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Macroeconomic Determinants of Environmental Degradation in India: An Empirical Investigation

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Abstract: Climate change is increasingly recognized as a driver of zoonotic disease emergence, reshaping ecological interactions and amplifying risks to human and animal health. Rising temperatures, altered precipitation patterns, and extreme weather events accelerate vector breeding cycles, disrupt habitats, and intensify human-animal contact, thereby expanding opportunities for pathogen spillover. This review aims to synthesize evidence on climate-linked zoonotic threats and examine how vaccine equity and policy integration within a One Health framework can strengthen global preparedness. A narrative literature review was conducted using PubMed, Scopus, Web of Science, and Google Scholar, covering publications from 2005 to 2025. Keywords included climate change, zoonotic diseases, One Health, surveillance, vaccine equity, and health disparities. Evidence highlights climate-sensitive diseases such as malaria, Rift Valley fever, and leptospirosis as major global health challenges. Surveillance systems, including the Global Outbreak Alert and Response Network, the Global Early Warning System, the International Pathogen Surveillance Network, and the Global Influenza Surveillance and Response System, provide critical early warning capacity but remain unevenly implemented in low- and middle-income countries. Vaccine equity challenges persist among displaced populations, rural communities, and marginalized groups, with barriers linked to infrastructure, misinformation, and systemic inequities. Embedding climate resilience, equity, and community participation into One Health strategies is essential for mitigating zoonotic threats. Strengthened interdisciplinary collaboration, digital innovation, and policy harmonization will be pivotal in advancing surveillance, prevention, and vaccine equity, thereby enhancing global preparedness against future climate-driven zoonotic disease risks.

Keywords: Climate Change; Zoonoses; One Health; Disease Surveillance; Vaccine Equity; Health Disparities

1. Introduction

Environmental degradation has emerged as one of the most pressing challenges confronting contemporary economies, particularly in developing and emerging countries undergoing rapid structural transformation. Accelerated economic growth, industrial expansion, urbanization, and rising energy demand have substantially improved material well-being, yet these processes have simultaneously intensified pressures on ecosystems and environmental quality. Increasing greenhouse gas emissions, deteriorating air and water quality, deforestation, and biodiversity loss now pose serious threats to sustainable development, public health, and long-term economic resilience [1,2]. The growing recognition that environmental constraints may undermine future growth trajectories has placed the growth–environment nexus at the center of policy and academic debates.

India represents a particularly important case in this context. As the world's most populous country and one of the fastest-growing major economies, India has experienced profound structural changes over the past three decades. The transition from an agrarian to a more industrial- and service-oriented economy, coupled with rapid urbanization and rising energy consumption, has significantly altered the country's environmental landscape. India is currently among the largest emitters of carbon dioxide globally, largely due to its continued reliance on fossil fuels, expanding industrial base, and growing transport sector [3]. At the same time, the country remains highly vulnerable to environmental stress and climate change, as reflected in the increasing frequency of extreme weather events, severe air pollution in urban centers, and mounting pressure on land and water resources [4]. These dynamics underscore the urgency of understanding the macroeconomic drivers of environmental degradation in the Indian context.

The relationship between economic development and environmental degradation has been widely examined in both theoretical and empirical literature. Early studies emphasized an inherent trade-off between growth and environmental quality, suggesting that higher levels of production and consumption inevitably lead to increased pollution and resource depletion [5]. Subsequently, the Environmental Kuznets Curve (EKC) hypothesis proposed a nonlinear relationship between income and environmental degradation, whereby environmental pressure initially increases with economic growth but eventually declines beyond a certain income threshold due to structural change, technological progress, and stronger environmental regulations [6]. Although the EKC hypothesis has generated mixed empirical evidence, it remains a dominant analytical framework for examining growth–environment interactions in developing and emerging economies.

Beyond income growth, recent research highlights the importance of broader macroeconomic factors in shaping environmental outcomes. Energy consumption—particularly from non-renewable sources—has been consistently identified as a major driver of environmental degradation and carbon emissions [7]. Trade openness influences environmental quality through scale, composition, and technique effects, with the net impact depending on the stringency of environmental regulations and production structures [8]. Financial development plays an increasingly important role, as it can either intensify environmental degradation by facilitating energy-intensive investment or mitigate it by promoting green finance and clean technologies [9]. Similarly, urbanization exerts complex and often ambiguous effects, generating both efficiency gains through agglomeration and environmental stress through congestion, waste generation, and rising energy demand [10].

In the Indian and emerging-economy literature, however, empirical evidence on the macroeconomic determinants of environmental degradation remains fragmented and inconclusive. A large share of existing studies for India focuses narrowly on the growth–emissions nexus or on testing the EKC hypothesis using limited sets of explanatory variables [11,12]. While these studies provide useful insights, they often neglect the simultaneous roles of financial development, trade openness, urbanization, and energy structure, thereby offering only a partial understanding of the underlying macroeconomic mechanisms. Moreover, many earlier studies rely on outdated data, short sample periods, or single-equation frameworks that fail to capture both long-run equilibrium relationships and short-run adjustment dynamics. This limitation is particularly critical given India's rapidly evolving economic structure, increasing integration into global markets, and recent policy shifts toward renewable energy, green finance, and carbon neutrality commitments.

A further gap in the literature relates to the methodological dimension. Much of the existing Indian evidence is based on conventional cointegration or static regression techniques, which impose restrictive assumptions regarding the order of integration of variables and often lack robustness in small samples. In contrast, relatively few studies employ flexible time-series approaches capable of accommodating mixed integration orders and capturing dynamic interactions among macroeconomic variables and environmental indicators. This methodological shortcoming restricts the reliability of policy inferences derived from existing findings.

Against this backdrop, the present study seeks to provide a comprehensive and updated empirical assessment of the macroeconomic determinants of environmental degradation in India. Specifically, it aims to (i) examine the long-run and short-run relationships between environmental degradation and key macroeconomic variables—economic growth, energy consumption, financial development, trade openness, and urbanization—and (ii) assess whether India's growth trajectory is compatible with environmental sustainability objectives. The study employs the Auto-Regressive Distributed Lag (ARDL) approach, which is particularly well-suited for small samples and allows variables with mixed orders of integration to be analysed within a unified framework [13].

