

Article

Revisiting the Growth–Environment Nexus in South Africa: Short-Term and Long-Term Evidence from an ARDL-Based EKC Model with Trade Openness and Energy Intensity

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Abstract

This study investigates the relationship between economic growth, trade openness, energy intensity, and carbon dioxide (CO₂) emissions in South Africa within the Environmental Kuznets Curve (EKC) framework over the period 1970–2022. Using quarterly time series data and the Autoregressive Distributed Lag (ARDL) modelling approach, the study examines both the short-term and long-term dynamics between economic activity and environmental degradation. Descriptive statistics, correlation analysis, unit root tests, ARDL bounds testing, error-correction modelling, Granger causality analysis, and diagnostic tests were employed to ensure robust empirical results. The Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests indicate that all variables are integrated of order one, I(1), thereby satisfying the conditions for ARDL estimation. The ARDL bounds test confirms the existence of a long-term cointegrating relationship among carbon emissions, economic growth, trade openness, and energy intensity. The long-term results reveal a statistically significant negative coefficient for economic growth and a positive coefficient for the squared income term, indicating a U-shaped relationship between income and carbon emissions. Consequently, the conventional Environmental Kuznets Curve hypothesis is not supported for South Africa. The findings suggest that economic growth initially reduces environmental degradation; however, beyond a certain income threshold, further economic expansion increases carbon emissions. Trade openness and energy intensity exert positive and statistically significant effects on carbon emissions in the long run, implying that increased integration into global markets and continued dependence on energy-intensive production contribute to environmental degradation. The Error-Correction Model (ECM) reveals a negative and highly significant adjustment coefficient (−0.928), indicating that approximately 92.8% of short-term disequilibrium is corrected within one period. Granger causality results further show a unidirectional causal relationship running from trade openness to carbon emissions, while no significant causal relationship is found between economic growth and carbon emissions. The study concludes that economic growth alone is insufficient to achieve environmental sustainability in South Africa. Policy efforts should therefore focus on promoting renewable energy adoption, improving energy efficiency, strengthening environmental regulations, encouraging cleaner production technologies, and integrating environmental considerations into trade and industrial policies. These measures are essential for achieving sustainable economic development while meeting national climate-change-mitigation objectives.



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Keywords: Environmental Kuznets Curve (EKC); carbon emissions; economic growth; trade openness; energy intensity

1. Introduction

The relationship between economic growth and environmental degradation remains a central issue in environmental economics, particularly in the context of climate change and sustainable development. The Environmental Kuznets Curve (EKC) hypothesis [1] proposes an inverted U-shaped relationship between income per capita and environmental degradation. In the early stages of economic development, environmental pressure increases due to industrialization, urbanization, and rising energy consumption. However, beyond a certain income threshold, further economic growth is expected to reduce environmental degradation through technological progress, structural transformation, and stricter environmental regulation.

From a historical perspective, carbon emissions have increased alongside economic expansion, particularly in developing economies that rely heavily on fossil fuels. South Africa provides a relevant case study due to its coal-dependent energy structure and energy-intensive industrial base. Empirical trends from 1970 to 2022 indicate that CO₂ emissions increased from approximately 314 million tonnes to peaks exceeding 480 million tonnes, reflecting the scale effect of economic growth. During the same period, GDP per capita exhibited fluctuations characterized by phases of expansion and contraction, influenced by structural changes and macroeconomic shocks such as the post-apartheid transition and the 2008 global financial crisis. Despite some stabilization in emissions in recent years, the overall trend suggests that economic growth remains closely linked to environmental degradation.

To provide preliminary insights into this relationship, Figure 1 presents a scatter plot of CO₂ emissions against GDP per capita for South Africa. The figure is constructed using data obtained from the World Bank World Development Indicators database, ensuring consistency and reliability of the underlying time series variables.

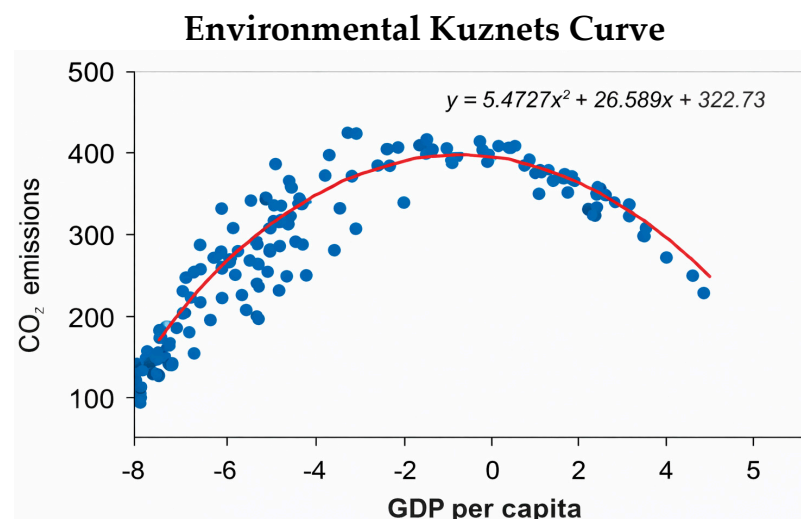


Figure 1. Environmental Kuznets Curve (CO₂ emissions vs. GDP per capita, 1970–2022). Source: authors' own computation (World Bank Data, 2026 [2]).

