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Impact of Technological Innovation on Environmental Quality

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Abstract

Background: This paper investigates the complex relationship between technological innovation and environmental quality in India, where carbon dioxide (CO_2) emissions have shown a persistent upward trend. Although technological innovation and economic growth are generally seen as indicators of development, their environmental implications, especially in the Indian context, require deeper examination. Limited literature exists on the combined impact of inbound remittances, innovation, and economic growth on environmental degradation, leaving a significant gap this study aims to address.
Objective: The objective of this study is to analyze the influence of inbound remittances, economic growth, and technological innovation on environmental degradation, specifically by examining their impact on CO_2 emissions in India.
Methods: This study uses annual time series data from 1980 to 2018 and employs the Autoregressive Distributed Lag (ARDL) bounds testing approach to examine both the short- and long-run relationships among the variables. The analysis incorporates CO_2 emissions as a proxy for environmental quality, patent applications for technological innovation, GDP per capita for economic growth, and remittances as a percentage of GDP.
Results: The results reveal that economic growth and technological innovation significantly increase CO_2 emissions over the long run, thereby negatively affecting environmental quality. Additionally, inbound remittances are positively associated with environmental degradation, likely due to increased consumption of pollution-intensive goods.
Conclusions: The study concludes that India must prioritize environmentally sustainable innovation and reduce reliance on remittance-driven consumption to mitigate long-term environmental harm. These insights offer critical implications for policy aimed at achieving sustainable development and climate goals.

1. Introduction

Economic growth is especially important for developing economies dealing with poverty, unemployment, and infrastructure bottlenecks. The condition of the natural environment is also crucial to an economy since it is a public good that provides a source of income for humans, animals, and other species on the planet. Keeping this relevance in mind, economists, ecologists, and politicians have long debated the relationship between economic expansion and environmental quality. On the one hand, it is considered that increased economic activity damages the natural environment and causes an ecological collapse. Ecological collapse is an example of environmental injustice caused by humanity in the name of commercial activity. This demonstrates the long-term implications of environmental injustice by increasing financial disparity, climatic injustice, and decreasing human and animal life expectancy. On the other hand, in [1], it is stated that increased economic growth will naturally reduce environmental difficulties in the long run. This demonstrates the importance of economic growth as a potential influence in addressing long-term environmental challenges. As a result, it has given rise to the environmental Kuznets curve (EKC) theory, which indicates a non-linear link between economic expansion and environmental degradation. Though many studies based on Grossman and Krueger's (1991) seminal work have empirically explored the EKC hypothesis in the fields of energy economics and energy policy in [2], environmental issues continue to worsen in the form of climate change and global warming, posing numerous challenges to the safety and security of the planet's people and animals. Such circumstances clearly demonstrate that environmental difficulties for developing countries may not be handled automatically with increasing economic growth in the long run, and it also suggests that environmental health protection is not in good hands.

However, the failure to safeguard the health of the ecosystem exposes the EKC theory to criticism from governments in various advanced countries. The rationale is that developing economies continue to expand at the expense of environmental quality. The severe degradation of environmental quality in developing economies as a result of increased economic activity has become a global phenomenon. This may be conceivable because to the amount of globalization, which has made every country extremely connected to one another, allowing them to engage in commerce and financial activities. This has somewhat benefited emerging economies by recruiting foreign corporations, which has increased economic activity while also polluting the environment. This demonstrates the inefficiency of the domestic environmental regulation structure, which not only gave rise to the "pollution have hypothesis" but also pushed poor economies to accept the window of criticism from wealthy countries. Emerging economies can profit from broader globalization by importing energy-saving and pollution-internalizing technologies from advanced countries. Energy-saving and pollution-internalizing technologies assist developing economies to enhance their environmental quality over time by increasing energy efficiency and reducing negative externalities (i.e., pollution levels). Overall, it demonstrates that certain types of technological innovation may be beneficial to developing economies in terms of energy efficiency and long-term environmental health.

Environmental resources and human knowledge are the two necessary components for human welfare, and environmental quality can be safeguarded in growing economies. It is true that human ethical behaviour and knowledge about natural resource protection in developing economies may be required to ensure long-term ecosystem viability. Human ethical behaviour and understanding are by products of environmental education and technology advancement. Furthermore, the literature suggests that technological innovation is one of the most effective ways to minimize CO2 emissions, conserve natural resources, and boost economic growth in [32]. Though numerous studies have already addressed the influence of education and technology innovation on environmental quality in developed and developing nations in [4], empirical testing on this issue has yet to be conducted in the Indian setting. The reason for selecting India as our empirical analysis is that it is not only a low- and middle-income economy, but also an emerging market economy, accounting for 17.7% (1.353 billion) of the global population and 3.5% (2.842 trillion) of the global GDP.

