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Macroeconomic Dynamics of Environmental Degradation in India: Evidence and Limits of Structural Transition Toward Sustainability

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ABSTRACT: Understanding the macroeconomic determinants of environmental degradation is critical for designing effective and evidence-based sustainability policies in emerging economies. This study provides a comprehensive empirical re-examination of the growth–energy–environment nexus in India over the period 1990–2023 within an extended macroeconomic framework. It integrates key structural drivers—economic growth, energy consumption, industrialization, trade openness, urbanization, and renewable energy—into a unified analytical model to capture the complex interactions between development processes and environmental outcomes. Methodologically, the study employs the Autoregressive Distributed Lag (ARDL) bounds testing approach within an error-correction framework, allowing for the estimation of both long-run equilibrium relationships and short-run dynamic adjustments under mixed orders of integration. The robustness of long-run estimates is further assessed using alternative cointegration techniques, while diagnostic and stability tests ensure the reliability of the empirical specification. The results confirm the presence of a stable long-run cointegrating relationship among the variables. However, the estimated long-run elasticities are heterogeneous and generally weak in statistical strength. Economic growth and energy consumption exhibit positive but modest associations with environmental degradation, indicating the persistence of scale effects and structural dependence on fossil fuel–based energy systems. In contrast, the effects of trade openness and industrialization are not statistically robust, suggesting that structural transformation and globalization have not yet translated into consistent environmental efficiency gains. Renewable energy does not demonstrate a significant long-run mitigating effect, reflecting its limited penetration and integration within the broader energy system. Short-run dynamics reveal asymmetric adjustment patterns. Energy consumption shows a negative and significant short-run effect, implying transitional efficiency gains, whereas industrialization contributes positively to environmental pressure in the short term. Urbanization exhibits divergent temporal effects, with short-run improvements but long-run environmental costs. The significant error-correction term indicates gradual convergence toward equilibrium. Overall, the findings highlight a nuanced and evolving relationship between macroeconomic processes and environmental degradation in India, underscoring the need for structurally aligned and context-specific policy interventions.

Keywords: Environmental degradation; Economic growth; Energy consumption; Renewable energy; Trade openness; Urbanization; Industrialization; ARDL bounds testing; India

1. Introduction

Environmental degradation has increasingly emerged as a structural constraint on sustainable development, particularly in emerging economies undergoing rapid economic and demographic transformation. The expansion of economic activity—driven by industrialization, urbanization, and rising energy demand—has generated substantial gains in income, productivity, and welfare. However, these processes have simultaneously intensified pressures on ecological systems through rising greenhouse gas emissions, deteriorating air and water quality, and accelerated depletion of natural resources [1,2]. These developments raise fundamental concerns regarding the long-run compatibility between economic growth and environmental sustainability. Consequently, the integration of environmental objectives into development planning—often articulated within broader paradigms of ecological transformation or "ecological civilization"—has become a central focus of both policy discourse and academic inquiry. Recent contributions in Ecological Civilization emphasize that environmental outcomes are increasingly shaped by policy-driven governance frameworks, institutional quality, and coordinated sustainability transitions rather than by passive income dynamics alone [3–5].

India represents a particularly important empirical context for examining these dynamics. As one of the fastest-growing major economies, the country has undergone profound structural changes since the early 1990s, including economic liberalization, industrial expansion, rapid urbanization, and increasing integration into global markets. These transformations have been accompanied by a sustained increase in energy demand, largely met through fossil fuel–based sources, thereby contributing to a steady rise in carbon emissions. At the same time, India faces significant environmental vulnerabilities, including severe urban air pollution, water scarcity, land degradation, and heightened exposure to climate-related risks [6,7]. The coexistence of strong developmental imperatives and escalating ecological pressures necessitates a systematic and macroeconomically grounded analysis of the determinants of environmental degradation within a long-run structural framework, particularly in light of emerging evidence that institutional and policy variables critically mediate the growth–environment relationship [3,4].

From a theoretical standpoint, the relationship between economic development and environmental outcomes has been extensively debated. Early perspectives emphasized a direct trade-off between growth and environmental quality, while the Environmental Kuznets Curve (EKC) hypothesis introduced a nonlinear framework, positing that environmental degradation may eventually decline beyond a certain income threshold due to structural transformation, technological progress, and strengthened regulatory institutions [8,9]. However, empirical evidence on the EKC remains mixed, context-dependent, and often sensitive to model specification, particularly in rapidly transforming economies characterized by evolving institutional and policy environments. More recent literature, including studies published in Ecological Civilization, critiques the EKC for its limited capacity to capture policy-driven ecological transitions and highlights the role of state-led environmental governance, green finance, and institutional reforms in shaping environmental trajectories [3–5].

In response to these limitations, contemporary research has shifted toward a broader macroeconomic and structural perspective, recognizing that environmental degradation is the outcome of multiple interrelated drivers. Energy consumption—especially from carbon-intensive sources—remains a primary determinant of emissions [10], while trade openness influences environmental outcomes through scale, composition, and technique effects that depend on regulatory quality and technological capability [11]. Urbanization introduces additional complexity by generating both efficiency gains through agglomeration economies and environmental pressures through congestion, infrastructure deficits, and rising resource demand [12]. Similarly, industrialization reflects a dynamic process in which early-stage expansion is typically pollution-intensive, whereas later stages may involve technological upgrading and efficiency improvements. Importantly, recent evidence underscores the role of green finance and institutional quality in mediating these relationships, particularly in emerging Asian economies undergoing sustainability transitions [4,5].

Despite a growing body of empirical work, evidence for India remains fragmented and, in several cases, methodologically constrained. A substantial portion of the existing literature focuses narrowly on the growth–emissions nexus or on testing the EKC hypothesis, often relying on limited variable sets and static econometric frameworks [13,14]. Such approaches provide only partial insights into the underlying mechanisms and frequently overlook the dynamic interactions among macroeconomic variables. Moreover, many studies impose restrictive assumptions regarding integration properties or fail to distinguish between long-run equilibrium relationships and short-run adjustment dynamics adequately. These limitations are particularly consequential in the Indian context, where structural changes, policy interventions, and external shocks have significantly altered the growth–environment relationship over time.

From a methodological perspective, there is a clear need for empirical approaches capable of accommodating mixed orders of integration, small-sample properties, and dynamic adjustment processes. The autoregressive distributed lag (ARDL) framework addresses these requirements by enabling the simultaneous estimation of long-run relationships and short-run dynamics within a unified error-correction structure, while maintaining flexibility with respect to the integration properties of the variables [15]. This makes it particularly well-suited for analyzing evolving macroeconomic–environment linkages in India over an extended time horizon.

Against this backdrop, the present study provides a comprehensive and updated empirical assessment of the macroeconomic determinants of environmental degradation in India over the period 1990–2023. Environmental degradation is proxied by CO_2 emissions, capturing climate-related environmental pressure, and is examined in relation to key macroeconomic variables, including economic growth, energy consumption, industrialization, trade openness, urbanization, and renewable energy use. By employing an ARDL–error correction model (ECM) framework [16], the analysis explicitly distinguishes between long-run structural relationships and short-run adjustment processes, thereby enabling a more nuanced and empirically grounded interpretation of the growth–energy–environment nexus.

The contribution of this study is threefold. First, it integrates multiple macroeconomic drivers within a coherent and theoretically informed empirical framework, moving beyond the narrow focus of earlier studies. Second, it explicitly accounts for dynamic and asymmetric relationships, emphasizing the distinction between short-run transitional effects and long-run structural linkages. Third, it adopts a cautious and methodologically rigorous approach to inference, avoiding overgeneralization and recognizing the inherent limitations of aggregate time-series analysis.

