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Economic Growth, CO₂ Emissions, Population, and Renewable Electricity in India: An ARDL Approach

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How To Cite: Maarof, M.A. Economic Growth, CO₂ Emissions, Population, and Renewable Electricity in India: An ARDL Approach. *Global South & Sustainable Development* 2026, 1(1), 26. <https://doi.org/10.53941/gssd.2026.100026>

Received: 17 June 2026
 Revised: 11 September 2026
 Accepted: 14 September 2026
 Published: 28 September 2026

Abstract: This study examines the dynamic relationships among economic growth, CO₂ emissions, population, and renewable electricity generation in India using annual data for 2004–2024 and temporally disaggregated quarterly series constructed for 2004Q1–2024Q4. The study employs the Autoregressive Distributed Lag (ARDL) framework to investigate short-run dynamics and test for the existence of a long-run relationship among the variables. Unit root tests confirm the suitability of the ARDL approach. The Bounds Test does not provide sufficient statistical evidence of a long-run levels relationship among CO₂ emissions, economic growth, population, and renewable electricity generation. The short-run results indicate that economic growth has a positive and statistically significant effect on CO₂ emissions, suggesting continued environmental pressure associated with rising economic activity and reliance on conventional energy sources. Population changes also exhibit a dynamic pattern, with a negative and statistically significant contemporaneous effect and a positive and statistically significant first-lag effect, indicating that demographic changes may influence emissions with a time lag. Renewable electricity generation has a positive and statistically significant contemporaneous association with CO₂ emissions, which may reflect the transitional nature of India's energy system, where renewable capacity expands alongside rising energy demand and continued dependence on conventional sources. The error-correction coefficient is negative and statistically significant, but its interpretation is treated cautiously because the Bounds Test does not confirm a long-run relationship. Diagnostic and stability tests indicate that the estimated specification is statistically adequate and structurally stable. The findings highlight the importance of renewable energy investment, energy efficiency, and integrated policies to support economic growth while reducing CO₂ emissions.

Keywords: economic growth; CO₂ emissions; population; renewable electricity; India; ARDL

1. Introduction

In recent years, India has experienced rapid and sustained economic growth. This success is primarily attributed to advancements in industry, increased connectivity with the world, technological modernization, and a growing need for energy. While this economic transformation helped raise income levels, reduce poverty, and improve infrastructure, it also led to serious environmental problems. Among the most serious of these problems are deteriorating air quality, exacerbated global warming, increased greenhouse gas emissions, and the rapid depletion of natural resources [1,2].

The link between environmental health and economic progress remains a topic of discussion in environmental economics. According to the Environmental Kuznets Curve (EKC) hypothesis, environmental degradation occurs



during the early stages of economic development. However, once a country reaches a certain level of income, pollution levels begin to decline due to technological advancements and changes in its economic structure [3,4]. However, evidence on the relationship between economic growth, energy use, and environmental quality varies across countries and development contexts. Studies of developing countries have documented the environmental implications of economic growth [5], while evidence from BRI countries highlights the role of economic activity, energy consumption, and other factors in shaping CO₂ emissions [6]. Comparative evidence from Australia and Canada also demonstrates that the relationship between renewable energy consumption, economic growth, trade, urbanisation, and environmental quality can differ across national contexts [7].

Today, the deteriorating environmental situation in India has become a very important issue for decision-makers. Air pollution in major cities often exceeds internationally accepted safe levels. Moreover, carbon emissions from transportation, energy production, and industry are considered the main source of increasing environmental problems [8–10]. These pressing issues raise serious questions about the future viability of the Indian economy.

To address these concerns, India has launched several initiatives aimed at promoting sustainable development. These include increasing the use of renewable energy, developing plans to reduce carbon emissions, and improving energy efficiency. Clean energy, particularly solar and wind power, is a crucial component of a plan to reduce reliance on traditional fuels and achieve long-term environmental goals [11–14]. However, despite these efforts towards using technology that respects the environment, well-known fossil fuels still dominate the country's energy system, weakening the effectiveness of environmental policies in general [10–15].

Recent research indicates a link between the economies of newly formed nations and the strength of their carbon emissions, particularly carbon dioxide, with each element influencing various other factors. These economic developments aim to increase energy demand, leading to higher targets, especially in sectors reliant on oil and gas. However, scientists explain that this correlation persists as new forms of economic cooperation emerge, alongside the shift towards more diverse energy sources [16–19].

From a methodological standpoint, the Autoregressive Distributed Lag (ARDL) model emerges as a prominent approach for understanding long-term relationships between economic and environmental indicators. This method is highly efficient due to its ability to handle integrated variables at different levels, making it particularly well-suited for analyzing time-series data in developing countries such as India [15,20,21]. Previous studies in developing and emerging economies have shown a consistent relationship between economic progress, energy consumption, and environmental degradation. For example, evidence from ASEAN-6 countries highlights the important role of economic growth, energy consumption, and globalization in explaining CO₂ emissions [19].

Previous research has focused on the role of renewable energy sources and technological advancements in reducing environmental impact. Evidence shows that increased adoption of clean energy contributes to reducing carbon emissions and simultaneously advances economic goals, thus supporting long-term sustainability [10–12]. Despite ongoing efforts, the pace of the transition to sustainable development is still insufficient to fully address the negative environmental impacts of rapid industrial expansion and urbanization.

Furthermore, continued urbanization and rapid population growth exacerbate India's environmental challenges, driving increased demand for housing, transportation, infrastructure, and electricity. These rising demands lead to higher pollution levels, posing a significant obstacle to achieving environmental sustainability goals [22,23]. Achieving sustainable development requires a delicate balance between a range of essential elements, such as promoting economic growth, implementing sustainable environmental practices, encouraging technological innovation, and making tangible structural changes to the economy.