The figure illustrates a non-linear relationship broadly consistent with the EKC hypothesis. At lower levels of income, increases in GDP per capita are associated with rising emissions, reflecting the scale effect of economic activity. At higher income levels, the curve begins to flatten, suggesting gradual improvements in efficiency. However, the absence of a clear downward trend indicates that South Africa has not yet reached the EKC turning point.

Although the Environmental Kuznets Curve (EKC) hypothesis has been widely tested, empirical evidence remains mixed, particularly in developing and emerging economies. In the South African context, findings are notably inconsistent. For example, using an Autoregressive Distributed Lag (ARDL) model over the period 1980–2014 [3], find evidence of a long-term relationship between economic growth and CO₂ emissions but fail to confirm the existence of the EKC hypothesis. In contrast, applying a dynamic ARDL simulation model for the period 1990–2018 [4], economic growth increases carbon emissions in both the short and long run, indicating the dominance of the scale effect and the absence of a turning point. Moreover, these contrasting findings highlight the ongoing debate and the need for further empirical investigation.

Despite these contributions, an important gap remains in the literature. Existing studies often focus narrowly on the growth–emissions nexus and fail to adequately incorporate other critical determinants, such as trade openness and energy intensity. This limitation is particularly relevant for South Africa, where high energy intensity and carbon-intensive trade structures may significantly influence emissions dynamics. In addition, there is limited country-specific evidence that clearly distinguishes between short-term adjustments and long-term equilibrium relationships within an integrated framework.

This study addresses these gaps by examining the relationship between economic growth and carbon emissions in South Africa within an augmented EKC framework that incorporates trade openness and energy intensity over the period 1970–2022. The specific objectives are as follows:

- (i) Test the validity of the Environmental Kuznets Curve hypothesis;
- (ii) Estimate the short-term and long-term effects of economic growth on carbon emissions;
- (iii) Examine the role of trade openness and energy intensity;
- (iv) Determine whether South Africa has reached the EKC turning point.

This study contributes to the literature in three important ways. First, it provides updated, comprehensive time series evidence for South Africa over a long time span, capturing historical and structural dynamics often overlooked in previous studies. Second, it extends the EKC framework by explicitly incorporating trade openness and energy intensity, which are critical in a coal-dependent economy. Third, it employs the Autoregressive Distributed Lag (ARDL) approach to distinguish between short-term dynamics and long-term equilibrium relationships, thereby offering more robust and policy-relevant insights into the growth–environment nexus.

The study contributes to the literature in several ways. First, it provides a comprehensive, country-specific analysis using a long time series (1970–2022) that captures structural dynamics often overlooked in panel studies. Second, it integrates trade openness and energy intensity within the EKC framework, offering a more complete understanding of the drivers of emissions. Third, it employs the Autoregressive Distributed Lag (ARDL) approach to distinguish between short-term and long-term dynamics, providing policy-relevant insights into the timing and nature of environmental adjustments. Finally, it contributes to the ongoing debate on whether emerging economies can achieve decoupling between economic growth and carbon emissions.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature on the Environmental Kuznets Curve and related empirical studies. Section 3 provides an overview of carbon emissions in South Africa. Section 4 discusses the empirical model and methodology used in the study. Section 5 presents and discusses the empirical results, while the final section concludes the study and provides policy recommendations.

2. Literature Review

2.1. Theoretical Literature

The relationship between economic growth, trade openness, and carbon emissions is most rigorously conceptualized within the Environmental Kuznets Curve (EKC) hypothesis. The EKC posits a non-linear, inverted U-shaped relationship between income and environmental degradation [1,5]. In the early stages of economic development, environmental pressure intensifies as industrialization, urbanization, and energy consumption expand. However, beyond a critical income threshold, further economic growth is expected to reduce environmental degradation through structural transformation, technological advancement, and the implementation of more stringent environmental regulations.

Despite its widespread application, the EKC hypothesis is not universally valid and has been subject to substantial theoretical and empirical critique. The inverted U-shaped relationship is highly conditional and depends on country-specific factors such as institutional quality, energy structure, and technological capability [6,7]. This implies that economic growth alone does not guarantee environmental improvement. Rather, the transition to lower emissions depends on whether economies can restructure production systems, adopt cleaner technologies, and enforce effective environmental policies. This limitation is particularly relevant in the context of South Africa, where a carbon-intensive industrial base and heavy reliance on coal-based energy may delay or prevent the realization of the EKC turning point [8,9].

The mechanisms underpinning the EKC can be understood through three interrelated channels: structural transformation, technological progress, and behavioural and institutional responses. Structural transformation refers to the shift in economic activity from energy-intensive sectors such as mining and heavy manufacturing toward less carbon-intensive sectors such as services and advanced manufacturing. However, in economies where this transition is incomplete, emissions may remain persistently high despite increases in income. Technological progress represents a second critical mechanism, as improvements in energy efficiency, renewable energy adoption, and pollution control technologies reduce emissions per unit of output. The effectiveness of this channel depends on sustained investment in innovation and supportive regulatory frameworks [10].