Overall, the study contributes to the evolving literature on ecological sustainability and green transformation by providing a structurally grounded and policy-relevant analysis of how macroeconomic processes interact with environmental outcomes in a large and rapidly transforming economy. In doing so, it offers important insights into the extent to which India’s development trajectory is aligned with the objectives of environmentally sustainable and low-carbon growth.

2. Literature Review

A substantial and rapidly expanding body of literature has examined the determinants of environmental degradation across theoretical, empirical, and policy-oriented dimensions. This section provides a structured and updated synthesis of the literature with explicit incorporation of (i) post-2020 advances in ecological civilization and sustainability transitions, and (ii) a comparative analytical perspective between India and China—two major emerging economies with distinct but increasingly convergent transformation pathways.

2.1. Global Evidence on Macroeconomic Drivers of Environmental Degradation

The analytical foundation of the growth–environment nexus originates from the Environmental Kuznets Curve (EKC) hypothesis, which posits a non-linear (inverted U-shaped) relationship between income and environmental degradation [8]. While early cross-country studies supported this hypothesis [17,18], more recent evidence using advanced econometric techniques has produced heterogeneous and pollutant-specific outcomes, thereby questioning its generalizability [19,20].

Contemporary literature increasingly moves beyond EKC toward structurally grounded frameworks, emphasizing the role of macroeconomic drivers such as energy consumption, trade openness, and financial development. Fossil fuel–based energy consumption remains the most consistent determinant of environmental degradation globally [21,22], whereas renewable energy deployment contributes significantly to emission mitigation, conditional on policy and institutional support [23].

Trade openness and financial development exhibit theoretically ambiguous and empirically mixed effects. While trade may facilitate technology transfer and efficiency gains [24], it can also reinforce pollution-intensive specialization [25]. Similarly, financial development can either promote green investment or intensify resource use depending on regulatory structures [26–28]. Recent studies extend this framework by incorporating green finance instruments, which are increasingly recognized as critical enablers of low-carbon transitions [29,30].

2.2. Green Finance and Climate Finance: Emerging Evidence (Post-2020)

Following the Paris Agreement, the literature on green and climate finance has expanded significantly. Green finance encompasses financial mechanisms that channel capital toward environmentally sustainable activities, including renewable energy, energy efficiency, and climate-resilient infrastructure [29].

Recent empirical studies (2020–2024) demonstrate that green bonds, sustainable banking, and climate funds are associated with measurable reductions in carbon intensity and improvements in environmental performance [31,32]. Institutional frameworks—such as the Green Climate Fund and evolving carbon markets—play a pivotal role in mobilizing large-scale investment [33,34].

However, the literature remains limited by aggregation biases, insufficient sectoral disaggregation, and a lack of country-specific time-series analyses—particularly for large emerging economies such as India.

2.3. Asian Context (Post-2015): Ecological Civilization, Energy Transition, and Policy Innovation

The Asian literature on environmental sustainability has undergone a substantive transformation in the post-2015 period, reflecting the increasing centrality of policy-driven ecological transitions, energy system restructuring, and institutional innovation. Recent contributions (2020–2024) explicitly emphasize the role of integrated governance frameworks in shaping environmental outcomes, moving beyond conventional income-driven explanations. In particular, emerging scholarship on China's ecological transformation—such as [35–39]—demonstrates that environmental performance is increasingly determined by institutional design, policy coherence, and state capacity rather than passive structural change.

A central theme in the post-2015 literature is the transition toward low-carbon energy systems. Recent empirical studies (post-2020) provide robust evidence that the expansion of renewable energy capacity—particularly solar and wind—has contributed to emissions mitigation across Asian economies, although its overall effectiveness remains moderated by persistent dependence on coal and rising aggregate energy demand [32–34]. This body of work highlights that the environmental benefits of renewable energy are conditional upon complementary institutional factors, including regulatory quality, financial development, and technological innovation.

China's experience represents a particularly important case of policy-driven environmental transformation. Large-scale interventions—such as anti-smog regulations and the national emissions trading system—have generated measurable improvements in air quality, emission intensity, and firm-level technological upgrading [40–42]. These findings underscore the effectiveness of combining command-and-control regulation with market-based instruments within a coordinated policy framework.

A defining feature of the contemporary Asian discourse is the institutionalization of sustainability through the Ecological Civilization paradigm. This framework integrates environmental objectives into macroeconomic planning, fiscal policy, and governance structures, thereby reconfiguring the relationship between growth and environmental sustainability [43–45]. Recent studies demonstrate that ecological civilization has contributed to improvements in environmental quality, green innovation, and public health outcomes, while maintaining economic growth trajectories [35–39].

In parallel, the literature highlights the growing importance of green finance in supporting the energy transition. Empirical evidence indicates that green credit policies, sustainable banking frameworks, and green bond markets have facilitated investment in renewable energy and environmentally sustainable technologies across Asia [46,47]. However, cross-country analyses reveal substantial heterogeneity in transition pathways, reflecting differences in institutional capacity, policy coordination, and financing constraints [48].

Despite these advances, several limitations persist. Existing studies are often confined to single-country or sector-specific analyses, limiting generalizability. Furthermore, the integration of policy innovations—such as emissions trading systems, ecological governance frameworks, and green finance—into comprehensive macroeconomic models remains limited. There is also insufficient attention to the dynamic interactions among energy transition, financial development, and traditional macroeconomic drivers such as trade openness and urbanization.

2.4. Comparative Perspective: India and China's Transformation Pathways

A dedicated comparative assessment of India and China—two structurally significant emerging economies with divergent yet increasingly interconnected environmental transition trajectories—provides critical insights into the role of institutional design, policy coherence, and macroeconomic structures in shaping environmental outcomes.

China's transformation is characterized by a state-led and institutionally coordinated approach to environmental governance. The formal integration of Ecological Civilization into national development strategy has enabled the alignment of environmental objectives with industrial policy, fiscal instruments, and technological upgrading. Empirical studies demonstrate that this integrated framework has contributed to measurable reductions in emission intensity, improvements in environmental quality, and accelerated diffusion of green technologies [37,49,50]. Furthermore, the large-scale deployment of renewable energy and the operationalization of market-based instruments such as the Chinese Emissions Trading System have reinforced China's transition toward a lower-carbon development pathway [51,52].

In contrast, India's environmental transition is characterized by a more decentralized and market-oriented policy framework, reflecting its federal governance structure and developmental priorities. While India has achieved significant progress in expanding renewable energy capacity, this expansion has not been matched by equivalent levels of institutional integration, grid modernization, or policy coordination. Continued reliance on coal-based energy, coupled with evolving but still nascent green finance mechanisms, constrains the pace and effectiveness of environmental transition.

Recent comparative studies explicitly examining India–China dynamics (2020–2024) provide systematic evidence of these divergences. For instance, studies [35,53] show that China's coordinated policy architecture has facilitated faster reductions in carbon intensity relative to India. Similarly, further study [54] highlights the role of institutional capacity and regulatory enforcement in enhancing environmental performance in China, while identifying governance fragmentation and financing constraints as key limitations in India's transition pathway. It was further demonstrated [55] that India's energy transition remains constrained by structural dependencies on fossil fuels and infrastructure bottlenecks, despite policy commitments toward decarbonization.

This comparative evidence indicates that China's integrated and state-driven approach has yielded relatively faster and more consistent improvements in environmental outcomes, whereas India's transition remains gradual, uneven, and structurally mediated. The divergence underscores the importance of policy coherence, institutional capacity, and governance effectiveness in shaping the macroeconomic environment nexus.

From an analytical perspective, this comparison reinforces that environmental outcomes are not solely determined by income levels or market forces, but are critically shaped by institutional frameworks and policy regimes. While China exemplifies a coordinated model of ecological transformation, India's pathway reflects a more incremental transition influenced by macroeconomic constraints, energy security considerations, and evolving governance structures.

2.5. Renewable Energy Transition and Investment Frameworks

Renewable energy transition is central to global climate mitigation strategies. Theoretical frameworks emphasize structural transformation, technological innovation, and investment mobilization as key drivers [56].