Despite the abundance of studies in this area, much more research is urgently needed. Firstly, much current research focuses on analyzing simple relationships, such as the link between economic growth and pollution or between energy consumption and emissions, without adopting a holistic approach that connects growth, the environment, and sustainable development more broadly. Secondly, there is a significant lack of research that utilizes up-to-date data reflecting political and social changes in countries like India. Third, advanced economic models, such as the Autoregressive Distributed Lag (ARDL) model, have not been sufficiently utilized to gain a comprehensive understanding of the short- and long-term interactions related to sustainability. Accordingly, this study aims to analyze the dynamic relationship between economic growth, environmental pollution, and sustainable development in India using the ARDL model. More specifically, the study examines the relationship between economic growth and environmental degradation, and whether expanding renewable energy and implementing sustainable policies contribute to reducing the correlation between growth and emissions.

This study contributes by providing new empirical evidence on the relationship between growth and the environment in India, through the integration of sustainability aspects and the application of an advanced

econometric model. We anticipate that the findings will provide important policy recommendations for achieving the Sustainable Development Goals by balancing economic growth with environmental protection.

2. Methodology

2.1. Study Context: India

This study examines India as one of the world's largest and fastest-growing economies. India has experienced substantial growth in industrial activity and urban expansion, accompanied by increasing energy demand. Located in South Asia, India has diverse geographical and climatic conditions that influence regional economic activities, energy resources, and environmental conditions. With a population exceeding 1.4 billion, India is one of the world's most populous countries. Rapid population growth, together with continued economic development, has placed considerable pressure on natural resources and ecosystems. The study context includes major industrial and metropolitan cities such as Delhi, Mumbai, Kolkata, and Chennai. These cities are important drivers of economic growth, but they also contribute significantly to carbon dioxide emissions and environmental pollution.

The Indian economy comprises several major sectors, including agriculture, industry, and services. India remains highly dependent on fossil fuels as a major source of energy. However, the country has increasingly invested in renewable and clean energy sources, particularly solar and wind power, as part of its efforts to support sustainable economic development and reduce environmental pressures. Despite these efforts, India continues to face significant environmental challenges associated with rapid population growth, industrial expansion, and increasing energy demand.

From an environmental perspective, India is highly exposed to the effects of climate change, including rising temperatures, changing climatic conditions, and deteriorating air quality. These interconnected economic, energy, demographic, and environmental challenges make India a relevant case for examining the relationships among economic growth, the transition toward renewable energy, population growth, and environmental degradation within a comprehensive analytical framework.

2.2. Data Collection and Sources

This study, based on quarterly data covering the period from 2004Q1 to 2024Q4, aims to explore the relationship between economic performance, environmental pollution, population growth, and the development of renewable energy sources in India. This period was carefully chosen because it offers easy data access and represents a time of significant transformations in the Indian economy and energy sector.

To achieve its objectives, the study focuses on several key factors: economic development is measured by Gross Domestic Product (GDP), expressed in U.S. dollars, while environmental pollution is measured by per capita CO₂ emissions. Population trends are measured using total population. Clean energy development is assessed using renewable electricity generation (RE), measured as the percentage of electricity generated from renewable energy sources relative to total electricity generation. These variables were selected because they are commonly used in research examining the relationships among economic activity, population pressures, energy transitions, and environmental impacts.

Data for GDP, carbon dioxide emissions, and population size were obtained from the World Development Indicators database [2]. Data for the renewable energy index were obtained from the International Renewable Energy Agency [11] because it is accurate and continuously updated in this field.

Since the original data for GDP, CO₂ emissions, population, and renewable energy were available on an annual basis, the annual series were converted into quarterly observations using the Quadratic Match Sum procedure available in EViews 13. This temporal disaggregation procedure was used to generate quarterly observations for the period 2004Q1–2024Q4 while maintaining consistency with the corresponding annual data. The procedure was applied consistently during the data-processing stage to obtain quarterly series suitable for the subsequent econometric analysis.

Because the original information is annual, the quarterly observations generated through temporal disaggregation should not be interpreted as independently observed quarterly measurements. The Quadratic Match Sum procedure was used to distribute the annual information across quarters while maintaining consistency with the corresponding annual observations. However, the appropriateness of this procedure differs conceptually across variables. For flow-related variables such as GDP and electricity generation, temporal disaggregation provides a way of constructing higher-frequency series while maintaining consistency with annual totals. For stock or intensity-related variables such as population and CO₂ emissions, the resulting quarterly values should be interpreted as interpolated representations of the annual information rather than directly observed quarterly outcomes. Accordingly, the quarterly ARDL estimates are used primarily to explore potential dynamic patterns

within the temporally disaggregated series and are not interpreted as equivalent to estimates based on genuinely observed quarterly data.

Additional information from the [22] and the United Nations Statistics Database was also consulted to support the reliability and consistency of the data used in the analysis [23].

During data processing, all variables were transformed into natural logarithms to reduce differences in scale and facilitate the interpretation of the estimated coefficients as elasticities.

2.3. Econometric Model Specification (ARDL Approach)

In this study, the Autoregressive Distributed Lag (ARDL) model, developed by [20], is applied to examine the dynamic relationship between economic growth, environmental pollution, population growth, and renewable energy. This model is well-suited for this type of research because it allows for the exploration of relationships over both short and long time periods, regardless of whether the variables are stationary at level $I(0)$ or at first difference, $I(1)$.

The general form of the model is illustrated as follows:

$$CO_{2t} = f(GDP_t, POP_t, RE_t) \quad (1)$$

where:

- CO_{2t} represents the amount of carbon dioxide emitted by each person and is considered a measure of the extent of environmental pollution.
- GDP_t represents economic growth
- POP_t represents population
- RE_t represents the amount of electricity produced from renewable energy sources as a percentage of total electricity production.