Behavioural and institutional dynamics further shape the relationship between growth and environmental quality. As income levels rise, societies tend to place greater value on environmental protection, leading to stronger regulatory frameworks and increased demand for cleaner production processes. However, this response is neither automatic nor uniform, as it depends on governance capacity, policy enforcement, and public awareness. The EKC should therefore be interpreted as a conditional framework in which environmental improvement is achieved only when economic growth is accompanied by appropriate institutional and technological changes.

The inclusion of trade openness introduces an additional layer of complexity into this framework. According to the trade–environment literature, the impact of trade on environmental outcomes operates through scale, composition, and technique effects [11]. The scale effect suggests that increased production associated with trade expansion may raise emissions, particularly in economies that specialize in carbon-intensive exports. The composition effect reflects shifts in the structure of production toward less polluting sectors, while the technique effect captures improvements in environmental performance resulting from technology transfer and increased efficiency [12,13]. The overall environmental impact of trade openness, therefore, depends on the relative dominance of these effects.

In addition, energy intensity plays a critical role in mediating the relationship between economic growth and carbon emissions. Energy intensity reflects the amount of energy required to produce a unit of economic output and serves as an indicator of an economy's efficiency and carbon intensity. In South Africa, high energy intensity is closely linked to the dominance of coal in electricity generation and the prevalence of energy-intensive industries. As a result, even with economic growth and trade integration, high energy intensity can sustain elevated levels of carbon emissions unless accompanied by structural and technological change.

In the South African context, the interaction between economic growth, trade openness, and energy intensity is shaped by a combination of industrial structure, energy dependence, and policy effectiveness. While trade integration creates opportunities for technological upgrading and efficiency gains, its environmental benefits depend on domestic industries' ability to absorb and implement cleaner technologies. Similarly, economic growth can either exacerbate or reduce emissions depending on whether it is accompanied by structural transformation and improvements in energy efficiency.

Taken together, the theoretical literature demonstrates that the EKC provides a valuable but inherently conditional framework for analysing the relationship between economic growth and environmental degradation. Its applicability depends on the interaction between structural change, technological progress, institutional quality, trade dynamics, and energy efficiency. This perspective provides a strong theoretical basis for evaluating how policy interventions, technological innovation, and trade openness can jointly influence South Africa's transition toward a lower-carbon development path.

2.2. Empirical Literature

Empirical investigations into the Environmental Kuznets Curve (EKC) and the role of trade openness in shaping carbon emissions have produced diverse and often conflicting results, reflecting differences in methodology, sample periods, and country-specific characteristics. Evidence from developed economies generally suggests that the relationship between economic growth and environmental quality is mediated by technological progress and institutional strength, although the magnitude and direction of these effects vary across studies.

Using panel fixed effects for 24 OECD countries over the period 2005–2022 [14], the paper finds that trade liberalization contributes to economic growth while simultaneously reducing CO₂ emissions through structural transformation and the adoption of cleaner technologies. Similarly, applying a dynamic panel Generalized Method of Moments (GMM) approach for the period 2000–2020 [15], the paper reported that renewable energy adoption and green technological innovation significantly reduce emissions, although globalization combined with carbon-intensive trade can offset these gains. In contrast, employing a two-step system GMM estimator with Driscoll–Kraay standard errors over the period 2001–2022 [16], the paper demonstrated that the environmental benefits of trade openness are conditional on the quality of natural resource governance, suggesting that institutional factors play a decisive role in determining environmental outcomes. Evidence from Europe [17], based on panel data analysis, further indicates that economic growth reduces emissions only within circular economy systems, while linear production systems continue to generate environmental degradation.

Studies from developing regions reveal even greater heterogeneity, particularly in relation to non-linear and threshold effects. Using panel quantile regression for 22 Asian countries over the period 2000–2019 [18], the paper finds that trade openness initially increases emissions but reduces them beyond a certain income threshold, providing partial support for the EKC hypothesis. By contrast, employing regression and wavelet analysis

for low-income and environmentally degraded economies over the period 2001–2020 [19], the paper showed that the effects of economic growth and foreign direct investment on emissions vary significantly across different stages of development and levels of technological capacity. These findings suggest that the relationship between growth, trade, and emissions is not only non-linear but also highly dependent on structural and technological conditions.

Empirical evidence from Africa remains relatively limited and methodologically diverse, but it highlights the importance of institutional and structural constraints. Using partial least squares structural equation modelling for 48 Sub-Saharan African countries over the period 2000–2023 [20], the paper found that environmental sustainability may negatively affect economic growth in the absence of strong governance structures. However, the study also demonstrates that effective institutional frameworks can mitigate this trade-off, reinforcing the argument that policy and governance are central to achieving sustainable development outcomes.

South Africa presents a particularly complex and policy-relevant case, given its high carbon intensity and dependence on coal-based energy. Empirical findings for the country are mixed and often sensitive to model specification and estimation techniques. An Autoregressive Distributed Lag (ARDL) model for the period 1990–2020 [4], the study identified both inverted U-shaped and U-shaped relationships between per capita GDP and CO₂ emissions, indicating instability in the EKC relationship. Applying ARDL bounds testing for the period 1971–2019 [21], the study found that economic growth continues to increase emissions, although urbanization contributes to emission reductions. Analysing data from 1990 to 2021 using time series techniques [22], the paper shows that green growth initiatives improve environmental quality, while trade openness has limited and statistically insignificant effects. Employing asymmetric panel methods for the period 1991–2022, the paper [23] demonstrated that reductions in electricity consumption significantly decrease emissions, while the impact of income varies across different economic phases.