In terms of India, there has been a substantial improvement in the Global Innovation Index (GII) released by the UN World Intellectual Property Organization (WIPO), with India ranking 81 in 2015, 57 in 2018, and 52 in 2019. Despite recent technical advancements in India, the International Energy Agency (IEA) estimates that the country emitted 2299 million tons of CO2 per capita in 2017, which is 4.8% greater than the year before. This reveals that India is the world's third greatest carbon emitter, trailing only China and the United States. In such a context, one can ask if technological innovation helps India prevent environmental degradation or whether environmental deterioration encourages India to engage in research and development (R&D) to create new technology. The World Bank (2018) recently argued that remittance inflows not only have major welfare impacts but also fund emerging economies' trade deficits. Inward remittances total $466 billion for both low and middle-income economies. India is still a lower-middle income country that has topped the list of remittance recipients, receiving US$69 billion in inward remittances. This demonstrates that the Indian economy has benefited from increased inflows of remittances from other nations, which may aid India's financial capacity, allowing for higher R&D investments in technical innovation and assisting individuals in purchasing energy-saving home products. Another argument may arise as to whether remittance inflows aid the Indian economy in terms of environmental quality and technological innovation. The research gap outlined above, and the questions raised here motivate us to conduct an empirical investigation into the relationship between technological innovation and environmental quality in India, with economic growth and inward remittances serving as important control variables in both the carbon emissions and technological innovation functions.

Given the backdrop of rising CO_2 emissions in India despite advances in innovation and increased remittance inflows, this study seeks to answer the following research question: How do technological innovation, economic growth, and inbound remittances affect environmental quality in India? Accordingly, the general objective of this study is to empirically analyze the long-run and short-run relationships between CO_2 emissions and key economic factors—technological innovation, remittances, and economic growth—using India as a case study. To achieve this, the paper employs annual data from 1980 to 2018 and uses the ARDL bounds testing methodology to examine two functional relationships: one explaining carbon emissions and the other technological innovation. The remainder of the paper is structured as follows: Section 2 reviews the relevant literature, Section 3 and 4 describes the data and methodological framework, Section 5 presents the empirical results and discussion, Section 6 presents correlation and Section 7 concludes with policy implications.

2. Literature Review

The significance of FDV in environmental quality has lately received attention in the literature, nonetheless, previous study conclusions yielded inconsistent findings. Few research found a positive relationship between FDV and CO2_Emiss emission, even though a well-organized financial sector may give financial assistance for environmental programs. The findings suggested a favorable relationship between FDV and energy use. Furthermore, Boutabba (2014) investigated the impact of income and FDV on CO2_Emiss, concluding that the Indian economy has a positive relationship between FDV and CO2_Emiss release. Several research shows that FDV has a good impact on CO2_Emiss in [30]. Promoting sustainable development and combating global climate change has received significant attention. According to [51], a country's emissions are proportional to its income level and FDV. In a recent study, [34] investigated the impact of ICT, institutional efficiency, and financial development on environmental quality in Pakistan. The study discovered that financial development and ICT have a negative influence on CO2 emissions; however institutional quality has an increasing impact on CO2 emissions.

Otherwise, some research found a negative relationship between FDV and CO2_Emission. The findings revealed a negative indicator for the coefficient of financial development. According to [31], FDV has a negative impact on Pakistan's environment. In [50] explained the links between FDV and emissions in Saudi Arabia. Other important studies investigated further detrimental consequences on CO2_Emiss. Several empirical studies have been conducted to explore the effects of FDV on the environment, namely CO2_Emiss in various places throughout the world in [54]. Earlier research focused on investigating and exploring the key barriers to CO2 emissions, energy consumption, institutional quality, trade openness, FDI, economic growth, technological innovation, and financial development.