Empirical studies confirm that renewable energy investment reduces emissions, particularly when supported by stable policy regimes and financial incentives [29,57,58]. However, global assessments indicate that investment levels remain insufficient to meet climate targets, necessitating significant scaling-up through public–private partnerships [59].

A major limitation in the literature is the lack of integration between renewable energy dynamics and broader macroeconomic variables within unified econometric frameworks.

2.6. India's Carbon Neutrality Commitments and Policy Context

India's commitment to achieving net-zero emissions by 2070 and its "Panchamrit" targets under international climate frameworks have intensified scholarly attention [60].

Recent studies emphasize the importance of renewable energy expansion, energy efficiency improvements, and emerging technologies such as green hydrogen in achieving these targets [61–65]. However, empirical analyses linking these commitments to macroeconomic determinants remain limited, particularly within time-series frameworks.

2.7. Global Climate Governance and Institutional Frameworks

Global climate governance provides the overarching institutional context for national environmental policies. The Paris Agreement established legally binding commitments through nationally determined contributions (NDCs) [66].

Complementary frameworks, including the Sustainable Development Goals, integrate environmental sustainability into development planning [67].

Despite their importance, these institutional factors are rarely incorporated explicitly into econometric analyses, representing a significant gap in the literature.

2.8. Synthesis and Research Gaps

The revised literature review identifies the following critical gaps:

- Conceptual gap: Limited integration of ecological civilization, green finance, and macroeconomic drivers within a unified analytical framework.
- Empirical gap: Lack of country-specific, time-series evidence for India incorporating multiple macroeconomic determinants.
- Comparative gap: Insufficient analysis of divergent transition pathways between India and China.

- Policy gap: Weak integration of climate commitments and institutional frameworks into empirical models.
- Methodological gap: Limited use of dynamic models capturing short-run and long-run adjustments.

Addressing these gaps, the present study adopts a multivariate ARDL framework to examine both long-run equilibrium relationships and short-run dynamics between environmental degradation and macroeconomic determinants in India. By explicitly incorporating insights from ecological civilization, energy transition, and comparative development pathways, the study provides a more integrated, contemporary, and policy-relevant contribution to the literature on environmental sustainability in emerging economies.

3. Macroeconomic Determinants of Environmental Degradation in India

Environmental degradation in India is intrinsically linked to the country's macroeconomic structure, growth trajectory, and development strategy. Since the onset of economic liberalization in the early 1990s, India has undergone a rapid structural transformation characterized by sustained economic growth, industrial expansion, urbanization, and deeper global integration. While these processes have significantly enhanced income levels and reduced poverty, they have simultaneously intensified pressures on environmental systems through increased energy consumption, resource extraction, and pollution generation.

Recent empirical and theoretical contributions increasingly conceptualize environmental degradation not merely as a technological or regulatory failure, but as an outcome of underlying macroeconomic processes and structural dynamics [68–70]. In this context, environmental outcomes are shaped by the interaction between scale effects (expansion of economic activity), composition effects (sectoral transformation), and technique effects (technological change and regulatory interventions). This section provides a systematic and analytically grounded examination of 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 remains a central determinant of environmental degradation, primarily through scale effects associated with increased production and consumption. In the Indian context, sustained growth has generated rising demand for energy, infrastructure, land, and natural resources, thereby contributing to higher levels of carbon emissions, deforestation, and waste generation [71,72]. These effects have been particularly pronounced during phases of accelerated industrial and infrastructure development.

However, the growth–environment relationship is inherently non-linear. The Environmental Kuznets Curve (EKC) hypothesis posits an inverted U-shaped relationship, whereby environmental degradation initially increases with income but declines beyond a threshold level due to structural transformation, technological advancement, and improved regulatory frameworks [8,9]. Empirical evidence for India, however, remains inconclusive and pollutant-specific. While EKC-type dynamics have been observed for certain local pollutants (e.g., SO_2 and PM2.5), most studies report a monotonic positive relationship between income and CO_2 emissions [73–75].

This suggests that India has not yet reached the income threshold required for absolute decoupling of economic growth from carbon emissions. The persistence of energy-intensive growth patterns indicates that scale effects continue to dominate technique and composition effects, limiting the environmental gains from economic development.

3.2. Energy Consumption and Emission Intensity

Energy consumption constitutes the most direct and robust macroeconomic driver of environmental degradation in India. The country's energy system remains heavily reliant on fossil fuels, particularly coal, which dominates electricity generation and industrial energy use. Consequently, energy-related activities account for the largest share of India's CO_2 emissions [76].

Empirical studies consistently demonstrate a strong and statistically significant positive relationship between energy consumption and environmental degradation, irrespective of the indicator employed (CO_2 emissions, ecological footprint, or particulate matter) [77,78]. This relationship reflects both the scale of energy demand and the carbon intensity of the energy mix.

Although India has made notable progress in expanding renewable energy capacity, the overall energy transition remains incomplete. The continued dominance of fossil fuels, combined with rising per capita energy demand, implies that improvements in energy efficiency have not been sufficient to offset the environmental impacts of economic expansion. Thus, the elasticity of emissions with respect to energy consumption remains high, underscoring the centrality of energy transition policies in mitigating environmental degradation.

3.3. Industrialization and Structural Transformation

Industrialization represents a key channel through which macroeconomic transformation influences environmental outcomes. The expansion of manufacturing, construction, and extractive industries has contributed significantly to emissions, industrial waste, and resource depletion. While structural transformation from agriculture to industry and services is a hallmark of economic development, India's industrial growth has often been characterized by limited technological upgrading and weak environmental compliance.

A notable feature of India's industrial structure is the predominance of small and medium enterprises (SMEs), many of which operate with outdated technologies and low energy efficiency. This results in disproportionately high emission intensities relative to output. Empirical evidence indicates a positive and significant association between industrial value added and environmental degradation, particularly in terms of carbon emissions and ecological footprint [79].

From a structural perspective, the composition effect of industrialization in India has not yet shifted sufficiently toward cleaner and high-value-added sectors. As a result, industrial expansion continues to reinforce environmental pressures rather than contributing to their mitigation.

3.4. Urbanization and Environmental Stress

Urbanization is a critical demographic and spatial dimension of environmental degradation. Rapid urban population growth has increased demand for housing, transportation, energy, and public services, thereby intensifying environmental externalities such as air and water pollution, congestion, and solid waste accumulation [80].

Empirical studies for India indicate that urbanization exerts a positive and statistically significant effect on CO_2 emissions and particulate matter concentrations [81,82]. This reflects the concentration of energy-intensive economic activities, increased reliance on motorized transport, and infrastructure deficits in rapidly expanding urban areas.

Moreover, unplanned urban expansion has led to the conversion of ecologically sensitive land, including forests, wetlands, and agricultural areas, thereby reducing environmental resilience and increasing vulnerability to climate-related risks such as flooding and heat stress. While urbanization generates productivity gains through agglomeration economies, these benefits are often offset by environmental costs in the absence of effective urban planning and regulatory frameworks.

3.5. Trade Openness and Global Integration

Trade liberalization and global economic integration have introduced additional complexity into the growth–environment nexus. Trade openness affects environmental outcomes through three principal channels: scale effects (expansion of economic activity), composition effects (changes in industrial structure), and technique effects (technology transfer and efficiency improvements) [11].

The empirical evidence for India suggests that the net environmental impact of trade openness is predominantly adverse. Several studies find that trade liberalization has contributed to increased CO_2 emissions and ecological footprint, driven by the expansion of energy-intensive manufacturing and resource-based exports [83,84]. This is consistent with the "pollution haven" hypothesis, which posits that countries with relatively weaker environmental regulations may attract pollution-intensive industries.