A comparison of these studies reveals several important patterns. First, results are highly sensitive to the choice of methodology, with panel estimators such as fixed effects and GMM capturing cross-country heterogeneity but often failing to account for country-specific dynamics. Second, time series approaches such as ARDL provide more consistent insights into individual country behaviour but yield mixed evidence regarding the EKC hypothesis in South Africa. Third, the role of trade openness remains ambiguous, as its impact depends on whether scale effects dominate over technique and composition effects. Finally, the importance of energy-related variables, particularly electricity consumption and energy intensity, emerges consistently across studies, suggesting that ignoring these factors may lead to incomplete conclusions.

These inconsistencies highlight the need for a modelling approach that can simultaneously capture short-term dynamics and long-term equilibrium relationships while accounting for country-specific characteristics.

2.3. Conceptual Framework

The conceptual framework integrates economic growth, trade openness, and energy intensity within the Environmental Kuznets Curve hypothesis to explain carbon emission dynamics. Economic growth is expected to exert a non-linear effect on emissions, increasing environmental degradation in the early stages of development and potentially reducing it beyond a certain income threshold. However, this relationship is conditional on structural transformation, technological progress, and effective environmental regulation [8,24].

Trade openness influences emissions through scale, composition, and technique effects, reflecting the dual role of globalization in either increasing production-related emissions or facilitating the adoption of cleaner technologies. At the same time, energy intensity serves as a key moderating variable, capturing the efficiency of energy use and the carbon dependence of the economy. In South Africa, where coal dominates the energy mix, high energy intensity strengthens the link between economic growth and emissions, potentially offsetting the benefits of trade and technological progress.

Policy and institutional quality further condition these relationships by influencing the extent to which economies can transition toward cleaner production systems. As such, the interaction between economic growth, trade openness, and energy intensity determines the trajectory of carbon emissions (Figure 2).

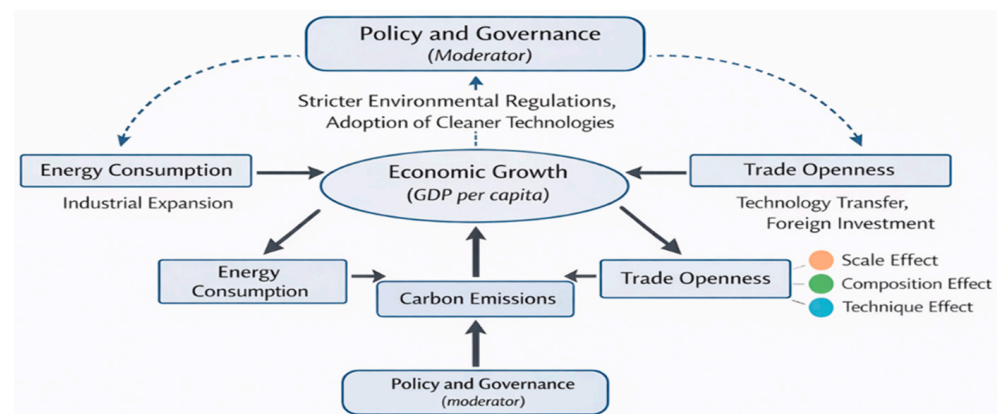


Figure 2. Conceptual framework. Source: authors' own computation.

This framework justifies the empirical strategy by supporting the use of the ARDL model, which can capture both short-term adjustments and long-term relationships among the variables. It also highlights energy intensity as a key transmission channel through which economic growth and trade openness affect environmental outcomes.

2.4. Research Gap

Despite the growing body of literature examining the relationship between economic growth and environmental degradation, several important gaps remain, particularly in the South African context.

First, empirical evidence on the validity of the Environmental Kuznets Curve (EKC) hypothesis remains inconclusive. While several studies report support for the conventional inverted U-shaped relationship between economic growth and carbon emissions, others find either no significant EKC relationship or alternative non-linear patterns. For example, evidence supporting the EKC hypothesis for South Africa is found [4], whereas differing results depending on the variables included, estimation techniques employed, and sample periods analysed are reported [21–23]. Similar inconsistencies have been documented in studies of emerging and developing economies, suggesting that the growth–environment nexus remains unresolved and warrants further country-specific investigation.

Second, although trade openness has been widely incorporated into EKC models, relatively few studies examine its interaction with energy structure and energy efficiency. Previous studies [14,15,18] demonstrate that the environmental effects of trade openness depend largely on the composition of production and the energy sources used in economic activities. However, in South Africa, where coal continues to dominate the energy mix, limited attention has been given to understanding how trade openness and energy intensity jointly influence carbon emissions. This omission may lead to an incomplete understanding of the environmental consequences of trade liberalization.