The ARDL model can be formulated in linear logarithmic form as follows:

$$\ln CO_{2t} = \beta_0 + \beta_1 \ln GDP_t + \beta_2 \ln POP_t + \beta_3 \ln RE_t + \varepsilon_t \quad (2)$$

The ARDL framework can also be expressed in an error-correction form to examine short-run dynamics and to assess adjustment behavior when evidence of a long-run levels relationship is established between the variables. Through this analytical method, we can examine how economic growth, population growth, and the use of renewable energy sources affect environmental pollution across various time periods, allowing us to track changes in the short and long term.

2.4. Estimation Procedure

Empirical analysis involves a set of stages. The first stage involves the Phillips–Perron (PP) unit root test to examine the stationarity properties of the variables and ensure that none of the variables is integrated of order two, $I(2)$, which would be incompatible with the ARDL bounds-testing approach. The second stage involves the ARDL Bounds Test to determine whether sufficient statistical evidence exists for a long-run levels relationship among the variables. The third stage involves estimating the ARDL model to identify the short-run dynamics and, where supported by the Bounds Test, the corresponding long-run coefficients. The second stage involves the ARDL Bounds Test to determine whether sufficient statistical evidence exists for a long-run levels relationship among the variables. The third stage involves estimating the ARDL model to identify the short-run dynamics and, where supported by the Bounds Test, the corresponding long-run coefficients.

The fourth stage involves examining the error-correction representation of the ARDL model to assess the dynamic adjustment component following short-run changes. The interpretation of the error-correction term is conditional on the outcome of the Bounds Test. If the Bounds Test supports a long-run levels relationship, the error-correction term can be interpreted as the speed of adjustment towards long-run equilibrium and is generally expected to be negative and statistically significant. If the Bounds Test does not support a long-run levels relationship, the error-correction coefficient is interpreted cautiously as a feature of the estimated dynamic specification rather than as evidence of adjustment towards an established long-run equilibrium. Finally, diagnostic tests are performed, including tests for serial correlation, heteroskedasticity, normality of residuals, and model stability.

3. Empirical Results and Discussion

3.1. Unit Root Test Results

Before estimating the Autoregressive Distributed Lag (ARDL) model, the stationarity properties of the study variables were examined using the Phillips–Perron (PP) test. The test was conducted under three different

The annual-data estimation results are presented in Table 2. These results provide a robustness benchmark based on the original annual observations for 2004–2024 and allow comparison with the results obtained from the temporally disaggregated quarterly data.

Table 2. Summary of ARDL Estimation Results for the Study Model during the Period 2004–2024.

Variable	Coefficient	Std. Error	t-Statistic	Prob. *
DCO2(-1)	0.283047	0.271273	1.043403	0.3158
GDP	0.019586	0.004482	4.369468	0.0008
GDP(-1)	−0.006745	0.005716	−1.180118	0.2591
POP	−0.009857	0.047378	−0.208052	0.8384
DRE	0.018737	0.014275	1.312530	0.2120
C	−0.030678	0.061929	−0.495372	0.6286
R-squared	0.665714	Mean dependent var		0.058897
Adjusted R-squared	0.537142	S.D. dependent var		0.069058
S.E. of regression	0.046983	Akaike info criterion		−3.025985
Sum squared resid	0.028696	Schwarz criterion		−2.727741
Log likelihood	34.74686	Hannan-Quinn criter.		−2.975510
F-statistic	5.177768	Durbin-Watson stat		1.907756
Prob(F-statistic)	0.007837			

* Note: *p*-values and any subsequent tests do not account for model. Source: Prepared by the researcher using EViews 13 software.

The comparison between the quarterly and annual specifications should be interpreted as a sensitivity analysis rather than as evidence of identical empirical relationships across frequencies. The annual estimates confirm the positive and statistically significant contemporaneous effect of GDP on changes in CO₂ emissions, which is consistent with the corresponding short-run finding in the quarterly specification. However, the annual model does not reproduce the statistically significant population and renewable-electricity effects observed in the temporally disaggregated quarterly model. This difference indicates that the quarterly coefficients should not be interpreted as direct evidence of independently observed quarterly economic relationships. Instead, they should be regarded as frequency-specific dynamic patterns generated from the annual information. The annual results therefore provide an important benchmark and indicate that the strongest evidence that remains robust across frequencies concerns the contemporaneous association between economic growth and changes in CO₂ emissions, whereas the population and renewable-electricity effects require more cautious interpretation.

3.2. Estimation of the Study Model Using the Autoregressive Distributed Lag (ARDL) Approach

After confirming the stationarity of the study variables using the Phillips–Perron unit root test, which indicated that the variables exhibit a mixture of integration orders, I(0) and I(1), the Autoregressive Distributed Lag (ARDL) approach was considered appropriate. This approach is particularly suitable for estimating both the short-run and long-run relationships among the variables, provided that none of the variables is integrated of order two, I(2).

The analysis was subsequently extended to the temporally disaggregated quarterly series to examine short-run dynamics at a finer temporal frequency.

The ARDL model was estimated to examine the relationship between environmental pollution, represented by per capita carbon dioxide (CO₂) emissions as the dependent variable, and economic growth (GDP), population (POP), and renewable electricity generation (RE) as the independent variables. The analysis aims to assess the effects of these variables on the level of environmental pollution in India.

Following the estimation of the model and the selection of the optimal lag lengths based on the Akaike Information Criterion (AIC), the results presented in Table 3 were obtained. These results provide the basis for examining the short-run dynamics and subsequently testing whether a statistically supported long-run levels relationship exists among the study variables.

Based on the Akaike Information Criterion (AIC), alternative ARDL specifications were estimated, and the optimal model was selected based on the lowest AIC value. The results indicated that the most appropriate specification was ARDL(1, 2, 2, 1), which includes one lag of the dependent variable, two lags of economic growth, two lags of population, and one lag of renewable electricity generation.