However, there is also evidence that foreign direct investment (FDI) and trade-related technology transfer can improve energy efficiency and reduce emission intensity in certain sectors [85]. The overall impact of trade openness, therefore, depends on the balance between scale and technique effects. In the Indian context, the dominance of scale effects suggests that the environmental costs of trade have outweighed its potential efficiency gains.

3.6. Fiscal Policy, Public Investment, and Environmental Outcomes

Fiscal policy constitutes a critical institutional mechanism influencing environmental outcomes through both expenditure and taxation channels. Public investment in infrastructure, energy, and industrial development can stimulate economic growth but may also exacerbate environmental degradation if sustainability considerations are not adequately integrated.

Historically, various subsidies—particularly for fossil fuels, fertilizers, and irrigation—have distorted price signals, encouraged overconsumption of natural resources, and contributed to environmental stress in India [86]. These distortions have reinforced carbon-intensive production and consumption patterns.

Conversely, fiscal instruments such as environmental taxation, green subsidies, and public investment in renewable energy and pollution control can play a significant role in mitigating environmental degradation. Empirical evidence indicates that green public expenditure and environmental taxes are associated with reductions in CO_2 emissions and ecological footprint [87,88].

The effectiveness of fiscal policy, however, is contingent upon institutional capacity, policy coherence, and the alignment of macroeconomic objectives with environmental sustainability. In the absence of coordinated policy frameworks, fiscal interventions may yield limited environmental benefits.

3.7. Synthesis of Macroeconomic Drivers

The macroeconomic determinants of environmental degradation in India reflect a complex and dynamic interaction between growth processes, structural transformation, and policy frameworks. Economic growth, energy consumption, industrialization, and urbanization exert strong positive pressures on environmental systems, primarily through scale and composition effects. In contrast, policy instruments—particularly renewable energy expansion and green fiscal measures—offer potential pathways for mitigating these effects.

The empirical literature [89–98] consistently indicates that India's current development trajectory remains environmentally intensive, with limited evidence of absolute decoupling between economic growth and environmental degradation. This underscores the need for a structural transition toward a low-carbon growth model, supported by technological innovation, energy transition, and coherent policy frameworks.

A comprehensive understanding of these macroeconomic linkages is therefore essential for designing development strategies that reconcile economic growth with environmental sustainability, particularly in the context of India's long-term climate commitments and evolving green transformation agenda.

4. Data and Methodology

4.1. Data Sources, Variable Definition, and Theoretical Framework

This study employs annual time-series data for India over the period 1990–2023 to examine the macroeconomic determinants of climate-related environmental pressure. The empirical specification is grounded in a theoretically integrated framework that moves beyond conventional reduced-form approaches and aligns with contemporary literature on environmental macroeconomics and sustainability transitions.

4.1.1. Conceptual Framework: Beyond EKC Toward Green Transformation

While the Environmental Kuznets Curve (EKC) hypothesis provides an initial heuristic linking income growth and environmental pressure, its empirical instability and limited capacity to incorporate institutional and policy dynamics are well documented. Accordingly, the EKC is not treated as a deterministic framework in this study; rather, it is retained in a reduced-form sense to capture potential non-linear income effects, while the broader specification explicitly incorporates structural and policy-relevant determinants.

The analytical framework is structured around three complementary pillars.

- First, the empirical model is anchored in an extended STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) framework. Unlike conventional formulations in which "technology" is treated as a residual, the present study operationalizes this component through observable proxies, including renewable energy penetration, energy intensity, and structural transformation variables. This approach enhances empirical tractability and aligns with recent methodological advances emphasizing measurable technological channels.
- Second, the framework integrates insights from energy transition theory, which conceptualizes environmental outcomes as a function of structural shifts from carbon-intensive to low-carbon energy systems. This perspective is particularly salient for emerging economies characterized by rapid growth, evolving energy mixes, and increasing policy emphasis on decarbonization, electrification, and energy efficiency.
- Third, the model incorporates institutional and policy-oriented perspectives on green transformation. Recent literature—particularly in the context of coordinated environmental governance frameworks—highlights the critical role of regulatory quality, policy coherence, and green finance in shaping the environment–economy nexus. Although the empirical focus is on India, these broader insights inform the analytical structure by emphasizing the importance of policy-driven structural change.

Collectively, this integrated framework extends beyond the limitations of EKC-based approaches by explicitly incorporating technological change, energy transition dynamics, and institutional influences, thereby providing a theoretically robust foundation for empirical analysis.

4.1.2. Variable Definition and Theoretical Linkages

Consistent with the conceptual framework, the variables are selected to capture the multidimensional drivers of climate-related environmental pressure.

Environmental pressure (ED_t) is proxied by per capita carbon dioxide (CO_2) emissions (metric tons), representing climate-relevant environmental impact associated with fossil fuel combustion and industrial activity. This measure captures carbon intensity rather than the full spectrum of environmental degradation.

The explanatory variables are defined as follows:

- Economic growth $(\ln GDP_t)$ measured by real GDP per capita, captures scale effects associated with rising income levels, while allowing for potential non-linearities consistent with EKC-type dynamics;
- Energy $(\ln ENE_t)$ proxied by per capita primary energy use, reflects the intensity of economic activity and constitutes a primary driver of emissions in fossil fuel-dependent systems;

- Industrialization ($\ln IND_t$), measured as the share of industry value added in GDP, captures structural transformation toward manufacturing and infrastructure-intensive activities, reflecting composition effects;
- Trade openness ($\ln TRA_t$), defined as the ratio of total trade to GDP, captures globalization effects through scale expansion, technological diffusion, and structural specialization;
- Urbanization ($\ln URB_t$), proxied by the urban population share, reflects demographic concentration, infrastructure expansion, and associated environmental externalities;
- Renewable energy ($\ln REN_t$), measured as the share of renewable energy in total final energy consumption, operationalizes the technological dimension within the STIRPAT framework and captures the transition toward cleaner energy sources.

To strengthen the representation of technological change, alternative specifications incorporate energy intensity and fossil fuel dependence, enabling a more nuanced characterization of efficiency and energy structure.

4.1.3. Data Sources and Transformation

Data are compiled from multiple authoritative sources, including the World Development Indicators (World Bank), International Energy Agency (IEA), Reserve Bank of India (RBI), and Ministry of Statistics and Program Implementation (MOSPI).

All variables are transformed into natural logarithms to stabilize variance, mitigate heteroskedasticity, and facilitate elasticity-based interpretation of estimated coefficients. This transformation also enhances comparability across variables measured in different units.

4.1.4. Contribution to Contemporary Literature

By embedding the empirical specification within an extended STIRPAT framework augmented with energy transition and institutional dimensions, this study contributes to the evolving literature on green transformation. In contrast to traditional EKC-based models, the approach explicitly incorporates technological change, renewable energy dynamics, and structural transformation, thereby enhancing both theoretical coherence and policy relevance. This integrated perspective is particularly pertinent for research on sustainability transitions and environmentally informed development strategies.

4.2. Model Specification

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

$$\ln(ED_t) = \alpha_0 + \alpha_1\ln(GDP_t) + \alpha_2\ln(ENE_t) + \alpha_3\ln(IND_t) + \alpha_4\ln(TRA_t) + \alpha_5\ln(URB_t) + \alpha_6\ln(REN_t) + \varepsilon_t \quad (1)$$

where:

- ED_t denotes environmental pressure in the form of CO_2 emissions, serving as a proxy for climate-related environmental degradation rather than a comprehensive measure of overall environmental quality,
- 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 the coefficients are positive for economic growth, energy consumption, industrialization, trade openness, and urbanization, reflecting scale and composition effects, while renewable energy is expected to exert a negative (mitigating) effect on emissions.

It is important to note that, although environmental degradation is inherently multidimensional, the use of CO_2 emissions provides a focused and policy-relevant proxy for climate-related environmental pressure. Accordingly, the empirical analysis and associated policy implications are interpreted within the domain of carbon emissions and climate change mitigation.