The contribution of this study is threefold. First, it extends the existing Indian literature by integrating multiple macroeconomic drivers of environmental degradation within a single coherent empirical model, thereby moving beyond the narrow growth–emissions focus of earlier studies. Second, it provides robust long-run and short-run estimates that capture the dynamic adjustment processes between economic activity and environmental quality. Third, the findings generate important policy-relevant insights for designing macroeconomic strategies that reconcile economic growth with environmental sustainability, in line with India's commitments under the Sustainable Development Goals and its long-term climate and carbon neutrality targets.

2. Literature Review

A substantial body of literature has examined the determinants of environmental degradation, spanning theoretical frameworks and empirical investigations across global, regional, and country-specific contexts. This section critically synthesizes the major strands of research, with particular emphasis on macroeconomic drivers, climate and green finance mechanisms, renewable energy transition frameworks, and global climate governance. It further identifies key conceptual, empirical, and methodological gaps, especially in relation to India and emerging economies.

2.1. Global Evidence on Macroeconomic Drivers of Environmental Degradation

The foundational literature on the relationship between economic development and environmental quality is anchored in the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shaped relationship between income per capita and environmental degradation [5]. Early cross-country studies provided initial empirical support, suggesting that environmental pressure rises during early stages of development and declines beyond a certain income threshold due to technological progress and regulatory improvements [14,15]. Subsequent global analyses using advanced panel econometric techniques have, however, produced mixed and often pollutant-specific results, questioning the universality of the EKC hypothesis [16,17].

Energy consumption has consistently emerged as the most robust determinant of environmental degradation. Extensive empirical evidence confirms that fossil fuel-based energy use is a primary driver of carbon emissions at the global level [18,19]. More recent studies emphasize that the structure of the energy mix, rather than energy consumption per se, is critical for environmental outcomes. Global panel analyses show that renewable energy deployment significantly mitigates emissions, whereas dependence on coal and oil exacerbates environmental degradation [20].

Trade openness and financial development have attracted growing attention in the literature. Trade is argued to influence environmental quality through scale, composition, and technique effects [8]. Empirical studies provide divergent conclusions: some report environmental improvements via technology diffusion and cleaner production processes [21], while others find that trade liberalization intensifies emissions by expanding pollution-intensive industries [22]. Similarly, the role of financial development remains ambiguous. While some studies suggest that financial deepening facilitates investment in clean technologies and improves environmental efficiency [23, 24], others show that financial liberalization accelerates industrial activity and energy demand, thereby worsening environmental outcomes [25].

More recent global studies extend this debate by explicitly incorporating green finance and climate finance mechanisms. Emerging evidence suggests that green financial instruments—such as green bonds, climate funds, and sustainable banking—play a significant role in reducing carbon intensity and supporting low-carbon transitions [26–28]. However, most global studies rely on cross-country panel data, with limited attention to country-specific institutional contexts and policy environments.

2.2. Green Finance and Climate Finance: Emerging Global Evidence

The literature on green and climate finance has expanded rapidly following the Paris Agreement and subsequent COP processes. Green finance is broadly defined as financial activities that support environmental improvement, climate mitigation, and sustainable development [26]. Recent global studies demonstrate that green finance contributes significantly to carbon emission reductions by directing capital towards renewable energy, energy efficiency, and clean infrastructure [27,28].

Institutional analyses highlight the growing role of climate finance mechanisms such as the Green Climate Fund, carbon markets, blended finance, and sustainable taxonomies in mobilizing private capital for climate action [29,30].

Empirical studies using panel data for emerging and developed economies show that higher levels of green credit and green bond issuance are associated with lower carbon intensity and improved environmental performance [31,32].

Despite these advances, important gaps persist. First, most empirical studies treat green finance as a macro-level index, without disaggregating institutional channels or sectoral allocation. Second, the majority of evidence is based on OECD or global samples, with limited country-specific analyses for large emerging economies such as India. Third, the interaction between traditional financial development and green finance remains underexplored, particularly in time-series frameworks.

2.3. Renewable Investment and Policy Transition Frameworks

The renewable energy transition has become central to global climate mitigation strategies. Theoretical frameworks emphasize the role of structural transformation, technological innovation, and investment mobilization in achieving low-carbon transitions [33]. Empirical studies show that renewable energy investment significantly reduces carbon emissions and enhances environmental sustainability, particularly in countries with supportive policy regimes and financial incentives [26,34].

Recent policy-oriented literature highlights the importance of integrated transition frameworks, combining energy policy, industrial strategy, and financial regulation [35]. Global investment reports indicate that renewable energy investment must triple by 2030 to meet Paris Agreement targets, underscoring the role of public–private partnerships and green finance instruments [36].

However, the literature remains fragmented in several respects. Most studies analyze renewable energy in isolation, without embedding it within broader macroeconomic frameworks. Furthermore, few empirical studies link renewable investment dynamics explicitly to financial development, trade openness, and urbanization within unified econometric models.

2.4. Carbon Neutrality and Energy Transition Commitments for India

India's climate commitments have received increasing scholarly attention following its announcement of net-zero emissions by 2070 and intermediate targets under the Paris Agreement and COP26 "Panchamrit" framework [37]. Policy studies emphasize that India's transition pathway must balance economic growth, energy security, and environmental sustainability [38,39].

Recent empirical research shows that renewable energy deployment and improvements in energy efficiency are critical for achieving India's carbon neutrality goals [40,41]. Climate policy assessments further highlight the role of green hydrogen, electric mobility, and climate finance in supporting India's low-carbon transition [42].

Nevertheless, the Indian literature exhibits notable limitations. First, most studies adopt scenario-based or simulation models, rather than econometric approaches grounded in historical data. Second, the macroeconomic determinants of environmental degradation are rarely examined in relation to India's long-term climate commitments. Third, the role of financial development and green finance in facilitating India's energy transition remains empirically under-investigated.

2.5. Global Climate Policy Agreements and Institutional Frameworks

Global climate governance provides the overarching institutional context for national environmental policies. The Paris Agreement established legally binding commitments to limit global warming and introduced nationally determined contributions (NDCs) as the core implementation mechanism [43]. Subsequent COP processes—particularly COP26, COP27, and COP28—have emphasized climate finance, adaptation funding, and loss-and-damage mechanisms [29,44].

The Sustainable Development Goals (SDGs), especially SDG 7 (clean energy), SDG 12 (sustainable consumption), and SDG 13 (climate action), further integrate environmental sustainability into global development agendas [45]. Institutional analyses argue that effective climate governance requires alignment between macroeconomic policy, financial systems, and environmental regulation [46].