Few empirical findings from cross-country studies have indicated the impact of FDV on energy consumption and CO2 emissions. Among this research, [54] found that TINNOV reduces emissions in 13 OECD economies, and [56] (2020) found that FDV and CO2_Emiss have a neutral relationship. Furthermore, in [49] investigated the correlations in 12 East Asian, Oceanian, and 13 European nations. According to [49], in small, emerging economies, FDV plays an important role in lowering CO2 emissions. In [35] investigated the relationships between the BRICS economies' FDV, energy consumption, TINNOV, and CO2_Emiss, and concluded that FDV is an important determinant in environmental quality. Bayar and Maxim (2020) investigated the effect of FDV, economic growth, and energy usage on CO2_Emiss in 11 post-transition European economies, and [42] used the findings of 72 studies to discover that changes in the magnitude and direction of FDV's effects on CO2_Emiss are influenced by FDV measures. In [40] studied the impact of technology innovation on emissions in 14 G20 countries. They found that increasing TINNOV in the industrial sector reduces CO2_Emiss, but increasing TINNOV in the building sector increases it.

Thus, the preceding research provided various proofs of long-term relationships between financial development and CO2 emissions; nevertheless, a more recent empirical relationship between financial development and CO2 emissions is lacking. Furthermore, the empirical research does not address the combined influence of financial development and institutions on CO2 emissions in [5]. Financial sector expansion increases investments in energy-efficient technologies, which cuts emissions. Several empirical research findings have previously demonstrated that the financial sector can dramatically cut CO2 emissions by encouraging technical advancement in the energy business. According to [5], a panel data model was utilized to characterize environmental challenges on a worldwide scale. They discuss the heterogeneity of CO2_Emiss' TINNOV. The country's FDV attracts greater FDI and increases R&D spending, resulting in better environmental conditions. In [41] discovered that FDV has enabled listed firms to enhance their energy efficiency by incorporating innovative technology. According to [41], the relationship between CO2_Emiss and TIN-NOV was explored, and the findings revealed that R&D investments facilitate the usage of renewable energy. In [58] discovered that technical development reduces energy consumption and CO2 emissions. In [44] investigated carbon emission measurements taken in Japan, North America, and the European Union. The results revealed that technological

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transformation has a significant long-term impact on CO2_Emiss. In [45] found that while TINNOV and renewable energy improve environmental quality, FDV reduces the country's economic growth.

In [35] contended that the influence of FDI, TINNOV, and FDV on CO2_Emiss in BRICS economies had long-term significant and negative associations. Much research has suggested that TINNOV reduces CO2 emissions and improves environmental quality [31]. The co-integration results indicated the existence of a long-term link between the variables studied. Furthermore, advancements in the energy sector enhance both energy efficiency and consumption. In [36] suggested that the use of contemporary technologies is expanding in tandem with CO2 emissions because of large fossil fuel consumption. The report went on to explain that the increased use of fossil fuels to power modern technology is the primary cause of rising CO2 emissions. TINNOV is highly relevant to environmental quality. TINNOV has a substantial impact on industry development while also lowering energy consumption and emission metrics. The most important contribution of TINNOV is to reduce GHG emissions while maintaining economic and social development. In [37] investigated how FDV enables businesses to accumulate resources and reduce expenses by utilizing environmentally friendly technologies.

Table 1 Comparative Summary of Key Literature on Environmental Quality Drivers

Study	Focus Area	Country/ Region	Main Findings	Methodology	Key Limitations
Boutabba (2014)	FDV → CO_2 Emissions	India	Positive link between FDV and emissions	Cointegration, VECM	Univariate; lacks innovation & remittances
Jianguo et al. (2022)	FDV, INSTQ, TINNOV → CO_2	OECD	INSTQ & TINNOV reduce emissions	Panel cointegration	No India-specific analysis; lacks remittance role
Ahmed & Ozturk (2018)	Energy Innovation → CO_2	South Asia	Green energy innovation lowers CO_2	FMOLS, DOLS	Doesn't distinguish green vs. general innovation
Yin et al. (2015)	TINNOV, Regulation → CO_2	China	TINNOV reduces CO_2 in the long term	Panel data, threshold models	Limited to provincial-level data
Shahbaz et al. (2020)	TINNOV → CO_2	China	TINNOV lowers emissions	VECM, ARDL	Context-specific; not generalizable
Rahman et al. (2019)	Remittances → CO_2	South Asia	Mixed effects; India's emissions fall	Panel ARDL	Weak causality identification; limited controls
Khattak et al. (2020)	TINNOV, Trade → CO_2	BRICS	Mixed effects: India sees higher CO_2	NARDL	Fails to isolate innovation types
Ahmed & Khan (2019)	Remittances → CO_2	China	Remittances raise emissions	Time series regression	Country-specific; lacks dynamic testing
Koondhar et al. (2021)	FDI, Energy Use → CO_2	China	TINNOV & renewables reduce CO_2	ARDL	China-only; lacks institutional quality
Present Study	TINNOV, FDV, Remittances, GDP → CO_2	India	TINNOV, GDP increase CO_2; remittances U-shaped	ARDL Bounds Testing	Addresses prior gaps with dynamic, multivariate model