Third, methodological limitations remain prevalent in the literature. Many studies employ panel-data techniques such as fixed effects, random effects, and Generalized Method of Moments (GMM) estimators to examine the growth–environment relationship across countries. While these approaches provide useful comparative insights, they may conceal country-specific characteristics, institutional differences, and structural features that influence emissions behaviour. Furthermore, some time series studies focus exclusively on either short-term or long-term relationships, thereby limiting our understanding of the adjustment process between economic growth and environmental quality. Consequently, uncertainty remains regarding whether observed changes in emissions reflect permanent structural transformations or temporary economic fluctuations.

Fourth, the role of energy intensity as a key determinant of environmental degradation remains relatively underexplored in South African EKC studies. Existing research has primarily focused on aggregate energy consumption, renewable energy use, or electricity consumption, while paying less attention to the efficiency with which energy is utilized in production processes. Several studies [9,23,25] highlighted the importance of energy intensity in explaining carbon emission dynamics, particularly in energy-intensive and resource-dependent economies. Given South Africa’s continued reliance on fossil-fuel-based energy production, the omission of energy intensity may result in an incomplete assessment of the drivers of carbon emissions.

To address these gaps, this study employs the Autoregressive Distributed Lag (ARDL) modelling framework to examine the short-term and long-term relationships among carbon emissions, economic growth, trade openness, and energy intensity in South Africa over the period 1970–2022. Unlike many previous studies, the analysis explicitly incorporates energy intensity within an EKC framework and focuses on a single country, thereby allowing for a more detailed assessment of country-specific dynamics. By doing so, the study contributes to the literature by providing updated empirical evidence on whether economic growth can be decoupled from carbon emissions in one of Africa’s most carbon-intensive economies.

3. Methodology

This study adopts a quantitative time series framework to examine the relationship between economic growth, trade openness, energy intensity, and carbon emissions in South Africa over the period 1970–2022.

To ensure comparability, all variables are expressed in constant prices and transformed into natural logarithms, allowing estimated coefficients to be interpreted as elasticities.

Rather than restating the theoretical foundations of the Environmental Kuznets Curve (EKC), the framework is operationalized empirically through a non-linear specification in which economic growth enters both in linear and squared forms. This allows for the testing of the inverted U-shaped relationship between income and environmental degradation [1,5].

3.1. Model Specification

To improve the analytical contribution of the study, the standard EKC model is extended by incorporating a bidirectional structural relationship between carbon emissions and economic activity. While most EKC studies model emissions as a function of income, this study additionally recognizes that environmental degradation may feed back into economic performance through productivity losses, environmental costs, and regulatory pressures [6].

Accordingly, the baseline EKC model is specified as:

$$\ln CO2_t = \beta_0 + \beta_1 \ln GDP_{pc,t} + \beta_2 (\ln GDP_{pc,t-i})^2 + \beta_3 \ln TO_t + \beta_4 \ln EI_t + \varepsilon_t \quad (1)$$

A positive coefficient (α_1) would indicate that emissions are associated with growth through industrial activity, while a negative coefficient would reflect environmental constraints on economic performance.

Data Sources

Quarterly data covering the period 1970 Q1–2022 Q4 were obtained from several reputable international and national databases. Real Gross Domestic Product (GDP) per capita, exports, imports, and other macroeconomic variables were sourced from the South African Reserve Bank (SARB) Online Statistical Query database, which provides historical quarterly time series data through its Quarterly Bulletin database, available at South African Reserve Bank Online Statistical Query (<https://www.sarb.co.za/en/home/what-we-do/statistics/releases/online-statistical-query?utm>, accessed on 15 February 2026). Trade openness was calculated as the ratio of the sum of exports and imports to GDP using quarterly data extracted from the SARB database.

Energy intensity data were obtained from the International Monetary Fund (IMF) Data Portal and the National Economic Accounts database, which provide access to quarterly macroeconomic and energy statistics through the IMF's official data repository, available at IMF Data Portal (<https://data.imf.org/en?utm>, accessed on 17 February 2026) and International Monetary Fund Data Resources (<https://www.imf.org/en/>, accessed on 17 February 2026).

Carbon dioxide (CO₂) emissions data were obtained from the World Bank's World Development Indicators database and Our World in Data. As these sources primarily provide annual observations, the annual CO₂ series was converted into quarterly observations using the quadratic-match average interpolation procedure in STATA to obtain a balanced quarterly dataset spanning 1970 Q1–2022 Q4. The interpolation procedure preserved annual totals while generating quarterly estimates suitable for time series econometric analysis.

The final dataset consisted of 212 quarterly observations and was used to examine the long-term and short-term relationships among carbon emissions, economic growth, trade openness, and energy intensity in South Africa.