However, empirical studies rarely incorporate global climate policy variables into econometric analyses of environmental degradation. Most treat climate agreements as exogenous policy backdrops, rather than endogenous institutional factors influencing economic–environment dynamics.

2.6. Synthesis and Research Gaps

The cumulative evidence reveals several critical gaps, particularly relevant for India and emerging economies:

- Conceptual gap: Existing studies largely examine environmental degradation through isolated lenses (growth, energy, or renewables), with limited integration of green finance, financial development, and climate policy frameworks within a single analytical structure.
- Empirical gap: There is a scarcity of country-specific time-series studies for India that simultaneously incorporate economic growth, energy use, trade openness, urbanization, financial development, and environmental outcomes.
- Policy gap: India's carbon neutrality commitments and climate finance initiatives are rarely embedded in empirical macroeconomic models, limiting policy relevance.
- Methodological gap: Most Indian studies rely on static or single-equation models and outdated data, with limited exploration of short-run dynamics and adjustment processes.

Recognizing these limitations, the present study contributes to the literature by adopting a multivariate ARDL framework to examine both long-run and short-run relationships between environmental degradation and key macroeconomic variables in India. By explicitly situating the analysis within the context of green finance, renewable energy transition, and global climate policy commitments, the study offers a more integrated and policy-relevant understanding of the environment–economy nexus in a major emerging economy.

3. Macroeconomic Determinants of Environmental Degradation in India

Environmental degradation in India is deeply embedded in the country's macroeconomic structure, growth dynamics, and development strategy. Since the initiation of economic reforms in the early 1990s, rapid economic expansion driven by liberalization, industrialization, and urbanization has substantially intensified pressures on ecological systems. Rising income levels, structural transformation, and increasing integration with global markets have collectively reshaped production and consumption patterns, leading to higher levels of energy use, resource extraction, and pollution. Recent empirical literature increasingly emphasizes that India's environmental challenges are not merely technological or institutional, but fundamentally macroeconomic in nature, reflecting the interaction between growth processes and policy frameworks [47–49]. This section critically examines the principal macroeconomic determinants of environmental degradation in India, focusing on economic growth, energy consumption, industrialization, urbanization, trade openness, and fiscal policy.

3.1. Economic Growth and Environmental Pressure

Economic growth, typically measured by real gross domestic product (GDP), remains one of the most influential determinants of environmental degradation. In India, sustained high growth rates have been associated with increased demand for energy, minerals, land, and infrastructure, resulting in rising carbon emissions, deforestation, and waste generation. The scale effect of growth—where higher production and consumption translate directly into greater environmental stress—has been particularly pronounced during periods of accelerated industrial and infrastructure expansion [50,51].

However, the growth–environment relationship is not strictly linear. The Environmental Kuznets Curve (EKC) hypothesis postulates an inverted U-shaped relationship, whereby environmental degradation initially increases with income but declines beyond a certain income threshold due to technological progress, structural shifts towards cleaner sectors, and stronger regulatory institutions. Recent empirical studies for India provide mixed evidence. While some studies identify EKC-type behaviour for selected pollutants such as SO_2 and $PM_{2.5}$, most find a monotonic positive relationship between income growth and CO_2 emissions, indicating that India has not yet reached the turning point required for decoupling growth from environmental degradation [52–54]. This suggests that income-driven improvements in environmental awareness and regulation have been insufficient to offset the pollution effects of energy-intensive growth.

3.2. Energy Consumption and Emission Intensity

Energy consumption constitutes one of the most significant macroeconomic drivers of environmental degradation in India. The country remains heavily dependent on fossil fuels, particularly coal, which accounts for a dominant share of electricity generation and industrial energy use. As a result, India is among the largest contributors to global CO_2 emissions, with energy-related activities being the principal source [55]. Rising per capita energy demand, coupled with rapid urbanization and industrial expansion, has intensified air pollution and climate-related risks.

Recent empirical studies consistently demonstrate a strong positive relationship between energy consumption and environmental degradation in India, irrespective of the environmental indicator used (CO_2 emissions, ecological footprint, or particulate matter) [56–58]. Although renewable energy capacity has expanded significantly in recent years, the overall energy mix remains carbon-intensive, and the energy intensity of GDP continues to be a major concern. The persistence of fossil-fuel-based growth strategies implies that economic expansion has not yet been effectively decoupled from environmental damage, underscoring the importance of accelerating the energy transition.

3.3. Industrialization and Structural Transformation

Industrialization has played a central role in shaping India's environmental outcomes. The expansion of manufacturing, construction, and extractive industries has significantly increased emissions of industrial pollutants, wastewater discharge, and solid waste generation. While structural transformation from agriculture to industry and services is a fundamental feature of economic development, India's industrial growth has often occurred with limited adoption of clean technologies and weak enforcement of environmental regulations [59].

Small and medium enterprises (SMEs), which constitute a large share of India's industrial base, frequently rely on outdated and energy-inefficient production methods, leading to disproportionately high pollution intensities. Empirical evidence suggests that industrial value added and manufacturing output are positively and significantly associated with environmental degradation, particularly in terms of CO_2 emissions and ecological footprint [60,61]. This indicates that India's pattern of industrialization remains environmentally unsustainable, with structural change reinforcing rather than alleviating ecological stress.

3.4. Urbanization and Environmental Stress

Rapid urbanization represents another critical macroeconomic determinant of environmental degradation in India. Urban population growth has increased demand for housing, transportation, energy, and public services, thereby intensifying air and water pollution, traffic congestion, and waste accumulation. Urban economic activities contribute substantially to GDP growth, but they also generate significant environmental externalities due to inadequate infrastructure, unplanned spatial expansion, and weak regulatory capacity [62].

Recent studies show that urbanization exerts a statistically significant positive effect on CO_2 emissions and particulate matter concentrations in Indian cities, reflecting the concentration of energy-intensive activities and motorized transport systems [63,64]. Moreover, urban expansion has led to the conversion of agricultural land, wetlands, and forest areas, reducing ecological resilience and increasing vulnerability to environmental risks such as flooding, heat stress, and water scarcity. Thus, while urban-led growth has enhanced economic productivity, it has simultaneously amplified environmental degradation.

3.5. Trade Openness and Global Integration

Trade liberalization and deeper integration into the global economy have also influenced environmental outcomes in India. On the one hand, trade openness can facilitate access to cleaner technologies, improve resource efficiency, and promote environmentally friendly production practices. On the other hand, it can stimulate the expansion of pollution-intensive industries driven by export demand and comparative advantage.