The goodness-of-fit measures indicate that the estimated ARDL model has good explanatory power. The coefficient of determination (R^2) was approximately 0.809845, while the adjusted R^2 was approximately 0.786076, indicating that the variables included in the model explain about 80.98% of the variation in the dependent variable under the estimated specification. The F-statistic was 34.07095, with a probability value of 0.0000, indicating that

the model is statistically significant as a whole. The Durbin–Watson statistic was approximately 2.186521; however, the assessment of the presence of serial correlation is based primarily on the results of the Breusch–Godfrey test presented later.

Table 3. Summary of ARDL Estimation Results for the Study Model during the Period 2004Q1–2024Q4.

Variable	Coefficient	Std. Error	t-Statistic	Prob. *
DCO2(-1)	0.753311	0.083256	9.048112	0.0000
GDP	0.011823	0.001116	10.59412	0.0000
GDP(-1)	−0.019940	0.002076	−9.604869	0.0000
GDP(-2)	0.008854	0.001335	6.633107	0.0000
POP	−0.351645	0.124738	−2.819070	0.0062
POP(-1)	0.602876	0.220956	2.728487	0.0080
POP(-2)	−0.254972	0.120567	−2.114782	0.0379
DRE	0.030487	0.006257	4.872063	0.0000
DRE(-1)	−0.029728	0.006594	−4.508243	0.0000
C	0.002843	0.005750	0.494406	0.6225
R-squared	0.809845	Mean dependent var		0.014220
Adjusted R-squared	0.786076	S.D. dependent var		0.021776
S.E. of regression	0.010072	Akaike info criterion		−6.244321
Sum squared resid	0.007304	Schwarz criterion		−5.950819
Log likelihood	266.0172	Hannan-Quinn criter.		−6.126484
F-statistic	34.07095	Durbin-Watson stat		2.186521
Prob(F-statistic)	0.000000			

* Note: *p*-values and any subsequent tests do not account for model. Source: Prepared by the researcher using EVIEWS 13 software.

Based on the AIC results and the model estimation diagnostics, the ARDL(1, 2, 2, 1) specification represents the optimal model for analyzing the dynamic relationships among the study variables. Accordingly, this model is used to conduct the Bounds Test to assess whether a statistically supported long-run levels relationship exists. If the Bounds Test confirms such a relationship, long-run coefficients and an error-correction representation can be interpreted accordingly. If the Bounds Test does not support a long-run relationship, the analysis is restricted to the estimated short-run dynamic specification, and the reported error-correction coefficient is interpreted cautiously as a feature of the dynamic model rather than as evidence of established long-run equilibrium.

Interpretation of the Quarterly Estimates

The quarterly specification, based on 82 usable observations from an original set of 84 temporally disaggregated observations, covering 2004Q1–2024Q4, provides a more detailed representation of the dynamic relationships among the variables. The reduction from 84 to 82 observations results from the loss of two observations associated with the lag structure of the estimated model.

The quarterly ARDL specification is therefore retained as a supplementary dynamic analysis rather than as the sole basis for inference. Its purpose is to examine how the temporal allocation of annual information may generate short-run patterns within the study period. Because these quarterly observations are model-generated, the analysis does not claim that the estimated quarterly coefficients represent independently observed quarterly economic responses. The original annual-data estimation is consequently treated as the principal robustness benchmark, while the quarterly results are interpreted as supplementary evidence subject to the limitations of temporal disaggregation.

3.3. Bounds Test

The next step is to test for the existence of a long-run relationship among the study variables using the Bounds Test, as presented in Table 4.

The results of the Bounds Test indicate that the F-statistic is 1.816, which is below the lower-bound $I(0)$ critical value at all conventional significance levels. Specifically, the critical values for the restricted sample are 2.474 at the 10% significance level, 2.920 at the 5% level, and 3.908 at the 1% level. Accordingly, the null hypothesis of no long-run relationship among carbon dioxide emissions (CO₂), economic growth (GDP), population (POP), and renewable electricity generation (RE) in India over the period 2004Q1–2024Q4 cannot be rejected.

From an economic perspective, this finding suggests that, although short-run effects and interactions exist among these variables, there is insufficient statistical evidence that they follow a stable and common long-run equilibrium path over the study period. This may be explained by the structural transformations experienced by

the Indian economy, including economic expansion, urbanization, and changes in energy consumption patterns, alongside the gradual expansion of renewable electricity generation, while conventional energy sources have continued to play an important role. Consequently, the increase in renewable electricity generation may not have been sufficient to bring about a stable long-run shift in the trajectory of CO₂ emissions, particularly given the continued growth in energy demand and economic activity.

Table 4. Boundary Test Results for the Measured Model.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.002843	0.005750	0.494406	0.6225
DCO2(-1) *	-0.246689	0.083256	-2.963007	0.0041
GDP(-1)	0.000737	0.000503	1.464428	0.1474
POP(-1)	-0.003741	0.004538	-0.824460	0.4124
DRE(-1)	0.000759	0.004974	0.152507	0.8792
D(GDP)	0.011823	0.001116	10.59412	0.0000
D(GDP(-1))	-0.008854	0.001335	-6.633107	0.0000
D(POP)	-0.351645	0.124738	-2.819070	0.0062
D(POP(-1))	0.254972	0.120567	2.114782	0.0379
D(DRE)	0.030487	0.006257	4.872063	0.0000
* <i>p</i> -value incompatible with t-Bounds distribution.				
Levels Equation				
Case 2: Restricted Constant and No Trend				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
GDP	0.002989	0.001793	1.666717	0.0999
POP	-0.015166	0.018280	-0.829646	0.4095
DRE	0.003075	0.020033	0.153509	0.8784
C	0.011525	0.023276	0.495152	0.6220
EC = DCO2 – (0.0030 × GDP – 0.0152 × POP + 0.0031 × DRE + 0.0115)				
F-Bounds Test		Null Hypothesis: No levels relationship		
Test Statistic	Value	Significance	I(0)	I(1)
Asymptotic: n = 1000				
F-statistic	1.815999	10%	2.37	3.2
K	3	5%	2.79	3.67
		2.5%	3.15	4.08
		1%	3.65	4.66
Actual Sample Size 82			Finite Sample: n = 80	
		10%	2.474	3.312
		5%	2.92	3.838
		1%	3.908	5.044

Source: Prepared by the researcher using EViews 13 software.

