial and technological innovations significantly and negatively impact India's ecological footprint in the long run.

Financial development can promote environmental sustainability by providing funding for green technologies and projects, improving risk management, and increasing transparency and accountability in environmental governance. For example, the development of green bonds and other sustainable finance instruments can help channel capital towards environmentally friendly investments. Additionally, financial innovation can help improve risk management practices, which can reduce environmental risks associated with economic activities. This hypothesis is supported by several prior studies that have found a negative relationship between financial development and environmental degradation. For example, Tamazian et al. (2009) found that financial development decreases CO_2 emissions in the BRIC countries. Chien et al. (2021) found that financial innovation has a negative and significant effect on carbon emissions in Asian economies. Chishti and Sinha (2022) showed that positive shocks from financial innovation substantially reduce CO_2 emissions in the BRICS countries.

Technological advancements can lead to the development of energy-efficient technologies, renewable energy sources, and cleaner production processes. This can help to reduce energy consumption and greenhouse gas emissions, thereby mitigating environmental degradation. For example, innovations in solar and wind energy technologies have made renewable energy more affordable and accessible, which can help to reduce reliance on fossil fuels. Additionally, innovations in energy storage and smart grids can help to improve energy efficiency and reduce energy waste. This hypothesis is supported by numerous prior studies that have found a negative relationship between technological innovation and environmental degradation. For example, Ahmad et al. (2020) found that technological innovations decrease the ecological footprint in emerging countries. Zameer et al. (2020) found that an increase in technological innovation decreases CO_2 emissions in India. Yang et al. (2021) found that an increase in technological innovations decreases the ecological footprint level in BICS countries. Koseoglu et al. (2022) found that an increase in green innovation reduces the ecological footprint level. Rout et al. (2022) found that technological innovation reduces the ecological footprint in BRICS countries. These studies suggest that technological innovation can promote environmental sustainability by leading to the development of more energy-efficient technologies, renewable energy sources, and cleaner production processes.

H2: GDP per capita has a significant and positive impact on India's ecological footprint in the long run.

This hypothesis is based on the argument that economic growth can lead to increased resource consumption and waste generation, contributing to environmental degradation. This hypothesis is supported by several prior studies that have found a positive relationship between economic growth and environmental degradation. For example, Usman et al. (2019) found a positive relationship between GDP and ecological footprint in India. Rana and Sharma (2019) found evidence of the Environmental Kuznets Curve (EKC) hypothesis in India, which suggests that environmental degradation initially increases with economic growth but then declines after a certain income level is reached.

H3: Energy consumption per capita has a significant and positive impact on India's ecological footprint in the long run.

This hypothesis is based on the argument that energy consumption, mainly from fossil fuels, is a significant contributor to greenhouse gas emissions and environmental pollution. This hypothesis is supported by numerous studies that have found a positive relationship between energy consumption and environmental degradation. For instance, Jayanthakumaran et al. (2012), Boutabba (2014), Ahmad et al. (2016), Pal and Mitra (2017), and Menon (2019) found a positive relationship between energy consumption and carbon emissions in India.

The summary statistics of the logarithmic data are presented in Table 1.

The results in Table 1 show that the variable with the highest mean is GDP (6.54), followed by TI (6.09), EC (2.39), EF (−0.30), and FI (−0.43). This indicates that GDP has the highest average value, whereas FI has the lowest. The order of the variables based on their median is the same as their means: GDP (6.45) > TI (5.97) > EC (2.42) > EF (−0.32) > FI (−0.46), which indicates a similar distribution of values for each variable as their means. While GDP has the highest value, FI has the lowest. Moreover, the standard deviations show that TI has the highest dispersion, whereas EF has the lowest dispersion. The skewness coefficients show that EC, EF, and GDP have positive skewness, whereas the remaining variables have negative skewness; that is, the EC, EF, and GDP distributions are skewed to the right, whereas the FI and TI distributions are skewed to the left. The kurtosis coefficients show that FI has the

TABLE 1 Descriptive Statistics.

	lnEC	lnEF	lnFI	lnGDP	lnTI
Mean	2.391	−0.299	−0.428	6.536	6.095
Median	2.416	−0.318	−0.465	6.453	5.970
Maximum	3.174	0.079	0.049	7.545	9.154
Minimum	1.649	−0.560	−1.078	5.856	2.662
Std. Dev.	0.456	0.197	0.293	0.511	2.252
Skewness	0.049	0.441	−0.496	0.424	−0.034
Kurtosis	1.830	2.002	2.837	1.933	1.484
Jarque-Bera	2.642	3.402	1.936	3.560	4.413
Probability	0.267	0.183	0.380	0.169	0.110

highest kurtosis value, whereas TI has the minimum, indicating that FI has the most peaked distribution, whereas TI has the flattest distribution. The probability values of the Jarque-Bera test statistics show that none of the test statistics are statistically significant at the traditional significance levels; that is, all variables are distributed normally.