The "pollution haven" hypothesis suggests that developing economies may attract environmentally harmful industries due to relatively lax environmental regulations. Empirical evidence for India remains nuanced. Several studies find that trade openness has contributed to higher CO_2 emissions and ecological footprint, particularly through the expansion of energy-intensive manufacturing and resource-based exports [65,66]. At the same time, some evidence suggests that technology transfer and foreign direct investment (FDI) may partially offset these effects by improving energy efficiency in certain sectors [67]. Overall, the net environmental impact of trade in India appears to be negative, reflecting the dominance of scale effects over technique effects.

3.6. Fiscal Policy, Public Investment, and Environmental Outcomes

Fiscal policy plays a dual role in shaping environmental degradation. Public investment in infrastructure, energy, and industrial development can stimulate economic growth but may also generate adverse environmental impacts if sustainability considerations are inadequately integrated. Historically, subsidies for fossil fuels, irrigation, fertilizers, and industrial inputs in India have distorted resource allocation, encouraged overconsumption, and exacerbated environmental stress [68].

Conversely, government expenditure on environmental protection, renewable energy, and pollution abatement can mitigate degradation and promote sustainable development. Recent empirical studies show that green public investment and environmental taxation have a statistically significant negative effect on CO_2 emissions and ecological footprint in India, indicating the potential of fiscal instruments to support environmental sustainability [69,70]. However, the effectiveness of fiscal policy depends critically on institutional capacity, policy coherence, and the alignment of macroeconomic objectives with environmental goals.

3.7. Synthesis of Macroeconomic Drivers

Taken together, the macroeconomic determinants of environmental degradation in India reflect a complex interaction between growth dynamics, structural transformation, and policy choices. Economic expansion has improved living standards and reduced poverty, but it has also intensified environmental stress through energy-intensive production patterns, rapid urbanization, and trade-driven industrialization. The empirical literature [71–76] consistently indicates that growth, energy consumption, industrial output, and urbanization exert positive and significant effects on environmental degradation, while policy instruments such as renewable energy promotion and green fiscal measures can partially mitigate these effects. Understanding these macroeconomic linkages is therefore essential for designing development strategies that reconcile economic growth with environmental sustainability.

4. Data and Methodology

4.1. Data Sources and Variable Description

This study employs annual time-series data for India over the period 1990–2023 to empirically examine the macroeconomic determinants of environmental degradation. The choice of variables is grounded in well-established theoretical frameworks, including the Environmental Kuznets Curve (EKC) hypothesis, the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model, and the broader empirical literature linking macroeconomic dynamics, structural transformation, and environmental outcomes.

Environmental degradation is proxied by carbon dioxide (CO_2) emissions per capita (metric tons), which is widely recognized as a comprehensive indicator of anthropogenic environmental pressure associated with fossil fuel combustion, industrial activity, and energy use. To strengthen the empirical representation of environmental stress, supplementary indicators—such as energy intensity and fossil fuel energy consumption—are employed in robustness analysis to capture efficiency and energy-structure effects.

The key explanatory variables include:

- (i) economic growth, measured by real GDP per capita (constant prices), capturing income-driven scale effects;
- (ii) energy consumption, proxied by per capita primary energy use, reflecting the intensity of production and consumption activities;
- (iii) industrialization, measured as the share of industry in GDP, representing pollution-intensive structural change;
- (iv) trade openness, defined as the ratio of total trade (exports plus imports) to GDP, capturing globalization-induced scale, composition, and technique effects;
- (v) urbanization, proxied by the urban population share, reflecting demographic pressures and infrastructure expansion; and
- (vi) renewable energy penetration, measured as the share of renewable energy in total final energy consumption, capturing technological transition and mitigation effects.

Data are obtained from the World Development Indicators (World Bank), International Energy Agency (IEA), Reserve Bank of India (RBI), and Ministry of Statistics and Programme Implementation (MOSPI). All variables are transformed into natural logarithms to stabilize variance, reduce heteroscedasticity, and allow estimated coefficients to be interpreted as elasticities.

4.2. Model Specification

To empirically analyse the relationship between macroeconomic factors and environmental degradation, the following long-run functional form is specified:

$$\ln(ED_t) = \alpha_0 + \alpha_1\ln(GDP_t) + \alpha_2\ln(ENE_t) + \alpha_3\ln(IND_t) + \alpha_4\ln(TRA_t) + \alpha_5\ln(URB_t) + \alpha_6\ln(REN_t) + \varepsilon_t$$

where:

- ED_t denotes environmental degradation (CO_2 emissions),
- GDP_t represents economic growth,
- ENE_t denotes energy consumption,
- IND_t captures industrialization,
- TRA_t represents trade openness,
- URB_t denotes urbanization,
- REN_t captures renewable energy penetration,
- ε_t is the stochastic error term.

The expected signs of coefficients are positive for GDP, energy use, industrialization, trade openness, and urbanization, while renewable energy is expected to exert a mitigating (negative) effect on environmental degradation.

4.3. Econometric Strategy

4.3.1. Unit Root and Structural Break Tests

The empirical analysis begins by examining the stochastic properties of the variables using the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests. These conventional tests are complemented with the Zivot–Andrews (ZA) structural break unit root test, which endogenously determines a single break in the intercept and/or trend. The inclusion of structural break tests is particularly important in the Indian context, given major policy and institutional shifts—such as the 1991 economic liberalization, the post-2008 global financial crisis, and recent climate and energy policy reforms—which may induce regime changes in the emissions–growth relationship.

4.3.2. Cointegration and Long-Run Estimation

Given the mixed order of integration, the study adopts the Autoregressive Distributed Lag (ARDL) bounds testing approach to cointegration, which is suitable for small samples and allows variables integrated of order I (0) and I (1) to be jointly modelled. The ARDL framework also accommodates potential endogeneity by incorporating lagged dependent and explanatory variables.

To further ensure robustness, long-run relationships are cross-validated using alternative cointegration estimators, namely Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR). These estimators correct for serial correlation and endogeneity, providing consistent long-run coefficients and serving as robustness checks against ARDL-based estimates.

4.3.3. Short-Run Dynamics and Error Correction

Upon confirming cointegration, short-run dynamics are estimated through an Error Correction Model (ECM). The error correction term captures the speed of adjustment toward the long-run equilibrium following short-run shocks. A statistically significant and negative ECT coefficient confirms the stability of the long-run relationship.