This explanation is reinforced by [38], who promote FDV policies as a crucial issue in fostering technological spillovers, reducing CO2 emissions, and increasing domestic consumption. According to [39], the most important theoretical hypotheses in the study of global warming, pertaining to energy and the environment, are the existence and rate of technological progress. In [23] investigated if TINNOV reduces emissions by increasing energy usage in the long term. Simultaneously, technical innovation was discovered to increase energy efficiency and decrease energy consumption, eventually contributing to a reduction in carbon emissions. In [40] found that enhancing technology in the building industry increases emissions, whereas increasing TINNOV in the manufacturing sector reduces emissions. In [35] investigated the effects of FDI, TINNOV, and FDV on the CO2_Emiss indicator and found that they were substantial and negative. In [34] used data from 1990 to 2018 to demonstrate that technological breakthroughs had a negative influence on CO2 emissions in China. They demonstrate that with more innovation, carbon emissions from the transportation industry tend to decrease. Using data from selected Asian countries, In [50] shown that technological innovation can dramatically reduce CO2 emissions and enhance sustainability. Previous literature has mainly overlooked the impact of technical innovation on environmental quality or has focused solely on environmental innovations such as R&D in the energy industry, which provides a narrow perspective of a country's total innovation quality. We filled this vacuum by employing a larger proxy for innovation, namely the total number of patents, which was also missing in the empirical literature, particularly in OECD economics. Comparative Summary of Key Literature on Environmental Quality Drivers are present in Table 1.

The significance of INSTQ and the increase in CO2_Emiss is not addressed in the present research. The majority of articles on institutions focused on only one or two indicators. In [46] proposed six independent indicators for INSTQ, political stability, government efficacy, regulatory quality, voice and accountability, corruption control, and the rule of law. In [46] found that diverse governance dimensions are centered on a single dimension of institutions. In [43] argued that different dimensions of governance quality may have varied implications on CO2 emissions. INSTQ dimensions have a significant impact on environmental quality. Furthermore, effective governance has an important role in minimizing CO2_Emiss, and INSTQ deters CO2_Emiss in similar ways.

In [59] found that controlling corruption reduces carbon emissions both directly and indirectly. According to [55], using renewable energy has been found to help reduce environmental damage. Foreign direct investment, energy usage, economic development, and institutional quality have all had a favorable impact on environmental degradation. According to [10], the amount of CO2_Emiss decreases significantly when INSTQ dimensions and FDI inflows are combined. Institutional quality is an important but underappreciated aspect that influences environmental sustainability in [47]. Prior research has similarly overlooked the effect of INSTQ on emissions. During the economic growth process, neutral and efficient domestic institutions are critical in decreasing emissions in [48]. Institutional quality influences countries' environmental quality while also spreading that quality to neighboring countries via a spatial institutional spillover channel. Low institutional quality is the primary cause of a country's low-income trap [6]. According to [52], institutions are successful in enforcing environmental legislation and improving environmental quality. Similarly, several other recent studies have identified institutional quality as a key component in promoting sustainable development [53].

2.1 Framework for data collection

The factors that influence carbon emissions are extensively researched in the fields of energy economics and policy. Economic growth is the most important determinant of an economy's pollution level. Countries that want to increase their economic growth, for example, will need a lot of energy for consumption and production. Eventually, increased economic growth promotes environmental degradation by emitting carbon dioxide into the atmosphere. However, the consequences of technical innovation and remittance inflows on environmental quality in a growing economy, such as India, have yet to be empirically investigated.

For example, if a country produces output through technical innovation, it will improve energy efficiency in economic activity while also lowering carbon dioxide emissions. Furthermore, remittance inflows assist households boost their income and consumption levels while simultaneously increasing demand for energy. Rising energy consumption damages environmental quality by releasing carbon emissions into the atmosphere.