4 | METHODOLOGY AND EMPIRICAL FINDINGS

This study employs two powerful cointegration tests to examine the effects of innovation on ecological degradation. The first is the ARDL Bounds cointegration test, which allows to employ of regressors with mixed integration levels, and the second is the Bayer-Hanck cointegration test, which combines several cointegration test statistics to produce a powerful test.

To implement the ARDL Bounds test, we estimate the following model:

$$\ln EF_t = \alpha + \beta_1 \ln EC_{t-1} + \beta_2 \ln FI_{t-1} + \beta_3 \ln GDP_{t-1} + \beta_4 \ln TI_{t-1} + \beta_5 \ln EF_{t-1} + \sum_{i=0}^{p} \delta_{1i} \Delta \ln EC_{t-i} + \sum_{i=0}^{p} \delta_{2i} \Delta \ln FI_{t-i} + \sum_{i=0}^{p} \delta_{3i} \Delta \ln GDP_{t-i} + \sum_{i=0}^{p} \delta_{4i} \Delta \ln TI_{t-i} + \sum_{i=1}^{p} \delta_{5i} \Delta \ln EF_{t-i} + e_t,$$

where p and Δ show the optimal lag length and the first difference operator, respectively. We test the null hypothesis of no-cointegration $\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0$, against the alternative of a long-run relationship using the F test statistic. To compare the computed test statistics, we use the critical values which are computed by Pesaran et al. (2001). They tabulated two sets of critical values; while one set is computed using the stationary regressors, the second set is calculated employing integrated regressors. If the calculated test statistic is lower than the I(0) critical value, then the null cannot be rejected. However, if the test statistic is higher than the I(1) critical value, we can reject the null hypothesis of no cointegration. There is an inconclusive situation when the test statistic lies between the I(0) and I(1) critical values.

In addition to the ARDL Bounds test, we also employ the Bayer-Hanck cointegration test. This test follows the method of Fisher (1932), which is a technique for meta-analysis that combines the p-values of several tests related to the same hypothesis into one test statistic. Meta-analysis is a powerful statistical technique as it combines the signals of moderate significance in each study while controlling for the risk of false positives. By doing so, it increases the statistical power of the analysis, thus providing a more accurate and reliable estimation of the overall effect size (see Yoon et al., 2021). Bayer and Hanck (2013) considered the following test statistic:

$$\chi^2 = -2\sum_{i=1}^{4} \ln(p_i),$$

where p denotes the p-values of test statistics of Engle-Granger, (1987), Johansen, (1988), Boswijk, (1994), and Banerjee et al. (1998). Small p-values result in a large test statistic, leading to the rejection of the null hypothesis. When all null hypotheses are valid, and the p-values are independent, the test statistic follows a Chi-squared distribution with 2 k degrees of freedom, where k represents the number of tests being combined.

4.1 | Empirical findings

As a first step in the empirical analysis, we test the stationarity properties of the variables using several unit root tests. We apply augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Zivot-Andrews (ZA) unit root tests to reveal the stationarity properties of the series. While both the ADF and PP unit root tests ignore the structural breaks in the data-generation process, the ZA unit root test allows one structural break while testing the unit root properties of the series. Model A allows for a change in the intercept, whereas Model C allows for a change in both the intercept and trend. Table 2 presents the results of unit root tests.[v]

The outcomes of the unit root tests show that all variables have a unit. Hence, we can apply the ARDL Bounds test and Bayer-Hanck cointegration test to examine the long-run relationship between the variables. Table 3 presents the results.