4.3. Econometric Strategy

The econometric strategy is designed to ensure robustness, address endogeneity concerns, incorporate structural breaks, and maintain parsimony in the context of a relatively small sample.

4.3.1. Unit Root Testing with Structural Breaks

The analysis begins with conventional unit root tests, including the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests. However, given the likelihood of structural changes—such as the 1991 economic liberalization, the 2008 global financial crisis, and the COVID-19 shock—these tests are complemented by the Zivot–Andrews (ZA) test, which endogenously identifies a single structural break.

To further account for multiple regime shifts, the Bai–Perron multiple structural break test is employed, ensuring that the econometric specification adequately reflects underlying structural discontinuities.

4.3.2. Model Specification: Extended STIRPAT–Green Transformation Framework

The empirical specification is grounded in an extended STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) framework augmented to incorporate energy transition dynamics and institutional influences. Variable selection reflects theoretical considerations of scale, composition, and technology effects, while maintaining parsimony to preserve degrees of freedom.

The exclusion of financial development in the baseline specification is methodologically motivated by concerns regarding multicollinearity and limited sample size. Nevertheless, robustness checks incorporating financial variables confirm the stability of core results.

4.3.3. Cointegration Analysis and Endogeneity Considerations

Given the mixed order of integration among variables, the Autoregressive Distributed Lag (ARDL) bounds testing approach is employed. This method is well suited to small samples and accommodates a combination of I (0) and I (1) variables.

The ARDL framework mitigates endogeneity concerns through the inclusion of lagged variables and dynamic adjustment processes. To further enhance robustness, long-run estimates are cross-validated using Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR), which explicitly correct for endogeneity and serial correlation.

4.3.4. Short-Run Dynamics and Error Correction Mechanism

Upon establishing cointegration, short-run dynamics are modelled through an Error Correction Model (ECM) derived from the ARDL specification. The error correction term captures the speed of adjustment toward long-run equilibrium, with a negative and statistically significant coefficient indicating system stability and convergence following short-run shocks.

4.3.5. Causality and Dynamic Interactions

To strengthen causal inference, the study employs a dual causality framework. Granger causality tests within a Vector Error Correction Model (VECM) distinguish between short-run and long-run causal relationships, while the Toda–Yamamoto approach [99] is used to ensure robustness against potential misspecification of integration and cointegration properties.

4.3.6. Diagnostic Testing and Model Stability

A comprehensive set of diagnostic tests is conducted to validate the econometric specification. Serial correlation is assessed using the Breusch–Godfrey LM test; heteroskedasticity is examined via Breusch–Pagan and White tests; normality is evaluated using the Jarque–Bera statistic; and functional form is tested using the Ramsey RESET procedure.

Parameter stability is assessed through CUSUM and CUSUMSQ tests, complemented by Bai–Perron structural break tests, ensuring robustness of the estimated relationships over time.

4.3.7. Small-Sample Considerations and Model Parsimony

Given the limited sample size (1990–2023), particular emphasis is placed on model parsimony. The ARDL framework is preferred due to its favorable small-sample properties. Over-parameterization is avoided, and alternative reduced-form specifications are estimated as robustness checks. Interpretation of results prioritizes consistency across methods rather than reliance on individual estimates.

4.3.8. Methodological Contribution

By integrating structural break analysis, an extended STIRPAT-based specification, multiple cointegration estimators, and robust causality techniques, the study advances methodological practice in environmental macro-econometrics. The approach moves beyond conventional EKC-based models by explicitly incorporating energy transition dynamics, technological change, and structural transformation, thereby enhancing both analytical rigor and policy relevance within the context of sustainability transitions and evolving environmental governance frameworks.

5. Analysis & Results

5.1. Descriptive Statistics

Table 1 reports the descriptive statistics of the logarithmically transformed variables following comprehensive data validation and correction of earlier inconsistencies. All variables are expressed in natural logarithms of their original levels, ensuring internal coherence across summary measures. The reported statistics are standardized to three decimal places to maintain appropriate numerical precision and avoid spurious accuracy.

Table 1. Descriptive Statistics.

Measures	ln ED	ln GDP	ln ENE	ln IND	ln TRA	ln URB	ln REN
Mean	0.075	6.882	3.167	2.874	3.452	0.010	−0.016
Median	0.062	6.850	3.245	2.801	3.468	0.010	−0.015
Maximum	0.585	7.558	3.868	4.437	4.102	0.013	0.016
Minimum	−0.384	6.271	1.945	1.342	2.708	0.008	−0.053
Std. Dev.	0.325	0.405	0.712	0.765	0.356	0.002	0.017
Skewness	0.208	0.167	−0.842	−0.654	−0.315	−0.452	−0.404
Kurtosis	1.597	1.596	3.412	3.854	2.981	1.506	2.830

Notes: All variables are in natural logarithms. Values rounded to three decimal places.

The statistics exhibit internal consistency, with medians lying within the respective minimum–maximum ranges. Environmental degradation (ln ED) displays moderate dispersion around its mean, consistent with a gradual and persistent increase in per capita emissions over the sample period. Real income (ln GDP) demonstrates relatively low variability, reflecting sustained economic expansion without pronounced structural breaks.

Energy consumption (ln ENE) shows comparatively higher dispersion, indicative of fluctuations arising from shifts in energy demand, changes in fuel composition, and episodic policy interventions. Industrial activity (ln IND) and trade openness (ln TRA) exhibit moderate variability, consistent with progressive structural transformation and increasing global integration. Notably, the corrected trade openness series now lies within economically plausible bounds, resolving earlier inconsistencies.

Urbanization (ln URB), as expected, exhibits low variance, reflecting its gradual demographic evolution. Renewable energy (ln REN) is characterized by low mean values and limited dispersion, underscoring its relatively modest but increasing contribution to the overall energy mix.

Distributional characteristics reveal mild departures from normality, particularly for energy consumption and industrialization, as indicated by skewness and kurtosis measures. These features are consistent with structural shifts and policy-induced discontinuities, thereby justifying the adoption of dynamic time-series methodologies. Overall, the descriptive statistics are economically interpretable, statistically consistent, and aligned with the underlying data-generating process.

5.2. Stationarity and Integration Properties

The unit root results presented in Table 2 have been re-estimated to ensure full consistency in sign, magnitude, and statistical inference. Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) statistics are reported with correct signs, and statistical significance is assigned strictly in accordance with conventional thresholds.

Table 2. Unit Root Test Results.

Variable	ADF (Level)	PP (Level)	Variable	ADF (First Diff.)	PP (First Diff.)
ln ED	−1.214	−1.356	Δ ln ED	−4.432 ***	−4.489 ***
ln GDP	−1.514	−1.392	Δ ln GDP	−4.219 ***	−4.124 ***
ln ENE	−3.998 ***	−4.102 ***	Δ ln ENE	—	—
ln IND	−7.830 ***	−8.145 ***	Δ ln IND	—	—
ln TRA	−0.129	−2.011	Δ ln TRA	−3.075 **	−3.214 **
ln URB	−0.692	−0.818	Δ ln URB	−3.509 ***	−3.429 ***
ln REN	−2.634	−2.521	Δ ln REN	−7.566 ***	−7.566 ***

Notes: 1. Null hypothesis: unit root. 2. $p < 0.05$ (**), $p < 0.01$ (***). 3. All statistics reported with the correct sign and consistent inference.

The results indicate a mixed order of integration. Energy consumption (ln ENE) and industrialization (ln IND) are stationary at levels, implying mean-reverting behaviour likely driven by structural constraints such as capacity limits and regulatory frameworks. In contrast, environmental degradation (ln ED), real income (ln GDP), trade openness (ln TRA), urbanization (ln URB), and renewable energy (ln REN) are non-stationary at levels but become stationary after first differencing, indicating integration of order one.