3.2. Variable Definition and Expected Relationships

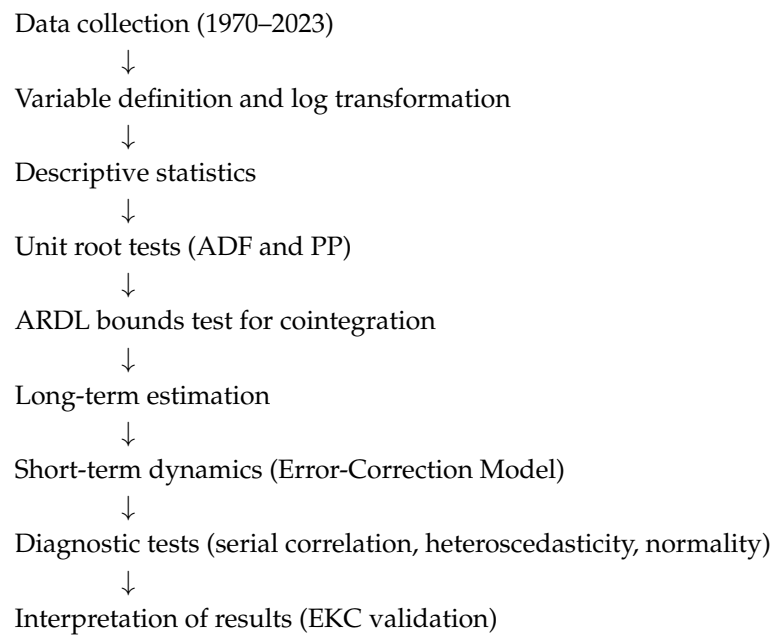
The model includes four key variables, selected based on theoretical relevance and the structural characteristics of the South African economy.

Carbon emissions (CO₂) serve as the dependent variable in the EKC framework and proxy environmental degradation. Economic growth (GDP per capita) captures the level of development and is expected to have a positive coefficient in its linear form and a negative coefficient in its squared form, consistent with the EKC hypothesis [1].

Energy intensity reflects the efficiency of energy use and is expected to have a positive relationship with emissions, as higher energy intensity indicates greater reliance on fossil fuels and inefficient production processes [6].

The effect of trade openness is theoretically ambiguous but not undefined. It operates through three well-established channels. The scale effect increases emissions through expanded production; the technique effect reduces emissions via technological improvements; and the composition effect reflects shifts in the industrial structure [26]. In the case of South Africa, where exports are relatively energy-intensive, the scale effect is expected to dominate in the short run, although the technique effect may become more relevant in the long run.

Flowchart of Data Processing and Empirical Analysis



3.3. Estimation Strategy: Long-Term and Short-Term Dynamics

The empirical analysis is conducted using the Autoregressive Distributed Lag (ARDL) bounds-testing approach [27]. This method is appropriate for small samples and allows for the estimation of both long-term equilibrium relationships and short-term dynamics within a unified framework. The empirical model is not entirely new; rather, it is based on the conventional Environmental Kuznets Curve (EKC) framework widely adopted in environmental economics literature. The model specification follows the augmented EKC approach in which carbon emissions are modelled as a function of economic growth, its squared term, trade openness, and energy intensity. Similar model specifications have been employed in previous studies investigating the growth–environment nexus, including those for the ARDL methodology [27] and more recent EKC studies [12,18,28,29].

The long-term relationship is derived from the ARDL model once cointegration among the variables is established. These coefficients capture the equilibrium impact of economic growth, trade openness, and energy intensity on carbon emissions.

Short-term dynamics are modelled through the following error-correction representation:

$$\Delta \ln CO2_t = \alpha_0 + \sum_{i=1}^p (\beta_i \Delta \ln CO2_{t-i}) + \sum_{i=0}^q (\gamma_i \Delta \ln GDPpc_{t-i}) + \sum_{i=0}^q \delta_i \Delta (\ln GDPpc_{t-i})^2 + \sum_{i=1}^r (\phi_i \Delta \ln TO_{t-i}) + \sum_{i=1}^s (\theta_i \Delta \ln EI_{t-i}) + \lambda ECT_{t-1} + \varepsilon_t \quad (2)$$

In this formulation, the difference variables capture short-term adjustments, while the Error-Correction Term (ECT) measures the speed at which deviations from long-term equilibrium are corrected. A negative and statistically significant ECT coefficient confirms the existence of a stable long-term relationship and indicates convergence following short-term shocks.

3.4. Diagnostic and Robustness Tests

To ensure the validity of the results, standard diagnostic tests are performed, including tests for serial correlation, heteroscedasticity, and normality of residuals [30].

Robustness is further assessed by alternative model specifications and sensitivity analysis, ensuring that the estimated relationships are not driven by model-specific assumptions.

4. Results and Discussion

4.1. Descriptive Statistics

Table 1 presents the descriptive statistics for the variables employed in the analysis. The dataset consists of 212 quarterly observations spanning the period 1970–2022. Carbon dioxide emissions ($\ln\text{CO}_2$) recorded a mean value of 0.72 with a standard deviation of 0.12, indicating relatively limited variation in emissions over the study period. This finding is consistent with South Africa’s long-standing dependence on coal-based energy production, which has historically contributed to persistently high but relatively stable emission levels [31,32].

Table 1. (a) Descriptive statistics. (b) Correlation matrix.