We can strongly reject the null hypothesis of no cointegration according to the test results of the ARDL Bounds and Bayer-Hanck cointegration tests. Thus, we can conclude that there is a long-run relationship between the variables. Next, we examine the long-run coefficients and report the results in Table 4.[vi]

The results in Table 4 indicate that all coefficients are statistically significant. While TI and FI have a negative coefficient, the remaining slope coefficients have positive coefficients, which supports the evidence that innovations have a healing effect on the environment, while GDP and EC have harmful effects. More precisely, a 1% increase in EC is associated with an approximately 0.41% increase in EF, holding all other variables constant. In addition, a 1% increase in FI decreases EF by 0.1334%, ceteris paribus. A 1% increase in GDP is associated with an average change of 0.2905% in EF, and a 1% increase in TI leads to a decrease in EF of 0.045% while holding all other variables constant. As a robustness check, we also estimate the long-run relationship using the fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS), and report the findings in Appendix Table C1, which support the findings in Table 4. Next, we provide estimates of the short-run coefficients, which are based on an error correction model, in Table 5.[vii]

The results in Table 5 suggest that only the one-lagged values of FI and TI are statistically significant and possess positive coefficients, indicating that the examined innovations have a detrimental impact on the environment in the short term. Furthermore, the error correction term is found to be statistically significant and falls within the range of 0 to -1, indicative of the error correction mechanism operating effectively, where any discrepancies from the equilibrium will be rectified.

The overall findings are summarized as follows:

Figure 1 indicates that while innovations do not significantly affect EF in the short run, both variables have a healing effect on the environment in the long run. However, economic growth has a detrimental effect on the environment in the short and long term, and energy consumption only harms the environment in the long run.

Consequently, the positive and statistically significant coefficient of energy consumption highlights the detrimental impact of energy consumption on the environment. This outcome, largely attributed to the substantial share of fossil fuel consumption in the total energy consumption, as depicted in Figure 2, firmly establishes the adverse effects of energy consumption on the environment.

TABLE 2 The Unit Root Test Results.

Series	ADF unit root test		Phillips-Perron unit root test		Zivot-Andrews unit root test	
	Intercept	Intercept and trend	Intercept	Intercept and trend	Model A	Model C
lnEF	0.917 (0.995) [0]	−2.131 (0.515) [0]	1.106 (0.997)	−2.131 (0.515)	−4.07 [0] {2007}	−3.832 [0] {2002}
lnEC	0.350 (0.978) [0]	−3.235 (0.094) [9]***	0.353 (0.979)	−2.372 (0.389)	−4.424 [3] {1999}	−4.698 [3] {2001}
lnFI	−1.158 (0.682) [7]	−2.288 (0.431) [0]	−2.229 (0.199)	−2.288 (0.431)	−3.712 [2] {1990}	−3.421 [2] {2003}
lnGDP	3.117 (1) [9]	−0.921 (0.942) [9]	6.314 (1)	−0.805 (0.957)	−3.014 [4] {1991}	−2.682 [4] {2003}
lnTI	−0.751 (0.823) [0]	−1.201 (0.898) [0]	−0.732 (0.828)	−1.522 (0.807)	−2.376 [1] {2011}	−3.219 [1] {2000}

Note: *** indicates significance at the 10% level. The numbers in parentheses show the *p*-value, the numbers in brackets show the optimal lag length, and the numbers in curly brackets show the structural break date. The critical values at the 10% level for the Zivot-Andrews unit root test for Models A and C are −4.58 and −4.82, respectively.

TABLE 3 Cointegration Test Results.

ARDL Bounds test	Bayer-Hanck test
4.294**	68.580*

Note: * and ** indicate statistical significance at the 1% and 5% levels, respectively. The upper critical value at the 5% level for the ARDL test is 3.49, and the critical value at the 1% level for the Bayer-Hanck test is 30.774.

TABLE 4 Long-Run Coefficients.

Variable	Coefficient	*t*-Statistic
lnEC	0.409*	4.175
lnFI	−0.133**	−2.460
lnGDP	0.290*	4.461
lnTI	−0.046*	−3.861
Intercept	−2.989*	−10.559

Note: * and ** indicate the significance at the 1% and 5% levels, respectively.

TABLE 5 Short-Run Coefficients.

Variable	Coefficient	*t*-Statistic
Δ (lnFI)	0.015	0.268
Δ ($lnFI_{t-1}$)	0.160**	2.522
Δ (lnGDP)	0.500*	7.270
Δ (lnTI)	−0.005	−0.322
Δ (lnT_{t-1})	0.036**	2.474
ECT	−0.641*	−5.447

Note: *, **, and *** indicate significance at the 1%, 5%, and 10% levels, respectively.