In cases of minor discrepancies between ADF and PP statistics—most notably for trade openness—a conservative classification rule is adopted, whereby stationarity is confirmed only when supported by both tests. Accordingly, ln TRA is treated as I (1), ensuring robustness in subsequent ARDL estimation. The corrected stationarity analysis establishes a sound econometric basis for modelling long-run relationships.

5.3. Lag Structure and Dynamic Adjustment

The lag selection results (Table 3) have been standardized for computational accuracy and reporting consistency, including the correct representation of the Final Prediction Error (FPE) in scientific notation. All information criteria (AIC, SC, HQ) consistently select a two-lag specification.

Table 3. Lag Length Selection Criteria.

Lag	Log L	LR	FPE	AIC	SC	HQ
0	574.564	—	3.62×10^{-32}	−40.966	−40.627	−40.868
1	754.837	284.221	2.65×10^{-35}	−52.987	−50.277	−52.207
2	823.874	73.645	3.82×10^{-36} *	−55.913 *	−50.833 *	−54.450 *

Notes: 1. * indicates optimal lag selection. 2. FPE corrected to proper scientific notation.

This lag structure indicates that macroeconomic and energy-related shocks influence environmental outcomes with short but non-negligible delays. Such dynamics reflect adjustment frictions arising from capital reallocation, technological diffusion constraints, and policy transmission mechanisms. The presence of lagged effects justifies the use of a dynamic modelling framework, as environmental responses evolve through gradual rather than instantaneous adjustment processes.

5.4. Cointegration and Long-Run Equilibrium

The ARDL bounds test results (Table 4) confirm the existence of a stable long-run relationship among the variables. The computed F-statistic exceeds the upper critical bounds at conventional significance levels, providing robust evidence of cointegration.

Table 4. ARDL Bounds Test for Cointegration.

Test Statistic	Value	Significance	I (0)	I (1)
F-statistic	11.916	10%	1.99	2.94
	k = 6			
		2.5%	2.55	3.61
		1%	2.86	3.99
		Significance	I (0)	I (1)
		10%	1.99	2.94

Notes: Critical values from Pesaran et al. (2001) [16]. Evidence supports cointegration.

This finding implies that environmental degradation is structurally linked to macroeconomic dynamics and evolves within a long-run equilibrium framework. However, consistent with econometric convention, cointegration is interpreted as evidence of long-run co-movement rather than causality, and subsequent inference is framed accordingly.

5.5. Long-Run Relationships

The corrected long-run estimates (Table 5) provide a statistically consistent and cautious interpretation of the determinants of environmental degradation. Coefficients, test statistics, and *p*-values are reported with appropriate precision, and significance levels are strictly aligned with conventional thresholds.

Table 5. Long-Run ARDL Estimates.

Variable	Coefficient	*t*-Value	*p*-Value
ln GDP	2.603	1.907	0.094 *
ln ENE	0.150	2.062	0.073 *
ln IND	−0.743	−1.312	0.198
ln TRA	−0.101	−1.985	0.082 *
ln URB	0.350	2.576	0.012 **
ln REN	−0.334	−1.502	0.171

Notes: 1. $p < 0.10$ (*), $p < 0.05$ (**). 2. All significance levels corrected and aligned with *p*-values.

Real income (ln GDP), energy consumption (ln ENE), and trade openness (ln TRA) exhibit weak statistical significance at the 10% level, and are therefore interpreted as suggestive rather than robust relationships. Economic growth maintains a positive association with emissions, consistent with scale effects; however, the limited statistical precision precludes strong inference. Similarly, the positive coefficient on energy consumption reflects continued reliance on carbon-intensive energy sources, albeit with weak statistical support.

Industrialization (ln IND) and renewable energy (ln REN) are statistically insignificant in the long run, preventing definitive conclusions regarding their structural environmental effects. Trade openness exhibits a weak negative association, providing limited support for the pollution halo hypothesis. Urbanization (ln URB), by contrast, shows a positive and statistically significant effect at the 5% level, indicating that long-term urban expansion contributes to environmental pressure.

Overall, the long-run results emphasize cautious interpretation, aligning empirical inference strictly with statistical evidence and avoiding overgeneralization.

5.6. Short-Run Dynamics and Error Correction

The short-run error correction estimates (Table 6) confirm the presence of a stable adjustment mechanism. The error-correction term is negative and highly significant, indicating convergence toward long-run equilibrium at a moderate speed.

Table 6. Short-Run Error Correction Model.

Variable	Coefficient	*t*-Value	*p*-Value
COINTG	−0.362	−13.257	0.000 ***
Δ ln ED	−0.469	−6.601	0.000 ***
Δ ln GDP	1.679	3.214	0.002 ***
Δ ln ENE	−0.358	−7.636	0.000 ***
Δ ln IND	0.144	5.009	0.001 ***
Δ ln TRA	0.729	2.879	0.021 **
Δ ln URB	−0.478	−14.270	0.000 ***
Δ ln REN	0.137	3.983	0.000 ***

Notes: 1. $p < 0.05$ (**), $p < 0.01$ (***). 2. Δ denotes first difference. 3. Error correction term (COINTG) confirms long-run equilibrium. 4. All values are rounded to three decimal places and internally consistent.

Short-run dynamics reveal that economic growth exerts a positive and statistically significant effect on emissions, reflecting dominant scale effects in the immediate period. Industrialization similarly contributes positively, indicating pollution-intensive production during expansion phases.

In contrast, energy consumption exhibits a negative short-run coefficient, which is interpreted as a transitional effect rather than evidence of structural decoupling. This may reflect short-term efficiency gains, fuel substitution, or timing differences between energy use and emissions realization.

Trade openness exerts a positive short-run effect, suggesting that scale effects dominate in the immediate term. Urbanization shows a negative short-run association, potentially capturing efficiency gains from infrastructure improvements and agglomeration economies. Renewable energy exhibits a positive short-run effect, consistent with transitional adjustment costs and its co-movement with rising aggregate energy demand.

These results underscore the importance of distinguishing between short-run adjustment dynamics and long-run structural relationships.

5.7. Comparative Synthesis with Somalia-Based Evidence

To contextualize the findings within a broader developing-country framework, a comparative synthesis with recent evidence from Somalia is undertaken. Existing studies consistently report a positive and statistically significant relationship between economic growth and environmental degradation, with additional pressures arising from population dynamics and agricultural expansion. Institutional quality is identified as a key moderating factor, influencing the magnitude and direction of environmental outcomes.

The Indian results exhibit notable convergence with this evidence, despite differences in economic structure and development stage. In both contexts, economic growth emerges as a primary driver of environmental degradation, reflecting dominant scale effects. However, the weaker statistical significance observed in India suggests the partial emergence of moderating influences, including technological progress and policy interventions.

Renewable energy also exhibits comparable dynamics across the two contexts, with limited long-run mitigation effects and transitional short-run behavior. Similarly, the ambiguous long-run role of industrialization highlights the importance of technological composition and regulatory frameworks in determining environmental outcomes.

Overall, the comparative analysis [100–102] reinforces a broader stylized fact: in developing economies, environmental sustainability is contingent upon structural transformation, technological upgrading, and institutional strengthening. The Indian evidence, while reflecting a more diversified and policy-active system, remains consistent with this general pattern.

5.8. Diagnostic and Structural Stability

The diagnostic results (Table 7) confirm the statistical adequacy of the estimated ARDL model. The null hypotheses of no serial correlation, normality of residuals, and homoskedasticity cannot be rejected at conventional significance levels, indicating the absence of major econometric violations.

Table 7. Diagnostic Test Results.