4.4. Causality Analysis

To address the reviewer's concern regarding the bidirectional nature of the growth–emissions nexus, the study explicitly incorporates causality analysis. First, pairwise and multivariate Granger causality tests are conducted within a Vector Error Correction Model (VECM) framework to distinguish between short-run and long-run causality.

Second, the analysis is extended using the Toda–Yamamoto (1995) causality approach [77], which is robust to integration and cointegration properties and avoids potential pre-test biases. This enables identification of the direction of causality between economic growth, energy consumption, and CO_2 emissions, thereby strengthening causal inference and mitigating simultaneity concerns.

4.5. Diagnostic, Stability, and Robustness Checks

Model adequacy is assessed through a comprehensive battery of post-estimation diagnostic tests, including the Breusch–Godfrey LM test for serial correlation, Breusch–Pagan and White tests for heteroscedasticity, Jarque–Bera test for normality, and Ramsey RESET test for functional form misspecification.

Parameter stability is examined using the CUSUM and CUSUM of Squares tests, while structural stability is further evaluated through Bai–Perron multiple structural break tests, which identify potential regime shifts in the emissions function.

Robustness checks are performed by (i) replacing CO_2 emissions with alternative environmental indicators such as energy intensity and total emissions, (ii) re-estimating the model using FMOLS, DOLS, and CCR estimators, and (iii) varying lag structures and sample sub-periods. The consistency of results across alternative specifications confirms the stability and reliability of the core findings.

4.6. Ethical Considerations and Methodological Limitations

The study relies exclusively on secondary data obtained from publicly available and reputable sources, ensuring transparency and reproducibility. Nonetheless, limitations remain. The use of aggregate national-level data may conceal regional heterogeneity and sector-specific emission dynamics, while CO_2 emissions capture only one dimension of environmental degradation. Moreover, although advanced econometric techniques and causality tests are employed, time-series methods cannot fully eliminate concerns related to omitted variables and measurement error.

Despite these constraints, the integration of structural break tests, multiple cointegration estimators, and causality analysis substantially enhances the methodological rigor of the study and strengthens the credibility of the empirical evidence on the macroeconomic drivers of environmental degradation in India.

5. Analysis and Results

5.1. Descriptive Statistics

Table 1 presents the descriptive statistics of the logarithmically transformed variables. The use of log transformations facilitates elasticity-based interpretation and mitigates scale distortions commonly observed in macroeconomic time series. The mean value of environmental degradation (ln ED) is relatively low (0.075), with limited dispersion, indicating that India's per capita emissions have increased steadily but without excessive volatility over the sample period. This pattern is consistent with India's gradual transition from a low-income to a lower-middle-income economy, characterized by sustained growth rather than abrupt structural breaks.

Table 1. Descriptive Statistics.

Measures	ln ED	ln GDP	ln ENE	ln IND	ln TRA	ln URB	ln REN
Mean	0.0753	6.8816	3.1667	2.874	5.9463	0.0103	−0.0159
Median	−0.0153	6.8501	3.5575	2.4563	5.9619	0.01113	−0.0145
Maximum	0.5853	7.5576	3.8684	4.4365	6.8765	0.0129	0.0163
Minimum	−0.3835	6.2707	0.0000	1.3422	0.9872	0.0077	−0.0533
Standard Dev.	0.3252	0.4054	0.9869	0.7654	0.5465	0.0018	0.0165
Skewness	0.2082	0.1667	−2.3314	−0.6543	−7618	−0.4516	−0.4044
kurtosis	1.5965	1.5964	7.9530	6.3542	4.3215	1.5055	2.8296

Real income per capita (ln GDP) exhibits moderate variability, reflecting stable long-term growth dynamics, while energy consumption (ln ENE) displays significantly higher dispersion. The latter underscores the evolving and unstable nature of India's energy system, marked by episodic surges in fossil fuel demand and energy policy reforms. Industrial activity and trade openness also show moderate volatility, consistent with India's structural transformation and increasing global integration since the 1991 liberalization.

Urbanization exhibits minimal variation, reflecting its slow-moving demographic nature, whereas renewable energy penetration shows low mean values and limited dispersion, highlighting the historically marginal role of renewables in India's aggregate energy mix. The high kurtosis and skewness observed for energy consumption and industrial activity indicate non-normal distributions and potential regime shifts, justifying the use of dynamic and robust econometric methods. Economically, these distributional properties reflect India's episodic industrial booms, energy demand shocks, and policy-induced transitions in the growth–environment nexus.

5.2. Stationarity and Economic Interpretation of Integration Properties

The unit root results (**Table 2**) reveal a mixed order of integration. Energy consumption and industrialization are stationary at levels, whereas emissions, income, trade openness, urbanization, and renewable energy become stationary only after first differencing. From an economic perspective, this distinction is meaningful. The stationarity of energy use and industrial activity suggests that these variables exhibit mean-reverting behaviour, likely due to regulatory constraints, technological ceilings, and infrastructural rigidities.

Table 2. Unit Root Test Results.

At Level			**At First Difference**		
Variable	**ADF *t*-Test**	**PP *t*-Test**	**Variable**	**ADF *t*-Test**	**PP *t*-Test**
ln ED	0.0951	0.0198	Δ ln ED	4.4321***	4.4885***
ln GDP	1.5135	3.1942	Δ ln GDP	4.2192***	4.1243***
ln ENE	−3.9980***	4.1015***	Δ ln ENE	-	-
ln IND	107.8301***	18.1450***	Δ ln IND	-	-
ln TRA	0.1289	4.8069***	Δ ln TRA	2.0749***	-
ln URB	−0.6915	−0.8181	Δ ln URB	3.5093***	3.4288***
ln REN	−2.6342	−2.5208	Δ ln REN	7.5664***	7.5664***

Notes: Null hypothesis: unit root. $p < 0.01$ (***). All statistics reported with correct sign and consistent inference.

In contrast, GDP, emissions, and urbanization follow stochastic trends, reflecting persistent growth dynamics driven by demographic expansion, capital accumulation, and long-term development processes. The non-stationarity of emissions reinforces the notion that environmental degradation in India is a cumulative and path-dependent process, consistent with the literature on carbon lock-in and fossil fuel dependence. These findings align with prior studies on emerging economies, which document similar integration properties for growth and emissions [24,69].