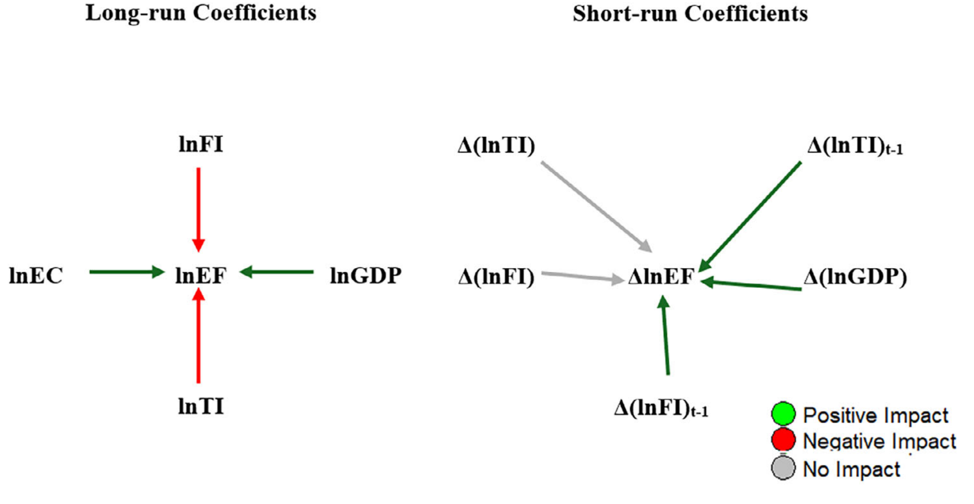

FIGURE 1 Summary of the findings.

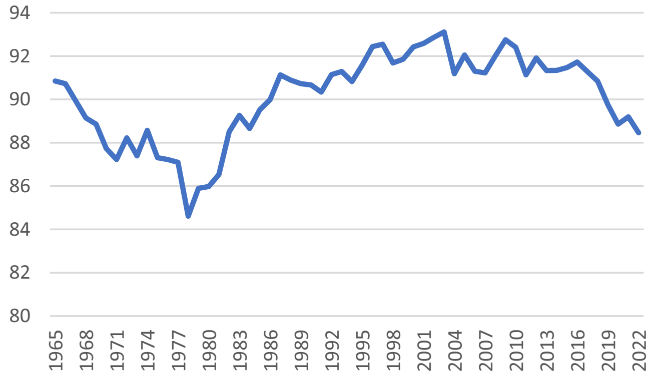

FIGURE 2 Share of fossil energy consumption (source: Energy Institute Statistical Review of World Energy).

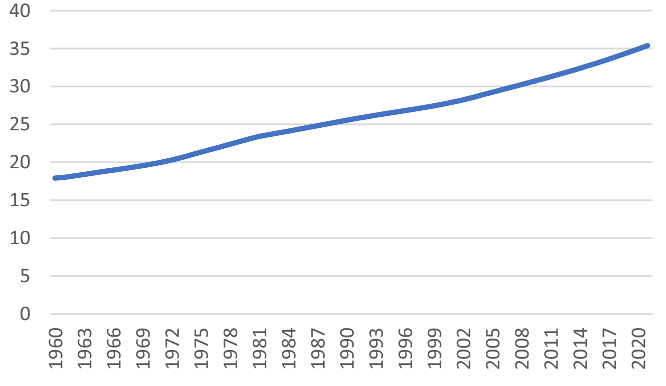

FIGURE 3 Urban population (% of the total population) (source: World Bank).

As depicted in Figure 2, the share of fossil energy consumption underwent a decline, reaching its lowest point in 1978. However, this proportion has gradually increased over the years, reaching 88.46% in 2022, indicating that a significant proportion of India's energy consumption is derived from fossil fuels such as coal, oil, and natural gas. The burning of these fuels releases greenhouse gases (GHGs) like carbon dioxide, contributing to global warming and climate change. Furthermore, the extraction, processing, and transportation of these fuels can lead to environmental degradation, such as deforestation, habitat destruction, and water pollution. The positive and significant coefficient of energy consumption aligns with the findings of Jayanthakumaran et al. (2012), Boutabba (2014), Ahmad et al. (2016), Pal and Mitra (2017), and Menon (2019) for India. As anticipated, the estimated coefficient of GDP is positive. This may be due to the urbanization trend in India, as depicted in Figure 3.