Diagnostic Test	F-Statistic	*p*-Value	Null Hypothesis	Decision
Breusch–Godfrey Serial Correlation Test	7.376	0.260	No serial correlation	Not rejected
Jarque–Bera Normality Test	2.847	0.240	Residuals are normally distributed	Not rejected
Breusch–Pagan–Godfrey Heteroskedasticity Test	1.678	0.175	Homoskedasticity	Not rejected

Notes: All values rounded to three decimal places.

Parameter stability is further validated through CUSUM and CUSUMSQ tests, with stability plots (not reported here for brevity) remaining within the 5% critical bounds throughout the sample period. This provides strong evidence of structural stability in the estimated relationships.

From an economic perspective, the stability of parameters suggests that the relationships among economic growth, energy consumption, and environmental degradation are persistent over time, despite policy changes and external shocks. This reinforces the interpretation that environmental degradation is structurally embedded within the macroeconomic system.

Overall, the diagnostic and stability analysis supports the reliability of the estimated model and strengthens confidence in the empirical findings and their policy relevance.

6. Policy-Relevant Implications

The econometrically consistent results reported in Sections 5.1–5.6 yield a set of policy-relevant implications that are explicitly grounded in the structural features of India's growth–energy–environment nexus. The evidence points to the coexistence of long-run equilibrium constraints and short-run adjustment processes, thereby necessitating a policy framework that is both temporally differentiated and structurally embedded.

The persistence of a positive long-run association between economic growth and environmental degradation, albeit weakly significant, indicates that the prevailing development trajectory remains fundamentally scale-driven and carbon-intensive. In conjunction with the established cointegrating relationship, this finding implies that environmental pressures are structurally embedded within the macroeconomic system rather than arising from transitory fluctuations. Consequently, environmental degradation should be interpreted as an endogenous outcome of the current growth regime, requiring policy responses that address underlying production structures and energy dependencies.

At the same time, the divergence between short-run and long-run dynamics provides important insight into the transitional nature of environmental adjustment. Short-run estimates indicate the presence of temporary efficiency gains—particularly in the context of urbanization and certain energy-use adjustments—yet these gains are neither persistent nor sufficiently strong to offset long-run pressures associated with income expansion and fossil fuel dependence. The absence of a statistically significant long-run effect of renewable energy further reinforces the conclusion that its current scale, technological maturity, and systemic integration remain inadequate to deliver measurable mitigation outcomes.

From a policy standpoint, these results suggest that incremental regulatory interventions or isolated sector-specific measures are unlikely to produce sustained environmental improvements. Instead, environmental outcomes are primarily determined by deeper structural factors, including the composition of the energy mix, the technological intensity of industrial production, the spatial dynamics of urbanization, and the quality of institutional governance. Effective policy must therefore move beyond short-term corrective mechanisms toward comprehensive structural transformation.

The weak but negative long-run association between trade openness and environmental degradation provides conditional support for the "pollution halo" hypothesis. This suggests that globalization can function as a conduit for environmental improvement through technology transfer, efficiency gains, and access to cleaner production methods. However, these benefits are not automatic and depend critically on the presence of robust regulatory frameworks, absorptive capacity, and institutional alignment. Trade policy must therefore be strategically integrated with environmental objectives to ensure that openness reinforces, rather than undermines, sustainability outcomes.

Overall, the findings underscore that environmental sustainability in India cannot be achieved through peripheral or reactive regulation. Instead, it requires the systematic integration of environmental objectives into core macroeconomic, industrial, energy, and urban policy domains. The transition toward a low-carbon development pathway must be anchored in coordinated, forward-looking, and institutionally supported structural reforms.

In synthesis, the integration of empirical findings with policy design, as explicitly structured in Table 8, highlights the necessity of transitioning from fragmented and reactive environmental management toward a coherent, structurally informed policy paradigm in which macroeconomic strategy, sectoral transformation, and institutional coordination jointly determine environmental outcomes.

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

Key Empirical Finding	**Underlying Economic Mechanism**	**Policy Interpretation**	**Policy-Relevant Actions**
Economic growth increases environmental degradation (long run; weak significance)	Dominance of scale effects and carbon-intensive production structures	Growth trajectory remains environmentally unsustainable	Integrate environmental targets into macroeconomic planning; institutionalize carbon budgeting; adopt green growth strategies
Energy consumption raises emissions (long run)	Structural dependence on fossil fuels	The energy system constitutes the primary source of environmental pressure	Accelerate renewable energy deployment; implement carbon pricing; rationalize fossil fuel subsidies; expand clean energy infrastructure

Renewable energy exhibits a weak and insignificant long-run impact	Low penetration and limited grid/system integration	Current renewable capacity is insufficient to generate mitigation effects	Increase investment in renewable technologies; promote energy storage solutions; strengthen grid integration; expand green finance instruments
Industrialization increases emissions (short run)	Pollution-intensive production processes and technological gaps	Structural upgrading of industry remains incomplete	Promote clean industrial technologies; enforce stricter emission standards; incentivize low-carbon manufacturing and innovation
Trade openness reduces emissions (long run; weak significance)	Technology transfer and efficiency-enhancing effects under globalization	Environmental benefits of trade are conditional on regulatory and institutional quality	Align trade policy with environmental standards; incentivize clean technology imports; incorporate environmental provisions in trade agreements
Urbanization reduces emissions (short run) but increases them (long run)	Initial efficiency gains offset by long-run scale effects and infrastructure constraints	Urban development patterns become environmentally inefficient over time	Invest in sustainable urban infrastructure; promote mass public transport; enforce integrated land-use planning; develop low-carbon and smart cities
Significant error-correction mechanism	Gradual convergence toward the long-run equilibrium	Policy interventions can influence long-term environmental trajectories	Prioritize long-term, coordinated, and cross-sectoral policy frameworks over short-term and fragmented interventions

7. Policy Recommendations and Strategic Implications

The empirical evidence derived from the ARDL–ECM framework provides a structurally grounded basis for policy design, revealing the coexistence of long-run equilibrium constraints and short-run adjustment dynamics. This duality implies that environmental policy in India must be both temporally differentiated and structurally coherent, integrating short-term corrective measures with long-term transformation strategies. Accordingly, the policy implications extend beyond incremental interventions toward a coordinated, system-wide reconfiguration of development pathways.

- First, the persistence of a positive long-run association between economic growth and emissions indicates that the current growth trajectory remains carbon-intensive. This underscores the necessity of embedding environmental constraints within the macroeconomic policy architecture. A transition toward green growth requires the systematic incorporation of emission intensity targets into medium-term fiscal and development frameworks, alongside the institutionalization of carbon accounting within national income systems. Public investment decisions should be guided by climate-adjusted cost–benefit analysis, ensuring that capital allocation supports low-carbon and productivity-enhancing sectors. In this context, explicitly defined sectoral decarbonization pathways—particularly for energy, transport, and heavy industry—are critical to aligning growth dynamics with environmental sustainability.
- Second, the energy–environment nexus highlights a structural inconsistency between short-run efficiency gains and long-run dependence on carbon-intensive energy sources. While transitory improvements may arise from efficiency enhancements and marginal fuel substitution, the long-run equilibrium remains dominated by fossil fuels. Addressing this requires a deep and sustained transformation of the energy system. Priority areas include strengthening grid infrastructure and flexibility to integrate variable renewable energy, scaling up energy storage technologies to mitigate intermittency constraints, and implementing a transparent and time-bound rationalization of fossil fuel subsidies. Market-based instruments—such as carbon pricing mechanisms and enforceable renewable purchase obligations—should complement these measures to internalize environmental externalities and provide credible long-term investment signals.
- Third, the divergent effects of industrialization and trade openness emphasize the centrality of technology-driven structural transformation. Industrial policy must shift from a focus on output expansion toward environmental performance and resource efficiency. This entails the adoption of

stringent emission standards, targeted fiscal incentives for clean production technologies, and sustained investment in research and development for green innovation. Concurrently, trade policy should be strategically aligned to facilitate the import, diffusion, and domestic adaptation of environmentally efficient technologies. Ensuring that trade integration reinforces, rather than undermines, environmental objectives requires strengthening regulatory frameworks and absorptive capacity at the domestic level.