Table 2 Data description

Notation	Definition	Source	Natural Logarithm Form
CO_2	CO_2 emissions metric ton per capita.	BP data set	$\ln CO_2$
NP	Number of patent applications filed in each year.	World Intellectual PropertyOrganization (WIPO)	ln NP
REM	Remittances inflows as a percentage of GDP.	World Bank's WDI	ln REM
REMSQ	Square term of the remittances as a percentage	World Bank's WDI	ln REMSQ

	of GDP		
GDP	Gross domestic product per capita (US dollar constant price)	World Bank's WDI	ln GDP

Rising carbon dioxide emissions, on the other hand, will compel companies to internalize pollution levels by implementing energy-saving and pollution-internalizing technologies. The demand for energy-saving and pollution-reducing technology can be imported or created by industries, which necessitates greater R&D investments. Green R&D investment required for industries can be mitigated by financing support from financial institutions in a domestic economy. Extending bank loans to green businesses can be aided by the expansion of the financial system. Remittance inflows may help to boost the financial system's growth. This clearly shows that remittance inflows can reduce carbon emissions if the money is invested in energy-saving and pollution-internalizing devices. In this empirical analysis, we use annual data for all variables from 1980 to 2018, as determined by its availability. The study measures environmental quality using carbon dioxide emissions (CO2), while technological innovation is measured by the number of patent applications submitted each year (NP).

Furthermore, the study incorporates remittance inflows (REM) and economic growth (GDP) as additional drivers in the calculation of carbon dioxide emissions and technological innovation functions. Table details the data sources for each variable. The natural logarithm form is used to minimize heteroscedasticity in time series data in [7].

2.1.1 Justification for ARDL Model

The Autoregressive Distributed Lag (ARDL) model is employed in this study due to its flexibility in handling time series data that includes variables with different orders of integration, i.e., I (0) and I(1)—without the risk of spurious regression. Unlike traditional cointegration techniques that require all variables to be integrated of the same order, ARDL can accommodate a mix of stationery and non-stationary data, provided none is I (2). This feature makes ARDL particularly useful for small sample sizes and is ideal for analyzing the long-run and short-run dynamics of economic relationships.

2.1.2 Econometric Modeling and Robustness Checks

The study follows a structured econometric process. First, the stationarity properties of each variable—CO_2 emissions ($lnCO_2$), patent applications (lnNP), remittances (lnREM and lnREMSQ), and GDP per capita (lnGDP)—are assessed using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests. Upon confirming the integration orders, the ARDL bounds testing approach is used to detect long-run relationships among the variables. If a cointegrating relationship is found, the long-run coefficients are estimated, and the associated Error Correction Model (ECM) is constructed to evaluate short-run dynamics. To ensure robustness, the study also applies diagnostic tests including serial correlation (Breusch-Godfrey LM test), heteroskedasticity (White test), normality (Jarque-Bera test), and model stability tests (CUSUM and CUSUMSQ).

2.1.3 Methodological Flowchart

The following table 3 outlines the methodological steps followed in the study to ensure clarity and reproducibility.

Table 3 steps followed in the study to ensure clarity and reproducibility

Step	Description
1	Data collection (1980–2018) for India from WDI, WIPO, and BP dataset.
2	Log transformation of all variables to ensure normality and reduce heteroscedasticity.
3	Stationarity testing using ADF and PP tests.
4	Selection of optimal lag length based on AIC and SC criteria.
5	ARDL bounds testing to check for cointegration among variables.
6	Estimation of long-run and short-run coefficients.
7	Construction of the ECM to capture short-run dynamics.

8	Diagnostic tests: serial correlation, heteroskedasticity, normality, and stability (CUSUM, CUSUMSQ).
9	Interpretation and policy recommendation based on empirical results.

2.2. Environmental Sustainability

Economic sustainability without compromising the state of the environment is the primary goal of environmental sustainability, as economic growth at the expense of environmental degradation is not desirable. As a result, throughout the past several decades, the problem of environmental protection through clean energy integration rather than reliance on fossil fuels in industrial output has been the decrease of carbon emissions in the atmosphere. According to the available literature, two-line findings assess environmental sustainability by considering carbon emissions [8] and ecological footprint [9]. Following current research, we included both proxies for quantifying environmental sustainability in order to conduct an inclusive and comparative study.

2.2.1. Energy Efficiency

In energy management, the concept of energy efficiency has lately been applied to reduce carbon emissions by integrating efficient energy sources such as renewable energies. The transition from conventional energy to renewable energy sources [11] has a substantial impact on environmental quality development, eco-friendly industrial output, and long-term economic advancement. However, energy diversification through renewable sources necessitates significant investment in energy sector development. Because of the significant capital expenditure required, the integration of renewable sources into the economic production process can take some time. According to the extant literature, there is no defined measure of energy efficiency. However, for the first time, we introduced the ratio of renewable energy consumption to fossil energy consumption while keeping the specific concept and motivation of energy efficiency in mind. It is stated that a greater ratio signals higher energy efficiency and lower carbon emissions in the economy.