Figure 3 illustrates a discernible trend of urbanization over the years, as an increasing number of individuals have relocated from rural areas to cities in pursuit of better job prospects and improved living conditions. This migration has resulted in the creation of new infrastructure, such as roads, buildings, and power plants, which contribute to carbon emissions through energy consumption and the release of CO_2 during the production of construction materials such as cement and steel. The adverse effects of GDP can also result from deforestation, as economic growth can lead to increased demand for land, resulting in deforestation and land-use changes. Figure 4 displays the annual deforestation in India.

As depicted in Figure 4, it is evident that the annual deforestation in India has been increasing since 1990. Deforestation results in the release of carbon dioxide, which was previously absorbed by the forests, into the

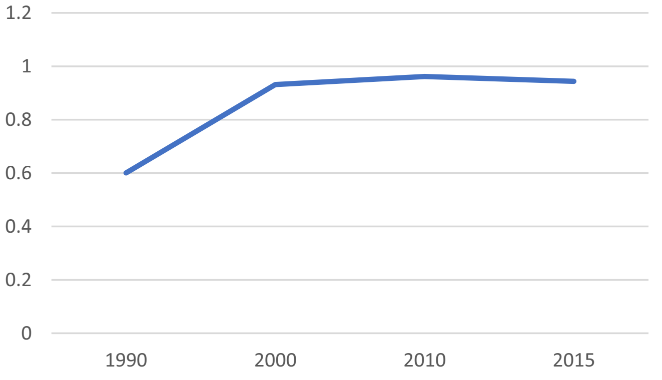

FIGURE 4 Annual deforestation as a share of forest area (source: UN Food and Agriculture Organization).

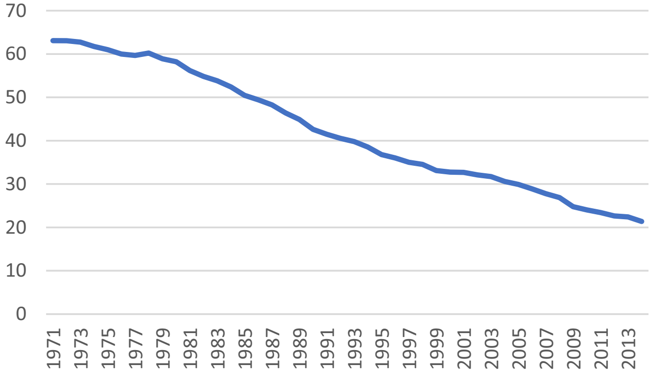

FIGURE 5 Combustible renewables and waste (% of total energy) (Source: World Bank).

atmosphere. This contributes to an increase in carbon emissions. The aforementioned finding regarding GDP in India aligns with the research conducted by Usman et al. (2019), Rana and Sharma (2019), Ozcan and Ulucak (2021), Hossain et al. (2023), and Uche et al. (2023).

The impact of financial innovation (FI) on ecological footprint is, in fact, negative. This suggests that the FI has a favorable influence on the environment. The possible reasons behind this impact are the encouragement of investment in green technologies and the enhancement of risk management. In 2015, the International Finance Corporation (IFC) pioneered the issuance of a green Masala bond, which raised approximately $49.2 million to finance private sector investments aimed at combating climate change in India. The proceeds from this bond were strategically allocated to invest in a green bond issued by Yes Bank. This collaborative effort between the IFC and Yes Bank demonstrates a strong commitment to promoting sustainable development and addressing climate change in India. By using innovative financial instruments like green Masala bonds, these organizations play a crucial role in mobilizing capital and fostering investments in environmentally responsible projects. Recent research conducted by Chishti and Sinha (2022) has confirmed this finding.

The negative coefficient of technological innovation is identified as statistically significant. This finding may be attributed to advancements in energy efficiency technologies. In order to depict the trend of energy efficiency, we included a graph of energy waste in Figure 5.