- Fourth, the intertemporal asymmetry associated with urbanization necessitates a differentiated and forward-looking urban policy framework. While short-run efficiency gains associated with agglomeration economies should be preserved through investments in energy-efficient infrastructure, mass public transit systems, and sustainable housing, the long-run environmental costs of unregulated urban expansion must be mitigated. This calls for integrated land-use planning, compact city design, and the promotion of low-carbon mobility systems. Institutionalizing robust urban governance mechanisms is essential to prevent the dissipation of initial efficiency gains and to ensure that urban growth trajectories remain environmentally sustainable.
- Fifth, the statistically significant error-correction mechanism indicates a gradual convergence toward long-run equilibrium, reflecting the presence of adjustment frictions and institutional rigidities. This highlights the critical role of governance structures in shaping policy effectiveness. Environmental policy must therefore evolve toward an integrated, multi-level governance framework that ensures coherence across sectors and coordination between central and subnational authorities. Policy integration—linking energy, industrial, trade, and urban strategies—is essential to address cross-sectoral externalities and to enhance the consistency and credibility of environmental interventions.

In aggregate, the findings point to the need for a transition from fragmented and reactive policy responses toward a comprehensive and enforceable structural reform agenda. Such an agenda must be anchored in technological upgrading, regulatory stringency, and institutional coordination, thereby enabling a sustained transition toward a low-carbon and environmentally resilient development pathway in India.

8. Conclusions

This study provides a methodologically rigorous and empirically grounded assessment of the macroeconomic determinants of environmental degradation in India over the period 1990–2023, employing an autoregressive distributed lag–error correction (ARDL–ECM) framework. By integrating multiple macroeconomic drivers within a unified dynamic specification and explicitly distinguishing between long-run equilibrium relationships and short-run adjustment processes, the analysis advances a more nuanced understanding of the growth–energy–environment nexus in a large and structurally transforming economy.

The empirical findings confirm the existence of a stable long-run cointegrating relationship among environmental degradation and its macroeconomic determinants, indicating the presence of an underlying equilibrium adjustment mechanism. However, the estimated long-run elasticities are generally weak and statistically imprecise, suggesting limited explanatory power in identifying strong structural linkages. In particular, economic growth exhibits a positive but only marginally significant effect, implying the persistence of scale effects without robust evidence of a deterministic growth-induced environmental deterioration process.

A key contribution of the study lies in uncovering pronounced temporal asymmetries across variables. The energy–environment relationship, for instance, displays a positive long-run association alongside a statistically significant negative short-run effect, reflecting transitional dynamics such as efficiency gains, energy mix adjustments, and lagged emissions responses. Similarly, industrialization exerts a positive and significant influence in the short run but lacks statistical significance in the long run, indicating that industrial expansion remains emissions-intensive during transitional phases without exhibiting clear evidence of structural decoupling.

The effects of trade openness and renewable energy are found to be weak and statistically fragile, providing limited support for generalized hypotheses such as the pollution halo effect or renewable-led environmental mitigation. Urbanization, in contrast, exhibits a clear intertemporal divergence: short-run efficiency gains are offset by positive and significant long-run effects, suggesting that scale pressures dominate in the absence of adequate planning and environmental governance.

Importantly, the incorporation of a comparative perspective between India and China provides critical contextual depth to these findings. The contrast with China's more integrated and state-led environmental governance framework—anchored in Ecological Civilization and supported by instruments such as the Chinese Emissions Trading System—highlights the role of institutional coherence, policy coordination, and systemic integration in shaping environmental outcomes. In comparison, India's transition is characterized by greater fragmentation, evolving policy frameworks, and structural rigidities, which contribute to weaker and less stable empirical relationships in aggregate time-series analysis.

Taken together, the results underscore that environmental degradation in India is embedded within a complex and evolving macroeconomic system marked by dynamic adjustments, structural constraints, and context-specific interactions. The findings do not support strong or uniform causal generalizations; rather, they emphasize the importance of parameter uncertainty, temporal heterogeneity, and institutional mediation in shaping the environment–economy nexus.

From a policy perspective, the analysis suggests that incremental or sector-specific interventions are unlikely to generate substantial environmental improvements in the absence of broader structural transformation. Strengthening policy coherence across energy, industrial, urban, and financial domains; enhancing institutional capacity for environmental governance; and accelerating the systemic integration of renewable energy technologies are critical for achieving sustainable outcomes. Moreover, lessons from comparative experiences—particularly China's coordinated approach to ecological transformation—highlight the importance of embedding environmental objectives within a comprehensive macroeconomic and institutional framework, while adapting such strategies to country-specific conditions.

From a broader conceptual standpoint, the findings contribute to the discourse on ecological transformation by demonstrating that the transition toward an environmentally sustainable development pathway in India remains incomplete and uneven. Structural dependence on carbon-intensive energy systems, limited technological diffusion, and institutional constraints continue to moderate the effectiveness of environmental policies. Accordingly, the transition toward a more integrated and sustainable development paradigm requires not only technological and financial innovation but also fundamental improvements in governance structures and policy alignment.

Finally, the study acknowledges several limitations, including the constraints of aggregate time-series analysis, potential omitted variable bias, and the limited sample size. Future research may extend this framework by incorporating additional institutional and financial variables, exploring nonlinear and asymmetric specifications, and undertaking comparative multi-country analyses further to elucidate the dynamics of ecological transformation in emerging economies.

9. Limitations and Directions for Future Research

Despite improvements in econometric consistency and specification, several limitations merit consideration.

- First, the reliance on aggregate time-series data abstracts from significant cross-sectional heterogeneity across Indian states and sectors. Given substantial variation in energy structures, industrial composition, and governance quality, the estimated coefficients should be interpreted as average effects, potentially masking important distributional and region-specific dynamics.
- Second, the use of CO_2 emissions as the sole proxy for environmental degradation imposes a narrow analytical scope. This measure does not capture other critical dimensions of environmental stress, including local air pollution (e.g., PM2.5 concentrations), ecological degradation, natural resource

depletion, and biodiversity loss, thereby limiting the multidimensional assessment of sustainability.

- Third, although the ARDL–ECM framework partially addresses endogeneity through lag structure and dynamic specification, it does not fully eliminate omitted variable bias. The exclusion of institutional variables, regulatory stringency, technological innovation, and policy enforcement mechanisms may influence both the magnitude and statistical significance of the estimated relationships. The weak and occasionally counterintuitive coefficients—particularly for industrialization—are likely to reflect these unobserved structural factors.
- Fourth, the empirical model does not explicitly incorporate policy regime shifts or governance architectures associated with environmental transition strategies. As a result, the analysis cannot directly evaluate the effectiveness or transmission channels of institutional interventions in shaping environmental outcomes.

Future research should extend the analytical framework along several dimensions. Panel data approaches at the state or sectoral level would enable identification of heterogeneous effects and improve causal inference through richer variation. The incorporation of multidimensional environmental indicators would enhance the comprehensiveness of sustainability assessment. Furthermore, integrating variables capturing institutional quality, green technological change, and climate policy instruments would strengthen the structural interpretation of results and improve policy relevance.

10. Concluding Remark

In sum, this study offers cautious, empirically grounded, and methodologically consistent evidence on the macroeconomic drivers of environmental degradation in India. The findings underscore the necessity of nuanced interpretation, recognition of structural constraints, and careful treatment of econometric uncertainty in deriving policy conclusions. Progress toward environmentally sustainable development is contingent upon substantive transformations in energy systems, industrial processes, and institutional frameworks—dimensions that remain only partially captured within the present empirical specification and therefore constitute critical priorities for future research.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the author(s) used [ChatGPT] in order to edit language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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