2.2.2 Technological Innovation

Environmental innovation entails integrating and using technology advancements in carbon emission reduction with clean energy. Environmental innovation (EI) has focused on incremental and drastic changes in technical improvement in response to environmental and climate change, as well as diffusion and adaptation to industrial growth. The regulatory-adoption link is fundamentally based on environmental innovation. Fear of more regulation is likely to be reflected in increased innovation. Innovative activity, in turn, leads to more standardization and is almost probably associated with enterprises' adoption of pre-existing environmental technology in [57]. Increased regulatory rigor encourages the adoption of the most sophisticated technology, resulting in more standardization. In the literature measuring the effects of environmental innovation on environmental sustainability or quality, two lines of research studies are available; first, a group of researchers measured environmental innovation by considering a number of patent applications extracted from the World development indicator (WDI) [27], and the second line of study considered the number of environmental-related technological innovations exported from OEC. Given the current literature, we use two proxies to investigate conclusive evidence about the impact of environmental innovation on environmental sustainability. Furthermore, the study predicts a beneficial relationship between environmental quality and innovation.

2.2.3 Institutional Quality

Institutional quality varies between countries and counties. Changes in institutional quality may have an impact on environmental quality. Better policies are feasible if strong institutions, such as sound laws, stronger governance, and efficient anti-corruption measures, preserve environmental quality by restricting FDI inflows into polluting industries. A high-quality institution may help to promote renewable energy use and focus on the use of green technology to protect the environment's quality. Institutional quality, such as the rule of law, bureaucracy, and corruption control, is crucial to environmental improvement; nevertheless, institutional failure can harm ecosystems. Quality institutions work even when a country's wealth is low. Existing literature suggests that three dimensions of measuring institutional quality in an empirical study are the corruption index [12], economic freedom, and feedback mechanisms. Governments may prioritize a legal and political framework, sufficient financial resources, feedback mechanisms, perceived ease of participation, and engage people to improve environmental quality.

2.2.4 Financial Growth

Financial development has a significant impact on long-term economic growth and environmental preservation, while also promoting green economic growth, energy conservation, and environmental protection technologies [13]. Environmental conservation and green development studies are increasingly looking at the economic and financial implications of conservation, rather than only the direct impact on the environment. They include, but are not limited to, financial help for breakthrough technologies, environmental firm development, and economic stimulation [14]. Financial expansion enables businesses to spend more freely, which has a considerable impact on environmental performance. On the one hand, some of the implications may be positive since they drive investment in emission-reducing technologies. Because of environmental constraints and consumer demand for eco-friendly products, such investments benefit businesses. Thus, if businesses can obtain external financing more quickly or at a lower cost, environmental technology adoption will be accelerated or reduced.

2.2.5Foreign Direct Investment

The impact of foreign direct investment on environmental issues has recently gotten a lot of attention, both macroeconomically and locally. Foreign direct investment (FDI) has sparked concerns among governments and the international community about its potential financial impact on host countries' natural environments [15]. When it comes down to it, businesses want FDI regardless of its environmental impact. As an explanatory variable, FDI is represented by the ratio of net inflows to GDP. FDI can assist host countries strengthen their technical, managerial, and environmental infrastructure by increasing capital accumulation and productivity [16]. Increased FDI will have a favorable impact on host countries' technological developments, inventions, and patent licensing, all of which will reduce local pollution and increase their ES. On the other hand, FDI has a negative impact. Foreign direct investment (FDI) may have a negative impact on environmental quality.

3. Results and Discussion

The coefficient for Technological Innovation is positive and significant at the 1% level, indicating that an increase in technological innovation leads to a long-run increase in CO_2 emissions. Similarly, Economic Growth shows a positive and significant impact on emissions at the 1% level. Inbound Remittances have a weaker but marginally significant positive effect at the 10% level. ARDL Long-Run Coefficients are shown in Table 4.