Figure 5 illustrates a decline in energy waste over time in India, suggesting that technological advancements in energy efficiency can contribute to reducing carbon emissions by enabling various sectors to consume less energy while maintaining or improving their performance. For instance, the use of energy-efficient appliances, LED lighting, and better insulation in buildings can result in substantial reductions in energy consumption, and consequently, lower carbon emissions. Additionally, technological innovations in renewable energy, carbon capture and storage, electric vehicles, smart grids, and energy management systems may also have a positive impact on the environment.

5 | CONCLUSION

India is a nation that has been considered a candidate for classification as a developed country, but at present, it is a developing nation that is striving to enhance its economic stature. In this investigation, we assessed the influence of financial and technological innovations on the environmental conditions in India from the period of 1973 to 2018. Our research uncovered a long-run relationship between these variables. The results indicate that the lagged impact of innovations on the environment is detrimental in the short term, but in the long term, both financial and technological innovations have a beneficial effect on the environment. Additionally, as anticipated, we discovered that both energy consumption and economic growth have a harmful impact on the environment in the long term.

To mitigate the deleterious impact of energy consumption, India requires a transition to cleaner and more sustainable energy sources, improved energy efficiency, and the implementation of robust environmental regulations and policies. Diversifying energy sources may help reduce reliance on fossil fuels, as fossil fuel consumption accounts for approximately 88% of total primary energy in India and is the primary source of carbon emissions. To balance economic growth and environmental protection, policymakers can adopt a range of strategies, such as promoting green technologies through incentives, tax breaks, and subsidies for green technology companies and consumers, implementing strict environmental regulations by setting limits on emissions, waste disposal, and resource extraction to minimize pollution and resource depletion, and encouraging waste management and recycling through public awareness campaigns, supply financial incentives for recycling, and implement strict penalties for improper waste disposal. Governments and businesses can use financial innovation to promote green investment and reduce carbon emissions, but they must also be mindful of the potential for financial innovation to lead to increased investment in polluting industries and increased speculation in carbon markets. Finally, policymakers can promote and adopt new technologies such as carbon capture and storage, smart grids, and energy management systems to reduce carbon emissions and help mitigate climate change.

This study has some significant limitations that should be acknowledged. First, the study employs data spanning from 1973 to 2018, which may not capture the most recent trends and developments. As time progresses, more up-to-date data become available, and future studies could leverage these data to re-evaluate the analysis and determine whether the findings still hold considering new information. Second, the study focuses solely on India, which raises concerns regarding the generalizability of the findings to other developing countries. Each nation has a unique economic structure, varying technological development levels, and distinct environmental challenges. For instance, a country like Brazil, with its vast Amazon rainforest and reliance on agriculture, may exhibit different dynamics between innovation and environmental impact compared with India. Future studies could expand the analysis to include a diverse range of developing countries, allowing for a more comprehensive understanding of the relationship between innovation and environmental sustainability across different contexts. Furthermore, the study concentrates exclusively on financial and technological innovations, overlooking the potential impact of other innovation types, such as social innovation or institutional innovation. These alternative forms of innovation can significantly influence environmental outcomes. For example, community-driven initiatives for sustainable resource management or policy reforms aimed at promoting green practices could yield substantial environmental benefits. Future research should incorporate these diverse innovation types into the analysis to provide a more holistic perspective. Moreover, while this study controls for several crucial variables, such as GDP per capita and energy consumption per capita, there may be other influential factors that have not been accounted for in the analysis. For instance, this study does not consider the impact of government policies, environmental regulations, or cultural factors, which can profoundly shape the relationship between innovation and environmental degradation. Stringent environmental regulations or cultural values that prioritize sustainability could mitigate the negative environmental impacts of certain innovations. Conversely, lax regulations or cultural norms that undervalue environmental concerns could intensify these impacts. Future studies could explore the impact of these additional variables to provide a more comprehensive understanding of the complex interplay between innovation and environmental sustainability. By addressing these limitations and exploring these new research directions, future studies can build upon the findings of this study and contribute to a more nuanced and contextualized understanding of the role of innovation in promoting environmental sustainability across diverse developing nations.

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CONFLICT OF INTEREST STATEMENT

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

DATA AVAILABILITY STATEMENT

The data are available upon request.

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ENDNOTES

[i] https://data.footprintnetwork.org/.

[ii] https://data.oecd.org/.

[iii] https://data.worldbank.org/.

[iv] https://www.energyinst.org/statistical-review.