Moreover, the effects of population and emissions may vary depending on the degree of urbanization, energy efficiency, technological development, and environmental policies. Therefore, the absence of evidence for a long-run relationship does not imply that there are no economic effects among the variables. Rather, it indicates that these effects did not take the form of a stable equilibrium relationship that could be statistically established during the study period. In contrast, the estimated dynamic specification indicates the presence of statistically significant short-run effects for some of the variables.

Therefore, the null hypothesis of no levels relationship cannot be rejected, indicating that the evidence is insufficient to establish a statistically significant long-run relationship among the variables.

3.4. Error-correction Model (ECM) Results

The Error-Correction Model (ECM) was estimated to examine the short-run dynamics among the study variables within the estimated dynamic specification. The results of the model (Table 5) help identify the short-run effects and assess the speed at which the dependent variable responds to changes in the explanatory variables and short-run shocks.

Table 5. Results of the error-correction Model.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(GDP)	0.011823	0.000974	12.14357	0.0000
D(GDP(-1))	−0.008854	0.001156	−7.660245	0.0000
D(POP)	−0.351645	0.111278	−3.160072	0.0023
D(POP(-1))	0.254972	0.112787	2.260646	0.0268
D(DRE)	0.030487	0.005710	5.338942	0.0000
CointEq(-1) *	−0.246689	0.079683	−3.095874	0.0028
R-squared	0.768616	Mean dependent var		0.000104
Adjusted R-squared	0.753393	S.D. dependent var		0.019741
S.E. of regression	0.009803	Akaike info criterion		−6.341882
Sum squared resid	0.007304	Schwarz criterion		−6.165781
Log likelihood	266.0172	Hannan-Quinn criter.		−6.271180
Durbin-Watson stat	2.186521			

Note: * indicates the error-correction term, CointEq(-1), representing the speed of adjustment toward the long-run equilibrium following a short-run deviation. Source: Prepared by the researcher using EViews 13 software.

The results of the ARDL(1, 2, 2, 1) model within the error-correction Model (ECM) framework reveal clear economic and statistical dynamics between carbon dioxide emissions and the explanatory variables over the period 2004Q1–2024Q4:

- The R-squared was 0.7686, while the Adjusted R-squared was 0.7534, indicating that the model explains approximately 76.86% of the variation in D(DCO₂), reflecting a relatively high explanatory power.
- The change in economic growth (GDP) had a positive and statistically significant short-run effect, with the coefficient of D(GDP) equal to 0.011823 and a probability value below 0.001. In contrast, the first lag of D(GDP), denoted as D(GDP(-1)), had a negative and statistically significant coefficient of −0.008854, with a probability value below 0.001. These findings indicate that the effect of economic growth on changes in carbon dioxide emissions is dynamic and is not confined to the current period, as emissions respond differently to contemporaneous and lagged changes in economic growth.
- The change in population (POP) had a negative and statistically significant short-run effect, with the coefficient of D(POP) equal to −0.351645 and a probability value of 0.0023. In contrast, the first lagged effect was positive and statistically significant, with the coefficient of D(POP(-1)) equal to 0.254972 and a probability value of 0.0268. These results suggest that the effect of changes in population on carbon dioxide emissions is dynamic, with the direction of the effect differing between the current and lagged periods.
- The change in renewable electricity generation (DRE) had a positive and statistically significant short-run effect, with the coefficient of D(DRE) equal to 0.030487 and a probability value below 0.001. According to the model specification, this finding indicates a positive association between changes in renewable electricity generation and changes in carbon dioxide emissions in the short run. This result may reflect the fact that the expansion of renewable electricity generation during the study period occurred alongside continued growth in energy demand and economic activity, as well as continued reliance on conventional energy sources. However, this interpretation should be regarded as a possible explanation of the result rather than direct evidence that renewable energy increases emissions.
- The error-correction coefficient, CointEq(-1), was −0.246689 and was negative and statistically significant at the 1% level ($p = 0.0028$), indicating the presence of an adjustment mechanism within the estimated dynamic specification. The coefficient suggests that approximately 24.67% of the previous period's disequilibrium is corrected within each quarter. However, since the Bounds Test did not provide sufficient statistical evidence of a long-run equilibrium relationship, this coefficient should be interpreted with caution and should not be regarded as independent evidence confirming the existence of a long-run relationship.

Overall, the results confirm the presence of clear short-run dynamics among the study variables, whereas the Bounds Test did not provide sufficient statistical evidence of a long-run equilibrium relationship. The findings indicate that some variables have statistically significant short-run effects on carbon dioxide emissions. At the same time, the error-correction coefficient should be interpreted cautiously in light of the absence of statistically established evidence of a long-run relationship.

3.5. Diagnostic Tests of the Estimated Model

To assess the adequacy of the estimated model and the reliability of its results, a set of diagnostic tests was conducted, including the Breusch–Godfrey Serial Correlation Lagrange Multiplier LM Test for serial correlation

in the residuals and the Autoregressive Conditional Heteroskedasticity (ARCH) Test for heteroskedasticity. The results are presented in Table 6.

Table 6. Summary of diagnostic test results for the estimated model.