(a)								
Variable	N	Mean	Std. Dev.	Median	Minimum	Maximum	Skewness	Kurtosis
$\ln\text{CO}_2$	212	0.72	0.12	0.72	0.42	1.02	−0.11	−0.40
$\ln\text{GDP}$	212	6.76	0.59	6.71	5.27	7.78	−0.34	−0.66
$\ln\text{GDP}^2$	212	46.04	7.85	45.07	27.73	60.54	−0.18	−0.84
$\ln\text{Trade}$	212	2.47	0.19	2.47	2.00	2.98	0.00	−0.40
$\ln\text{Energy}$	212	−0.28	0.28	−0.25	−0.98	0.25	−0.25	−0.98
(b)								
Variable	$\ln\text{CO}_2$	$\ln\text{GDP}$	$\ln\text{GDP}^2$	$\ln\text{Trade}$	$\ln\text{Energy}$			
$\ln\text{CO}_2$	1.0000	0.1084	0.1145	0.1401	−0.1043			
$\ln\text{GDP}$	0.1084	1.0000	0.9988	0.4022	−0.5358			
$\ln\text{GDP}^2$	0.1145	0.9988	1.0000	0.4114	−0.5622			
$\ln\text{Trade}$	0.1401	0.4022	0.4114	1.0000	−0.5607			
$\ln\text{Energy}$	−0.1043	−0.5358	−0.5622	−0.5607	1.0000			

Source: authors’ computation using RStudio 2026.05 (2026).

Economic growth ($\ln\text{GDP}$) exhibited a mean value of 6.76 and a standard deviation of 0.59, suggesting moderate fluctuations in per capita income over the sample period. The observed variation reflects South Africa’s experience of alternating periods of economic expansion and contraction associated with structural reforms, global economic shocks, and changing domestic economic conditions. Similar patterns have been documented in studies examining the growth–environment nexus in emerging economies [21,28].

Trade openness ($\ln\text{TO}$) recorded a mean value of 2.47 with relatively low dispersion, indicating that South Africa maintained a relatively stable degree of integration into international markets throughout the study period. This observation is consistent with the growing importance of trade liberalization and global economic integration in shaping environmental outcomes [12,14,15,18]. Similarly, energy intensity ($\ln\text{EI}$) exhibited a mean value of −0.28, reflecting variations in energy use efficiency over time. Given South Africa’s energy-intensive industrial structure, fluctuations in energy intensity are expected to have important implications for environmental sustainability and carbon emissions [9,25].

The distributional properties of the variables indicate that the data are generally well behaved. Specifically, the skewness values are relatively close to zero, while the kurtosis statistics suggest no serious departures from normality. These findings imply the absence of significant outlier problems and support the suitability of the variables for subsequent econometric analysis. Similar distributional characteristics have been reported in recent Environmental Kuznets Curve (EKC) studies employing time series data [24,33].

The correlation matrix reveals weak positive associations between carbon emissions and economic growth (0.1084) as well as trade openness (0.1401), suggesting that increases in economic activity and international trade may be associated with higher levels of environmental degradation. These preliminary relationships are consistent with the scale effect hypothesis, which argues that economic expansion and increased trade activity can raise production levels and energy consumption, thereby increasing carbon emissions [12,18]. Conversely, energy intensity displays a weak negative relationship with carbon emissions (−0.1043), implying that improvements in energy efficiency may contribute to reducing environmental pressure. This finding supports the growing body of literature emphasizing the importance of energy efficiency improvements in promoting sustainable development and reducing carbon-intensive growth patterns [34,35].

As expected within the Environmental Kuznets Curve (EKC) framework, $\ln\text{GDP}$ and $\ln\text{GDP}^2$ exhibit a very high correlation coefficient (0.9988) because the squared income term is directly derived from GDP per capita. Such a high correlation is common in EKC studies and does not necessarily indicate a multicollinearity problem, as the squared term is intentionally included to capture the potential non-linear relationship between economic growth and environmental degradation [17,24,28]. Overall, the descriptive statistics provide preliminary evidence regarding the characteristics of the variables and establish a foundation for the subsequent unit root, cointegration, and ARDL analyses.

4.2. Unit Root Test Results

Table 2 reports the results of the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests used to examine the stationarity properties of the variables. The results indicate that carbon emissions ($\ln\text{CO}_2$), economic growth ($\ln\text{GDP}$), trade openness ($\ln\text{TO}$), energy intensity ($\ln\text{EI}$), and the squared income term ($\ln\text{GDP}^2$) are non-stationary at levels, as the respective test statistics fail to reject the null hypothesis of a unit root at conventional significance levels. However, following first differencing, all variables become stationary at the 1% significance level under both the ADF and PP tests.

Table 2. (a) Unit root test results (ADF and PP). (b) ARDL lag selection result.

(a)					
Variable	ADF Statistic	ADF <i>p</i> -Value	PP Statistic	PP <i>p</i> -Value	Order of Integration
$\ln\text{CO}_2$ (Level)	−2.822	0.231	−210.400	0.010	Non-stationary
$\ln\text{GDP}$ (Level)	−2.449	0.388	−41.797	0.010	Non-stationary
$\ln\text{Trade}$ (Level)	−2.347	0.431	−125.336	0.010	Non-stationary
$\ln\text{Energy}$ (Level)	−1.455	0.805	−39.547	0.010	Non-stationary
$\ln\text{GDP}^2$ (Level)	−2.393	0.411	−43.412	0.010	Non-stationary
$\Delta\ln\text{CO}_2$	−9.954	0.010	−256.523	0.010	I(1)
$\Delta\ln\text{GDP}$	−6.067	0.010	−248.715	0.010	I(1)
$\Delta\ln\text{Trade}$	−8.443	0.010	−264.510	0.010	I(1)
$\Delta\ln\text{Energy}$	−9.714	0.010	−253.528	0.010	I(1)
$\Delta\ln\text{GDP}^2$	−6.113	0.010	−249.832	0.010	I(1)
(b)					
Dependent Variable	Selected ARDL Model				
$\ln\text{CO}_2$	ARDL(1, 0, 1, 2, 1)				

Source: authors' computation using RStudio 2026.05 (2026).