[v] We provide the results of unit root test for differenced data in Appendix, Table A1.

[vi] We present results of assumption tests in the Appendix Table B1 and Figure A1, which show that there is no autocorrelation, no heteroscedasticity, residuals are distributed as normal, and model is stable.

[vii] Since the lag of Δ(EC) is 0 in the short run, the outcomes do not contain any information about EC.

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APPENDIX

TABLE A1 Unit Root Test Results for Differenced Data.

Series	ADF unit root test		PP unit root test		ZA unit root test	
	Intercept	Intercept and trend	Intercept	Intercept and trend	Model A	Model C
ΔlnEF	−7.731 (0) [0]*	−7.949 (0) [0]*	−7.694 (0)*	−7.911 (0)*	−8.2963 (0) {2006}*	−8.6286 (0) {2006}*
ΔlnEC	−7.409 (0) [0]*	−7.343 (0) [0]*	−7.366 (0)*	−7.308 (0)*	−8.2742 (0) {2004}*	−8.3446 (0) {2004}*
ΔlnFI	−4.899 (0) [0]*	−5.185 (0.001) [0]*	−4.88 (0)*	−5.185 (0.001)*	−5.6815 (0) {1996}*	−5.4952 (0) {2011}**
ΔlnGDP	−6.595 (0) [0]*	−8.495 (0) [0]*	−6.635 (0)*	−12.344 (0)*	−4.8545 (8) {1988} ***	−4.9473 (8) {1991}***
ΔlnTI	−5.531 (0) [0]*	−5.484 (0) [0]*	−5.531 (0)*	−5.484 (0)*	−6.1461 (0) {2004}*	−6.1802 (0) {1992}*

Note: Δ indicates the first differences of data. The numbers in parentheses show the *p*-value, the numbers in brackets show the optimal lag length, and the numbers in curly brackets show the structural break date. *, **, and *** show the significance at the 1, 5, and 10% levels, respectively. The critical values at the 1%, 5%, and 10% levels for the ZA unit root test for Models A and C are −5.34, −4.94, −4.58 and −5.57, −5.08, −4.82, respectively.

TABLE B1 Test of Assumptions.

Title	Test Stat.	*p*-values
Breusch-Godfrey Serial Correlation LM Test (First order)	1.092	0.304
Breusch-Godfrey Serial Correlation LM Test (Second order)	1.369	0.269
Breusch-Pagan-Godfrey Heteroscedasticity Test	0.404	0.935
Jarque-Bera Normality Test	0.246	0.884

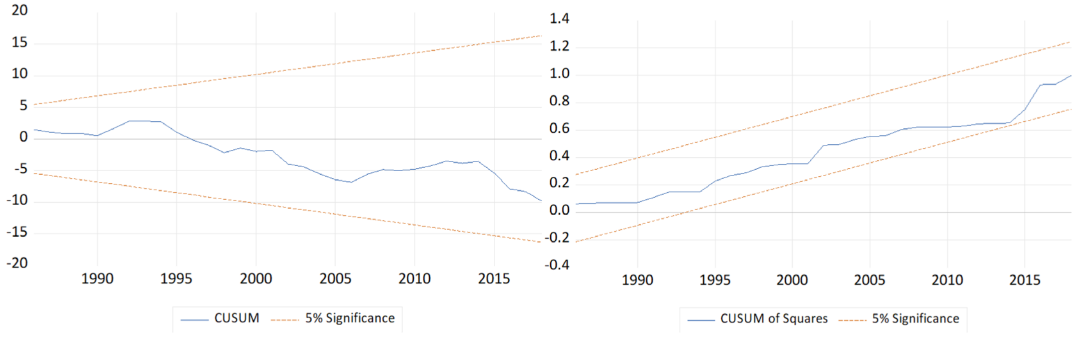

FIGURE A1 Stability Tests.

TABLE C1 Robustness Check.

	FMOLS		DOLS	
Variable	coefficient	*t*-Statistic	coefficient	*t*-Statistic
EC	0.344*	3.806	0.414*	4.136
FI	−0.105**	−2.158	−0.143**	−2.402
GDP	0.296*	5.487	0.327*	4.635
TI	−0.036*	−3.480	−0.050*	−3.970
Intercept	−2.881*	−12.961	−3.195*	−9.686

Note: * and ** show the significance at the 1% and 5% levels, respectively.