Test	Statistic	F-Statistic	Prob.
Serial Correlation Test	Breusch-Godfrey Serial Correlation LM Test:	0.807001	0.4503
Heteroskedasticity Test	Heteroskedasticity Test: ARCH	3.445212	0.0647

Source: Prepared by the researcher using EViews 13 software.

The results of the Breusch–Godfrey Serial Correlation LM Test show that the F-statistic is 0.807001, with a probability value (Prob.) of 0.4503, which is greater than the 5% significance level. Therefore, the null hypothesis of no serial correlation in the model residuals cannot be rejected. This indicates that there is no statistical evidence of a serial correlation problem in the residuals.

Regarding the ARCH Heteroskedasticity Test, the F-statistic is 3.445212, with a probability value (Prob.) of 0.0647. Since this value is greater than the conventional 5% significance level, the null hypothesis of homoskedastic residuals cannot be rejected. Thus, there is insufficient statistical evidence of heteroskedasticity in the model at the 5% significance level.

Overall, the diagnostic test results provide no statistical evidence of serial correlation or heteroskedasticity in the model residuals at the 5% significance level. These findings indicate that the estimated specification does not exhibit the principal diagnostic problems examined in the study.

3.6. Structural Stability Test of the Model Parameters

To assess the structural stability of the estimated model, the Cumulative Sum (CUSUM) test, as illustrated in Figure 1, can be employed.

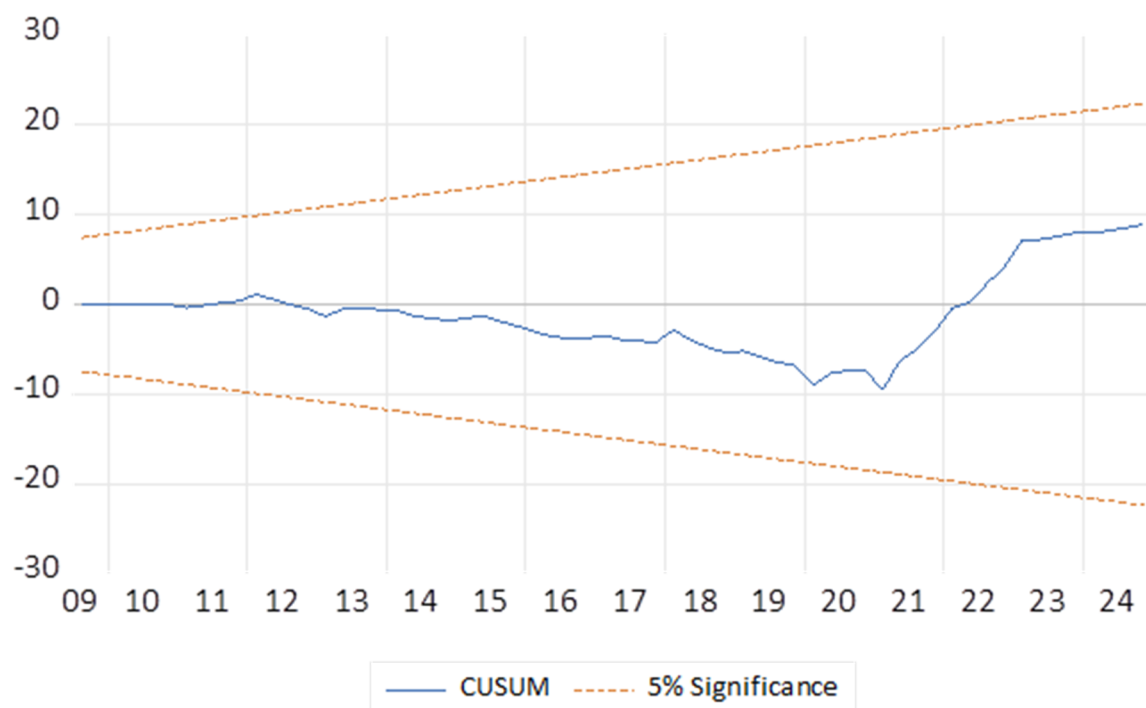


Figure 1. Structural Stability of the Estimated Model Using the CUSUM Test.

It can be observed that the cumulative sum of the residuals (CUSUM) remained within the critical bounds at the 5% significance level throughout the study period. This indicates that there is no statistical evidence of substantial structural changes in the model coefficients and supports the stability of the estimated parameters over the study period.

4. Discussion of Results

The empirical findings provide evidence of meaningful short-run interactions between economic growth, population dynamics, renewable electricity generation, and carbon dioxide emissions in India, while the Bounds Test does not support the existence of a statistically established long-run relationship among the variables. This distinction is important for interpreting the results because the estimated relationships are primarily dynamic and time-dependent rather than representing a statistically established long-run equilibrium, over the 2004Q1–2024Q4 period. The absence of evidence for long-run cointegration does not imply that the variables are economically unrelated; rather, it suggests that their interactions were not sufficiently stable to form a statistically identifiable long-run equilibrium relationship during the period examined.

The positive and statistically significant contemporaneous coefficient of economic growth provides evidence that increases in economic activity are associated with higher changes in CO₂ emissions in the short run. The coefficient of the current change in GDP is 0.011823 and is statistically significant at the 1% level. However, the first lag of economic growth carries a negative and statistically significant coefficient of -0.008854 . This combination indicates that the environmental effect of economic expansion is not uniform across time. Economic activity appears to generate additional environmental pressure in the current period, while the estimated lagged response is associated with a reduction in changes in CO₂ emissions in the subsequent period. Such a result is consistent with the broader literature emphasizing the close relationship between economic activity, energy demand, and environmental degradation [6], for example, identify economic growth as an important determinant of carbon emissions, while [19] and [18] similarly associate economic expansion with higher environmental pressure through increased energy use and related economic activities.