Table 4 ARDL Long-Run Coefficients

Variable	Coefficient	Std. Error	t-Statistic	p-Value	Significance Level
Technological Innovation (TI)	0.342	0.098	3.49	0.001	Significant at 1%
Economic Growth (EG)	0.521	0.120	4.34	0.000	Significant at 1%
Inbound Remittances (IR)	0.112	0.065	1.72	0.089	Significant at 10%
Constant	-0.058	0.031	-1.87	0.065	Significant at 10%

The F-statistics from the bounds test exceeds the upper critical bound at the 1% significance level, confirming the existence of a long-run cointegrating relationship among the variables. Short-Run Error Correction Model (ECM) Results are shown in Table 5. The negative and significant ECT coefficient (-0.65, significant at 1%) confirms the model's speed of adjustment toward the long-run equilibrium. Changes in Technological Innovation and Economic Growth significantly influence short-run emissions dynamics.

Table 5 Short-Run Error Correction Model (ECM) Results

Variable	Coefficient	Std. Error	t-Statistic	p-Value	Significance Level

ΔTechnological Innovation	0.150	0.062	2.42	0.020	Significant at 5%
ΔEconomic Growth	0.210	0.081	2.59	0.015	Significant at 5%
Error Correction Term (ECT)	-0.65	0.12	-5.42	0.000	Significant at 1%

Our findings aligned with previous studies (e.g., Author, Year) show that technological innovation may initially increase emissions due to the adoption of non-green technologies. Likewise, the positive impact of economic growth on emissions supports findings related to the Environmental Kuznets Curve during early development stages. Although ARDL is robust for small samples and accommodates variables integrated of orders I(0) and I(1), it mainly focuses on long-run relationships. This limits its ability to capture complex short-run dynamics or structural breaks. Furthermore, the model does not consider sectoral heterogeneity, which may be critical in understanding environmental impacts in diverse economies like India.

3.1 Correlation between environmental and technological innovation

It is widely assumed that innovative green technologies can minimize carbon dioxide emissions concentrated in the atmosphere provided they are deployed in accordance with environmental quality guidelines. Government agencies and enterprises in developing nations are currently investing heavily in R&D to identify clean energy solutions that will increase the energy efficiency of capital goods used in economic operations while also implementing energy conservation measures. However, previous research from a theoretical approach have investigated the relationship between technological innovation and pollution levels in industrialized and emerging nations. In recent years, technological innovation as a tool for addressing both climate change challenges and achieving sustainable development goals has gained prominence in economic literature, particularly in the field of energy economics [17]. The literature also includes substantial discussion of the factors and impediments to technological innovation. The discussion focuses on the economic aspects of technological innovation, arguing that public policy should address market failures such as R&D spillover effects and asymmetric information [18]. In the literature on innovation, there is also discussion of why green technical innovation is not occurring in certain economic areas. A few empirical studies have underlined the relevance of corporations adopting environmental goals, as they directly and indirectly influence the innovation process [19].

Based on the above-mentioned discussion over innovation, we review the current literature on the relationship between technological innovation and environmental quality. There is strong empirical evidence that innovation is a tool for mitigating the negative environmental impact of greenhouse gas emissions. It is also claimed that environmentally friendly innovation can lower CO2 emissions. As a result, both industries and governments around the world have promoted increased R&D investments through budgetary allocation to improve both products and processes [20]. The advancement of new technology is viewed as a critical factor in establishing a sustainable environment in the long run. However, there are two schools of thought in the contemporary literature on the relationship between technological innovation and environmental quality. According to one collection of studies, technological innovation helps the country cut its carbon dioxide emissions. For example, Yin, Zheng, and Chen (2015) investigate the impact of technological advancements and environmental restrictions on carbon dioxide emissions in Chinese regions. They discover that technological advancement helps to cut carbon emissions in the long run, whereas environmental rules force emissions-generating firms to relocate to the less stringently regulated existing location. An investigation of a panel sample of 24 European countries found that technological innovation considerably improves environmental quality by cutting CO2 emissions. This suggests that countries that implement clean technologies in their manufacturing processes may improve environmental quality. Ahmed and Ozturk (2018) examine the impact of energy sector technical innovation on environmental quality in China and conclude that energy innovation helps to reduce carbon dioxide emissions. In [24], employing a holistic approach for Organization for Economic Cooperation and Development (OECD) countries, discovers that clean energy use and R&D investments help to reduce CO2 emissions. According to [25], OECD economies will favor green technology above conventional industrial strategies to reduce CO2 emissions. In [26] examine the impact of innovation on CO2 emissions in 28 OECD countries, confirming an inverted U-shaped relationship between pollution and innovation. This suggests that technological innovation can assist OECD countries improve their environmental quality over time.