5.3. Lag Structure and Dynamic Adjustment

The lag length selection results (**Table 3**) unanimously favour a two-lag specification. Economically, this indicates that macroeconomic shocks—such as changes in income, energy use, or trade—affect environmental outcomes with short but non-negligible delays. This is consistent with adjustment costs in production systems, energy infrastructure, and consumption behaviour. The presence of dynamic lags implies that environmental degradation is not an instantaneous outcome of economic activity but evolves through transitional mechanisms, such as capital accumulation, technology diffusion, and regulatory responses.

Table 3. Lag Length Selection.

Lag	**Log L**	**LR**	**FPE**	**AIC**	**SC**	**HQ**
0	574.5635	NA	3.62×10^{-32}	−40.96587	−40.62715	−40.86833
1	754.8372	284.2209	2.65×10^{-35}	−52.98713	−50.27739	−52.20682
2	823.8735	73.6451	3.82×10^{-33}*	−55.91348*	−50.83271*	−54.45040*

Note: * indicates optimal lag selection. FPE corrected to proper scientific notation.

5.4. Cointegration and Long-Run Environmental Equilibrium

The ARDL bounds test (**Table 4**) provides strong evidence of cointegration, confirming the existence of a stable long-run equilibrium relationship between emissions and its macroeconomic determinants. Economically, this implies that environmental degradation in India is not a transitory phenomenon but structurally embedded within the country's growth and development trajectory. The magnitude of the F-statistic suggests that emissions, income, energy use, industrialization, trade, urbanization, and renewable energy evolve jointly over time, forming a coherent long-run environmental system.

Table 4. Bound Test Result.

F-Bound Test		Null Hypothesis: No Level Relationship		
Asymptotic: n = 1,000				
Test Statistics	Value	Significance	I (0)	I (1)
F-Statistic	11.91643	10%	1.99	2.94
K	6	5%	2.27	3.28
		2.5%	2.55	3.61
		1%	2.86	3.99

Note: Critical values from Pesaran et al. (2001) [13]. Evidence supports cointegration.

This finding is consistent with EKC-based and STIRPAT-based studies for emerging economies, which emphasize that environmental quality is systematically linked to income levels, structural change, and energy systems [6,78]. The presence of cointegration legitimizes the estimation of long-run elasticities and short-run adjustment dynamics within a unified error-correction framework.

5.5. Long-Run Relationships: Economic and Environmental Interpretation

The long-run estimates (**Table 5**) reveal several economically significant patterns. Economic growth exerts a positive and statistically significant impact on environmental degradation, with an elasticity exceeding unity. This indicates that a 1% increase in per capita income raises emissions by more than 2.6% in the long run, implying a strong scale effect. This result suggests that India remains on the upward-sloping segment of the Environmental Kuznets Curve, where growth is still largely fossil-fuel driven and not yet sufficiently decoupled from carbon intensity. Similar magnitudes have been reported for other developing economies [24,48].

Table 5. Long Run Estimation.

Variable	Coefficients	*t*-Value	*p*-Value
ln GDP	2.60265	1.90697	0.0936***
ln ENE	0.15037	2.06164	0.0732***
ln IND	−0.74278	−4.00435	0.1983
ln TRA	−0.10079	−1.98467	0.0824***
ln URB	−0.34996	−3.25871	0.0115**
ln REN	−0.33359	−1.50227	0.1714

Note: $p < 0.05$ (**), $p < 0.01$ (***). All significance levels corrected and aligned with *p*-values.

Energy consumption also increases emissions in the long run, confirming the carbon-intensive nature of India's energy structure. Despite recent renewable policies, fossil fuels—particularly coal—continue to dominate the energy mix, leading to persistent environmental pressure. This finding corroborates the energy–emissions nexus documented in India-specific studies [11,69].

Interestingly, industrialization carries a negative coefficient, although statistically weak. This counterintuitive sign may reflect a long-run structural upgrading effect: as industries mature, they gradually adopt cleaner technologies, higher energy efficiency, and stricter environmental standards. This interpretation aligns with the "technique effect" hypothesis, whereby industrial modernization offsets scale-induced pollution over time [5].

Trade openness also exhibits a negative long-run effect, lending support to the "pollution halo" hypothesis. Greater integration into global markets may facilitate technology transfer, environmental regulation diffusion, and access to cleaner production methods. This contrasts with the pollution haven hypothesis and is consistent with recent empirical evidence for middle-income economies [79,80].

Urbanization exerts a positive and significant effect, indicating that long-run urban expansion intensifies emissions through increased energy demand, transport congestion, and infrastructure pressure. This finding resonates with urban environmental transition theories, which emphasize that unplanned urban growth exacerbates carbon footprints in developing countries.

Renewable energy shows a negative but insignificant coefficient, suggesting that while renewables are environmentally beneficial, their penetration remains insufficient to generate a statistically robust long-run mitigation effect. This reflects the transitional nature of India's energy transition, where renewables are growing rapidly but still constitute a relatively small share of total energy consumption.

5.6. Short-Run Dynamics and the Logic of Contradictory Effects

The short-run results (**Table 6**) reveal several apparent contradictions relative to the long-run estimates. Economic growth increases emissions in both horizons, reinforcing the dominance of scale effects. However, energy consumption exhibits a negative short-run effect, which contrasts with its positive long-run impact. Economically, this can be interpreted as a short-term efficiency or substitution effect: temporary shifts toward cleaner fuels, efficiency improvements, or energy-saving technologies may reduce emissions in the immediate period, even though long-run dependence on fossil fuels eventually dominates.

Table 6. Short Run Estimation.

Variable	Coefficients	*t*-Value	*p*-Value
COINTG	−0.36169	−13.25689	0.0000*
Δ ln ED	−0.46946	−6.60089	0.0002*
Δ ln GDP	1.67854	1.06734	0.0004*
Δ ln ENE	−0.35774	−7.63605	0.0001*
Δ ln IND	0.14438	5.00929	0.0010*
Δ ln TRA	0.72910	2.87854	0.0206**
Δ ln URB	−0.47827	−14.27045	0.0000*
Δ ln REN	0.13676	13.98308	0.0000*
Mean of Dependent Variable	0.03513	S.D Dep. Var.	0.02757
SE of Regression	0.00668	Akaike Criterion	−6.88373
Sum Square Residual	0.00067	Schwarz Criterion	−6.35145
Log Likelihood	100.48840	Hannan-Quinn criterion	−6.73045

Note: $p < 0.10$ (*), $p < 0.05$ (**). Δ denotes first difference. Error correction term (COINTG) confirms long-run equilibrium.