At the same time, the opposite signs of the contemporaneous and lagged GDP coefficients suggest that the relationship between growth and environmental degradation should not be interpreted as a simple linear process. The positive contemporaneous response may reflect the continued importance of energy-intensive production and conventional energy sources during periods of economic expansion. The subsequent negative response, however, may indicate that the environmental consequences of growth can change as economic structures, energy efficiency, and production technologies evolve. This interpretation is broadly compatible with the Environmental Kuznets Curve perspective introduced by [3], according to which the relationship between economic development and environmental degradation may change as economies move through different stages of development. Similar concerns regarding the nonlinear and heterogeneous nature of the growth–environment relationship are also reflected in the studies of [1–5]. Nevertheless, the present results should not be interpreted as direct confirmation of the EKC hypothesis because the estimated model does not explicitly test the nonlinear income specification required to establish an inverted-U relationship.

The results concerning population changes are also dynamic. The contemporaneous coefficient of D(POP) is negative and statistically significant at the 1% level, with a value of -0.351645 , whereas its first lag is positive and statistically significant at the 5% level, with a coefficient of 0.254972. Thus, population changes do not exert a uniform immediate effect on carbon emissions. One possible explanation is that the negative contemporaneous coefficient may reflect the fact that demographic changes do not necessarily translate instantaneously into additional emissions and may depend on the existing structure of energy use, urbanization, productivity, and resource utilization. The positive lagged coefficient, by contrast, suggests that demographic pressures may influence emissions with a time delay as additional demand for housing, transportation, electricity, and infrastructure gradually materializes. This interpretation is consistent with the broader argument in the literature that population and urbanization can increase environmental pressure through their effects on energy demand and economic activity [1], as well as the [23], emphasize the importance of demographic and urbanization processes in understanding environmental outcomes in developing and emerging economies.

The findings for renewable electricity generation are particularly noteworthy. The coefficient of the current change in renewable electricity generation is positive and statistically significant, at 0.030487 with a probability value below 0.001. At first sight, this result may appear inconsistent with the conventional expectation that renewable energy should reduce environmental degradation. However, the estimated coefficient should be interpreted as a short-run association rather than as evidence that renewable electricity itself causes higher carbon emissions. The expansion of renewable electricity in India has taken place within an energy system that continues to experience increasing energy demand and substantial dependence on conventional energy sources. Consequently, growth in renewable generation may occur simultaneously with continued expansion of total electricity supply and fossil-fuel-based generation. The result therefore may capture the transitional characteristics of the energy system rather than the environmental effect of renewable energy after complete substitution of conventional sources.

This finding also differs from the general expectation reported in several previous studies that renewable energy can contribute to environmental improvement [7–12], and the evidence reported by [11] emphasize the environmental benefits associated with greater reliance on renewable energy. The difference between those findings and the present short-run result may be related to differences in countries, periods, variables, estimation techniques, and stages of energy transition. In the Indian case, the positive short-run coefficient may therefore reflect the possibility that renewable electricity expansion has occurred alongside broader increases in energy demand and continued reliance on conventional energy sources. Importantly, the current result should be interpreted cautiously because the estimated model does not establish a causal mechanism through which renewable electricity increases CO₂ emissions.

The absence of a statistically significant long-run relationship represents another important finding of the study. The Bounds Test produces an F-statistic of 1.816, which is below the lower-bound $I(0)$ critical values at the 10%, 5%, and 1% significance levels. Accordingly, the null hypothesis of no levels relationship cannot be rejected. This result differs from studies that report stable long-run relationships between economic activity, energy use, and environmental degradation. The difference may partly arise from the characteristics of the present dataset, which consists of quarterly observations for India over 2004Q1–2024Q4, a period characterized by substantial changes in economic activity, energy demand, renewable energy development, and demographic conditions. The result therefore suggests that the short-run interactions identified in the model did not develop into a sufficiently stable long-run equilibrium relationship over the sample period.

The absence of long-run cointegration also provides an important qualification to the interpretation of the error-correction results. The estimated error-correction coefficient is negative and statistically significant, with a value of -0.246689 . Taken mechanically within the estimated dynamic specification, the coefficient implies an adjustment of approximately 24.67% of the previous period's deviation per quarter. However, this adjustment should not be interpreted as evidence of convergence toward a stable long-run equilibrium because the Bounds Test does not support cointegration.

The diagnostic results provide evidence that the estimated specification does not exhibit the principal diagnostic problems examined in the study. The Breusch–Godfrey test produces a probability value of 0.4503, indicating no statistically significant evidence of serial correlation in the residuals. Similarly, the ARCH test has a probability value of 0.0647, which is above the conventional 5% significance level and therefore does not provide sufficient evidence of heteroskedasticity at that level. In addition, the CUSUM test indicates that the cumulative residuals remain within the critical bounds, supporting the structural stability of the estimated parameters over the sample period. These results suggest that the principal short-run relationships identified by the model are not accompanied by the main diagnostic problems examined in the study.

Overall, the empirical evidence points to significant short-run dynamics without sufficient statistical evidence of a stable long-run relationship between economic development, population changes, renewable electricity generation, and carbon emissions in India. Economic growth increases environmental pressure in the current period but exhibits a negative lagged effect, while population changes also display opposite contemporaneous and lagged responses. Renewable electricity generation is positively associated with changes in emissions in the short run, which may reflect the transitional nature of India's energy system and the simultaneous expansion of renewable and conventional energy sources. These findings reinforce the argument that the environmental consequences of economic and energy transformations depend not only on the direction of change but also on the timing through which those changes affect the economy and the energy system.