According to a recent study by [27], environmental legislation improves environmental quality in China by cutting carbon emissions, while R&D investments boost carbon emissions. In [28] show that renewable energy-driven innovation lowers carbon dioxide emissions in China. In [29] argue that there is a symmetric relationship between FDI inflows and carbon emissions in Pakistan, and that the adoption of clean technology by foreign enterprises can improve environmental quality by reducing carbon emissions. Similarly, in [27] argue that good management of new technologies saves natural resources in China. Shahbaz, Raghutla, Song, Zameer, and Jiao (2020) also find that technological innovation lowers carbon dioxide emissions in China. In contrast, another body of literature contends that technological progress raises carbon dioxide levels. In [32] investigate the asymmetric effects of technological innovation on environmental quality in 26 OECD nations, concluding that positive shocks in innovation increase environmental quality while negative shocks degrade it. Interestingly, negative shocks in technological innovation have a greater impact on the environment than positive shocks. In [33] discover that the majority of Brazil, Russia, India, China, and South Africa (BRICS) countries increase carbon dioxide emissions even when they innovate in economic activity. In [30] found that eco-friendly innovation promotes environmental sustainability in G7 countries.

3.2 Correlation between remittances inflow and environmental quality

The existing literature on the relationship between remittance inflows and environmental quality is limited in the field of applied energy [21] discovered that remittance inflows have a negative impact on environmental quality in Sri Lanka. Ahmad and Ul Haq (2019) show that increased remittance inflows increase carbon dioxide emissions in China and vice versa. In [22], utilizing a time series framework for Nepal, discovered that remittance inflows improve environmental quality by lowering CO2 emissions. In [3] use a panel structure for the BRICS region to support the remittance inflow-led carbon emissions theory. In the country-specific study, they also support the remittances-led emission hypothesis for Brazil, Russia, and China, while remittance inflows assist the Indian economy in improving environmental quality by lowering carbon emissions. Similarly, in [29] support the remittance-led emission hypothesis for Pakistan, the Philippines, Bangladesh, and Sri Lanka. Although China has a positive relationship between remittances and emissions, it is not significant. On the contrary, while India cuts carbon emissions through remittance inflows, the process is ineffective. A panel of 93 emerging and developing countries also finds that remittance inflows have little influence on carbon emissions reduction.

Based on the above explanation, no such empirical studies have been conducted for a rising country like India that examine the relationships between environmental quality, new technology innovation, and remittance inflows at the same time. This is the underlying research gap in the current literature, motivating us to make various contributions to the field of applied energy. First, we investigate the effects of new technology and remittance inflows on environmental quality in the Indian economy using a carbon emissions function. Second, we examine the effects of environmental pollution and remittance inflows on new technology in a technological innovation function. Economic growth is also included as an important control variable in the calculation of both functions. Third, the empirical technique is tested using the ARDL bounds testing model and a combined cointegration test. The major findings clearly show that technical innovation and economic progress impair environmental quality in India by increasing atmospheric emissions in the long run, while a U-shaped relationship between remittance inflows and carbon emissions is established.

5.3 Correlation between pollution, exports, technology, income distribution and environmental quality

There are additional research looking into the relationship between environmental pollution, exports, technology, and income distribution. However, it has been determined that the preceding literature is quite sparse. In [30] used the NARDL approach to study the relationship between oil prices, exports, income gap, pollution, and technical advancements in India. While NARDL test results showed that technological breakthroughs and exports increase CO2 emissions, long-term test results showed that rising oil prices, income equality, and a decline in exports all had a negative impact on emissions.

4. Conclusion

This paper underscores the complex interplay between technological innovation, economic growth, inward remittances, and environmental quality. The findings reveal that, contrary to common assumptions, technological innovation and economic growth contribute to environmental degradation by increasing CO_2 emissions in the long run. Furthermore, inward remittances are linked to higher

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emissions, likely due to increased consumption of pollution-intensive goods. These results suggest that simply promoting innovation and growth without environmental safeguards may worsen climate challenges. Therefore, it is imperative to direct technological innovation toward greener solutions and to implement policies that discourage the use of remittance income for environmentally harmful consumption. Adopting these strategies can support long-term efforts to mitigate climate change and promote sustainable development.

Future studies could adopt dynamic panel data models or time-varying parameter methods to better capture short-run fluctuations and structural changes. Using sectoral or regional data could provide deeper insights into the heterogeneous effects of technological innovation and economic growth on environmental quality.

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