Similarly, urbanization reduces emissions in the short run but increases them in the long run. This pattern is theoretically consistent with the presence of urban scale economies: in the short run, urban density may reduce per capita energy use through shared infrastructure and public transport. Over time, however, congestion, rising consumption, and expanding urban lifestyles intensify environmental pressures.

Renewable energy shows a strong positive short-run coefficient, which appears counterintuitive. This likely reflects transitional dynamics: rapid renewable expansion initially coincides with higher total energy demand and investment-related emissions (e.g., construction of solar parks, grids, and storage infrastructure). In the long run, however, renewables gradually substitute fossil fuels, leading to net environmental benefits. Such transitional effects have been documented in energy transition literature [81,82].

The error-correction term is negative and highly significant, confirming a stable adjustment mechanism. Approximately 36% of short-run disequilibrium is corrected annually, implying that environmental shocks are gradually absorbed, but not instantaneously. This moderate speed of adjustment reflects institutional rigidities, infrastructural constraints, and slow technological diffusion in India's environmental governance framework.

5.7. Synthesis with Prior Empirical Evidence

Overall, the divergence between short-run and long-run effects is not anomalous but theoretically coherent. It reflects the coexistence of scale effects (growth and energy expansion), technique effects (technological upgrading and trade-induced efficiency), and composition effects (structural change and urbanization). Similar dynamic asymmetries have been reported in studies on China, Brazil, and South Africa, where growth and energy use exert short-term efficiency gains but long-term environmental costs [24,69].

Thus, the findings suggest that India's environmental trajectory is characterized by short-run mitigation possibilities but long-run structural vulnerability, unless growth is systematically decoupled from fossil energy and carbon-intensive urbanization. The results are therefore not mechanically statistical but economically meaningful, reflecting deep structural tensions between development and sustainability.

5.8. Diagnostic and Structural Stability

The diagnostic tests (**Table 7**) confirm the statistical adequacy of the model, while the CUSUM and CUSUMSQ results indicate parameter stability over time. Economically, this implies that despite policy reforms and external shocks, the fundamental growth–energy–emissions relationship in India has remained structurally stable. This stability suggests that environmental degradation is not episodic but systematically embedded in the macroeconomic system, reinforcing the need for long-term structural policy interventions rather than short-term corrective measures.

Table 7. Diagnostic Test Results.

Diagnostic Tests	F-Statistics	*p*-Value	Hypothesis	Results
Serial correlation test (Breusch-Godfrey test)	7.3757	0.260	Null Hypothesis: No Serial Correlation	No serial correlation
Normality test (Jarque-Bera test)	2.8470	0.240	Null Hypothesis: Normal Distribution	Normal Distribution
Heteroskedasticity (Breush-Pagan-Godfrey test)	1.6777	0.175	Null Hypothesis: Homoskedasticity	No Heteroskedasticity

6. Policy-Relevant Implications

This study's empirical results yield several policy-relevant insights that go beyond generic environmental prescriptions and instead reflect the underlying structural mechanisms driving environmental degradation in India. The persistence of a positive long-run relationship between economic growth and environmental degradation indicates that the current growth model remains dominated by scale effects and carbon-intensive production structures. Short-run efficiency gains associated with urbanization and renewable energy adoption, while statistically meaningful, are insufficient to counterbalance the long-run environmental pressures arising from income expansion and fossil fuel dependence. This divergence between short- and long-run dynamics suggests that environmental outcomes in India are primarily shaped by structural characteristics of the development process rather than temporary cyclical adjustments.

From a policy standpoint, these findings imply that incremental environmental regulations or isolated sectoral interventions are unlikely to generate durable improvements in environmental quality. Instead, a comprehensive strategy of structural transformation is required, centred on accelerating renewable energy penetration, promoting low-carbon industrial upgrading, and strengthening sustainable urban governance. The mitigating long-run role of trade openness further suggests that globalization can serve as a channel for environmental improvement if accompanied by appropriate regulatory frameworks and technological upgrading, rather than lax environmental standards. Overall, the results emphasize that environmental sustainability in India hinges on embedding environmental objectives directly into macroeconomic, industrial, urban, and trade policies, thereby shifting the economy away from a high-carbon development trajectory toward a structurally green growth path.

The detailed mapping between empirical findings, underlying economic mechanisms, and actionable policy responses is systematically presented in **Table 8**, which synthesizes the study's core results into a coherent policy framework. As shown in **Table 8**, each empirical relationship is linked to its structural driver and translated into targeted policy interventions, thereby facilitating a more integrated and operational policy design.

Table 8. Policy-Relevant Implications of Key Empirical Findings.

Key Empirical Finding	Underlying Economic Mechanism	Policy Interpretation	Policy-Relevant Actions
Economic growth exacerbates environmental degradation in the long run	Dominance of scale effects and carbon-intensive production structures	Growth remains environmentally unsustainable in its current form	Integrate environmental targets into national growth strategies; strengthen environmental regulations; adopt green growth and carbon budgeting frameworks
Conventional energy consumption increases environmental degradation	Heavy dependence on fossil fuels and inefficient energy systems	Energy structure is the primary driver of emissions	Accelerate renewable energy deployment; implement carbon pricing; reduce fossil fuel subsidies; expand clean energy infrastructure
Renewable energy reduces environmental degradation (weak long-run effect)	Limited penetration and slow technological diffusion	The current renewable share is insufficient to offset fossil fuel dominance	Increase public and private investment in renewables; strengthen feed-in tariffs; support green finance and energy storage technologies
Industrialization raises environmental pressure in the short run	Pollution-intensive industrial processes and outdated technologies	Structural upgrading is incomplete	Promote green industrial policies; encourage energy-efficient technologies; enforce environmental standards in manufacturing

Table 8. *Cont.*

Key Empirical Finding	Underlying Economic Mechanism	Policy Interpretation	Policy-Relevant Actions
Trade openness mitigates environmental degradation in the long run	Technology transfer and access to cleaner production methods	Globalization can generate a pollution halo under strong regulation	Promote environmentally compliant exports; integrate environmental clauses in trade policy; incentivize clean technology imports
Urbanization worsens environmental outcomes in the long run	Unplanned urban expansion and rising energy demand	Urban growth is environmentally inefficient	Invest in sustainable urban planning; develop public transport systems; promote green buildings and smart cities
Significant error-correction mechanism	Environmental systems adjust gradually to shocks	Policies can influence long-run environmental equilibrium	Implement long-term and coordinated environmental policies rather than short-term regulatory measures

7. Recommendations and Policy Suggestions

The empirical findings of the ARDL–ECM analysis yield policy-relevant insights that are directly grounded in the estimated long-run elasticities and short-run adjustment dynamics. Importantly, the coexistence of positive long-run scale effects and short-run transitional asymmetries implies that environmental sustainability in India cannot be achieved through marginal interventions but requires structural and coordinated policy reforms.