From a policy perspective, the results suggest that expanding renewable electricity should be accompanied by broader structural changes in the energy system. Increasing renewable generation alone may not necessarily translate immediately into lower carbon emissions when overall energy demand is simultaneously increasing and conventional energy sources remain important. Policies aimed at improving energy efficiency, accelerating the substitution of fossil-fuel-based electricity, strengthening environmental regulation, and supporting cleaner technologies are therefore likely to be more effective when implemented as an integrated strategy. Such measures can help reduce the environmental pressure associated with economic expansion while allowing India to maintain its development objectives. The policy implications are broadly consistent with the literature emphasizing the importance of renewable energy, technological progress, and coordinated environmental and economic policies, while the present results highlight the importance of the short-run transition dynamics.

5. Conclusions

This study examined the dynamic relationship between carbon dioxide emissions, economic growth, population changes, and renewable electricity generation in India using original annual data for the period 2004–2024,

supplemented by a quarterly specification constructed through temporal disaggregation for 2004Q1–2024Q4. The analysis employed the Autoregressive Distributed Lag (ARDL) framework to investigate the short-run dynamics among the variables and to assess whether a stable long-run relationship could be established.

The Phillips–Perron unit root results indicated a combination of $I(0)$ and $I(1)$ variables, with none of the variables integrated at the second order, $I(2)$. This condition supports the suitability of the ARDL approach for the estimated model. The selected specification, ARDL(1, 2, 2, 1), also demonstrated relatively strong explanatory power, with an R-squared value of approximately 0.81 and a statistically significant overall F-statistic. These results indicate that the model provides a useful representation of the short-run dynamics examined in the study.

The most important finding concerns the distinction between short-run dynamics and long-run equilibrium. The Bounds Test produced an F-statistic of 1.816, which is below the finite-sample lower-bound $I(0)$ critical values of 2.474, 2.920, and 3.908 at the 10%, 5%, and 1% significance levels, respectively. Therefore, the null hypothesis of no levels relationship cannot be rejected. Accordingly, the evidence does not support the existence of a statistically established long-run equilibrium relationship among CO₂ emissions, economic growth, population, and renewable electricity generation over the study period.

The short-run results show that economic growth has a positive and statistically significant contemporaneous effect on changes in CO₂ emissions (0.011823), while its first lag has a negative and statistically significant effect (−0.008854). This indicates that the environmental consequences of economic expansion vary over time and cannot be adequately represented by a single contemporaneous effect. The finding suggests that India's economic expansion continues to generate environmental pressure in the short run, while subsequent periods may experience a partial reversal of this effect as economic and technological conditions adjust.

Population changes also exhibit a dynamic pattern, with a negative and statistically significant contemporaneous coefficient (−0.351645) and a positive and statistically significant first-lag coefficient (0.254972). This result indicates that demographic changes do not translate into environmental pressure instantaneously and that their effects may emerge with a time lag. The delayed positive response is consistent with the role of population dynamics in increasing demand for energy, transportation, housing, infrastructure, and other economic services.

Renewable electricity generation presents a particularly important short-run result. Its contemporaneous change is positively and significantly associated with changes in CO₂ emissions (0.030487). This finding should not be interpreted as evidence that renewable electricity inherently increases environmental pollution. Rather, it may reflect the transitional conditions of India's energy system, where renewable capacity has expanded alongside rising overall energy demand and continued dependence on conventional energy sources. The environmental benefits of renewable energy may therefore depend on the extent to which renewable electricity replaces, rather than simply supplements, fossil-fuel-based generation.

The error-correction coefficient is negative and statistically significant at −0.246689 ($p = 0.0028$), indicating an adjustment mechanism within the estimated dynamic specification. Nevertheless, because the Bounds Test does not establish long-run cointegration, the error-correction coefficient should be interpreted cautiously and should not be used alone to claim the existence of a stable long-run equilibrium. This distinction strengthens the methodological consistency of the study and prevents the empirical results from being interpreted beyond what the statistical evidence supports.

The diagnostic tests provide no evidence of serial correlation or ARCH heteroskedasticity at the 5% significance level, with probability values of 0.4503 and 0.0647, respectively. Meanwhile, the CUSUM test indicates that the estimated parameters remain structurally stable throughout the study period. These results support the adequacy and stability of the estimated specification within the limits of the variables and period considered.

Taken together, the findings indicate that changes in CO₂ emissions in India are closely associated with the timing and structure of economic and demographic changes and with the ongoing transformation of the electricity system. The evidence does not suggest that economic growth, population dynamics, and renewable electricity generation follow a stable common long-run path over the period studied. Instead, their effects on carbon emissions are predominantly dynamic and short-run in nature.

The policy implications are therefore centered on managing these short-run pressures while creating conditions for a more sustainable long-term transition. India should continue expanding renewable electricity infrastructure, but renewable deployment should be accompanied by measures that improve energy efficiency, accelerate the retirement or substitution of high-emission conventional generation, strengthen environmental standards, and promote cleaner production technologies. Greater coordination between economic, energy, and environmental policies could help reduce the environmental costs associated with continued economic development.

Finally, the results should be considered within the limitations of the study. The analysis is based on a relatively limited set of explanatory variables and a specific quarterly sample period. Future research could extend

the model by incorporating variables such as energy consumption by source, urbanization, trade openness, technological innovation, environmental policy measures, and energy intensity. Alternative nonlinear or asymmetric approaches may also provide further insight into whether the short-run relationships identified in this study evolve differently across periods or economic conditions. Such extensions would contribute to a more comprehensive understanding of India's transition toward environmentally sustainable economic development.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used in this study are publicly available from the World Development Indicators database of the World Bank, the International Renewable Energy Agency (IRENA), the United Nations Environment Programme (UNEP), and the United Nations Statistics Database. The quarterly series used in the empirical analysis were constructed from the original annual data using the Quadratic Match Sum procedure in EViews 13. The relevant institutional databases and reports were accessed through their official websites, as indicated in the reference list.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

I used ChatGPT (OpenAI) for translation, proofreading, and linguistic editing of the article. The remaining scientific content, statistical analysis, interpretation of the results, and conclusions were prepared by me.

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