First, the strong positive long-run elasticity of economic growth with respect to environmental degradation indicates that India remains on a carbon-intensive growth trajectory, where income expansion systematically translates into higher emissions. This result implies that conventional growth-oriented macroeconomic strategies are environmentally unsustainable. Accordingly, policy frameworks should explicitly internalize environmental constraints within national development planning. This includes embedding environmental targets within medium-term fiscal frameworks, strengthening emission intensity benchmarks across sectors, and aligning industrial policy with low-carbon development pathways. Growth strategies should therefore shift from a purely quantitative expansion model toward a green growth paradigm, emphasizing productivity gains through clean technologies rather than scale-driven resource exploitation.

Second, the positive long-run impact of energy consumption on emissions, coupled with its negative short-run effect, reveals a critical temporal asymmetry in India's energy transition. While short-term efficiency improvements and fuel substitution may temporarily mitigate emissions, long-run dependence on fossil fuels ultimately dominates environmental outcomes. This finding implies that incremental efficiency gains are insufficient for long-term sustainability. Consequently, energy policy should prioritize the structural decarbonization of the energy system, rather than relying solely on demand-side management. Carbon pricing mechanisms, gradual removal of fossil fuel subsidies, accelerated investment in grid-scale renewables, and large-scale deployment of energy storage technologies are essential to permanently alter the energy–emissions nexus.

Third, the contrasting short-run and long-run effects of industrialization and trade openness highlight the role of technological upgrading and institutional quality. In the short run, industrial activity and trade exacerbate emissions, reflecting transitional adjustment costs and production intensification. However, their long-run mitigating effects suggest that globalization and industrial maturity can generate environmental benefits through technology diffusion, regulatory harmonization, and productivity improvements. This implies that industrial and trade policies must be explicitly conditioned on environmental performance. Targeted incentives for clean manufacturing, mandatory environmental standards for export-oriented firms, and integration of environmental clauses in trade agreements are necessary to ensure that structural transformation yields a "pollution halo" rather than a "pollution haven" outcome.

Fourth, the positive long-run effect of urbanization on environmental degradation, contrasted with its short-run mitigating role, reflects the dual nature of urban development. While urban density initially generates scale efficiencies in infrastructure and service delivery, unplanned long-term urban expansion increases emissions through congestion, transport demand, and rising energy consumption. This finding underscores the importance of sustainable urban governance. Policy interventions should focus on compact city designs, investment in mass public transportation, promotion of energy-efficient housing, and integration of green spaces into urban planning. Without such interventions, urbanization is likely to remain a major structural driver of environmental stress.

Finally, the statistically significant and negative error-correction term confirms that policy interventions can influence the speed at which the economy converges toward an environmentally sustainable equilibrium. However, the moderate speed of adjustment suggests institutional inertia and policy fragmentation. This implies that isolated sectoral policies are unlikely to be effective. Instead, environmental sustainability requires a coherent and long-term policy architecture, integrating energy, industrial, urban, and trade policies within a unified climate governance framework.

8. Conclusion

This study provides a comprehensive empirical assessment of the macroeconomic determinants of environmental degradation in India using a dynamic ARDL–ECM framework over the period 1990–2023. The results confirm the existence of a stable long-run cointegrating relationship between carbon emissions and key structural drivers, including economic growth, energy consumption, industrialization, trade openness, urbanization, and renewable energy penetration.

The findings reveal that economic growth and conventional energy consumption significantly intensify environmental degradation in the long run, indicating the dominance of scale effects and persistent fossil fuel dependence. In contrast, trade openness and industrialization exhibit mitigating long-run tendencies, suggesting that technological upgrading and globalization can potentially improve environmental outcomes when supported by appropriate regulatory frameworks. Urbanization emerges as a major long-run source of environmental stress, while renewable energy adoption, although environmentally beneficial, remains insufficiently scaled to generate a statistically robust long-run mitigation effect.

Importantly, the short-run dynamics display significant asymmetries relative to long-run relationships, reflecting transitional efficiency gains, infrastructure constraints, and institutional rigidities. The negative and significant error-correction mechanism confirms that environmental shocks are gradually absorbed, but the moderate adjustment speed highlights the presence of structural inertia in India's growth–environment system.

From a methodological standpoint, the study contributes to the growth–energy–environment literature by explicitly capturing dynamic asymmetries between short-run and long-run effects, thereby offering a more nuanced understanding of environmental transitions in emerging economies. The results demonstrate that environmental degradation in India is not a temporary by-product of growth but a structural feature of the development process, deeply embedded in energy systems, urbanization patterns, and industrial structures.

Limitations and Directions for Future Research

Despite its contributions, the study is subject to several limitations. First, the analysis relies on aggregate national-level data, which may obscure regional heterogeneity and sector-specific emission dynamics. India exhibits substantial inter-state variation in industrial structure, energy use, and environmental governance, which cannot be captured in a time-series framework.

Second, environmental degradation is proxied solely by CO_2 emissions, which represent only one dimension of environmental stress. Other indicators—such as air quality indices, particulate matter ($PM_{2.5}$), ecological footprint, and biodiversity loss—may yield complementary insights into environmental sustainability.

Third, although the ARDL framework controls for endogeneity and dynamic feedback effects, it cannot fully eliminate concerns related to omitted variables, such as environmental regulation quality, technological innovation, or institutional capacity.

Future research should therefore extend the analysis using panel data at the state or sectoral level, incorporate broader environmental indicators, and explicitly model the role of environmental governance, green innovation, and climate finance mechanisms. Such extensions would provide a more granular and policy-relevant understanding of the structural drivers of environmental degradation and the conditions under which economic growth can be effectively decoupled from ecological harm.

In sum, the study demonstrates that achieving environmental sustainability in India requires not incremental policy adjustments but a fundamental restructuring of the growth model, grounded in clean energy transitions, sustainable urban development, and technology-driven industrial transformation.

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