The consistency between the ADF and PP results enhances confidence in the reliability of the stationarity findings and suggests that the variables follow a similar stochastic process. The presence of unit roots in macroeconomic and environmental variables is not unusual, as economic growth, trade integration, energy use, and carbon emissions generally exhibit persistent long-term trends associated with structural transformation, technological progress, and changes in production patterns. Similar integration properties have been reported in recent studies investigating the Environmental Kuznets Curve (EKC) hypothesis and carbon emissions dynamics [28,29,36].

The finding that all variables are integrated of order one, $I(1)$, is particularly important because it eliminates the risk of estimating spurious regression relationships and provides a valid basis for cointegration analysis. The ARDL bounds-testing approach is appropriate when variables are integrated of order zero, $I(0)$, order one, $I(1)$, or a combination of both, provided that none of the variables is integrated of order two, $I(2)$ [27]. Since none of the variables in this study are integrated beyond the first order, the fundamental assumptions required for the ARDL framework are satisfied.

The stationarity results therefore justify proceeding to the ARDL bounds cointegration analysis to determine whether a stable long-term equilibrium relationship exists among carbon emissions, economic growth, trade openness, and energy intensity. Establishing cointegration is particularly important within the EKC framework because the hypothesis is inherently concerned with long-term interactions between economic activity and environmental quality. Consequently, the unit root results provide a sound econometric foundation for the subsequent long-term and short-term analyses.

4.3. ARDL Estimation Results

Table 3 presents the estimated ARDL results examining the relationship between economic growth, trade openness, energy intensity, and carbon emissions in South Africa. The overall model is statistically significant, as indicated by the F-statistic of 3.879 ($p < 0.01$), suggesting that the explanatory variables jointly influence carbon emissions. The adjusted R-squared value of 0.1103 indicates that approximately 11% of the variation in carbon emissions is explained by the model. Although the explanatory power appears modest, this outcome is not uncommon in macroeconomic and environmental time series studies, where carbon emissions are influenced by a wide range of economic, technological, institutional, and policy-related factors that may not be fully captured within a single empirical framework [20,34].

Table 3. Model statistics.

Statistic	Value
R^2	0.1486
Adjusted R^2	0.1103
F-statistic	3.879
Prob(F-statistic)	0.00015

Source: authors' computation using RStudio 2026.05 (2026).

The estimated coefficient for economic growth ($\ln GDP$) is negative and statistically significant (-0.9911 , $p < 0.05$), while the coefficient of the squared income term ($\ln GDP^2$) is positive and statistically significant (0.0831 , $p < 0.01$). These findings provide evidence of a statistically significant non-linear relationship between economic growth and carbon emissions. However, contrary to the traditional Environmental Kuznets Curve (EKC) hypothesis, which predicts an inverted U-shaped relationship whereby environmental degradation initially increases and subsequently declines as income rises, the results indicate the existence of a U-shaped relationship. This implies that economic growth initially

contributes to reductions in carbon emissions, but beyond a certain income threshold, further economic expansion is associated with increasing environmental degradation.

The rejection of the conventional EKC hypothesis suggests that South Africa's economic development trajectory may not yet have reached a stage where technological progress, environmental regulation, and structural transformation are sufficiently strong to offset the environmental pressures associated with higher levels of production and consumption. This finding is consistent with recent studies that question the universal validity of the EKC hypothesis and emphasize that environmental outcomes remain highly dependent on country-specific institutional, technological, and energy conditions [17,24,33]. The result further supports the argument that continued economic growth alone is unlikely to guarantee environmental sustainability without complementary investments in cleaner technologies, renewable energy, and effective environmental policies.

With respect to trade openness, the results indicate a positive effect on carbon emissions, particularly through the second lag, which is statistically significant at the 1% level. This finding suggests that greater integration into international markets may contribute to increased environmental pressure in South Africa. One possible explanation is that trade expansion stimulates industrial production, transportation activities, and energy consumption, thereby increasing carbon emissions. This result is consistent with the scale effect argument and aligns with evidence from recent studies [12,14,15,18] that trade openness may increase environmental degradation when environmental regulations and green production practices are insufficiently developed.

Energy intensity also exhibits a positive lagged effect on carbon emissions, indicating that greater energy use relative to economic output contributes to environmental degradation. This finding reflects South Africa's continued dependence on carbon-intensive energy sources, particularly coal, which remains a dominant component of the national energy mix. The result is consistent with the findings in the literature [9,25,31,32] which argue that energy inefficiency and reliance on fossil fuels remain key drivers of carbon emissions in developing and emerging economies.

Overall, the ARDL results highlight the importance of economic structure, trade integration, and energy efficiency in shaping environmental outcomes in South Africa. The findings suggest that policies aimed at promoting sustainable growth should be accompanied by investments in renewable energy technologies, improvements in energy efficiency, stronger environmental regulations, and the adoption of cleaner production processes. Without such interventions, continued economic expansion and trade growth may exacerbate environmental degradation and undermine South Africa's long-term sustainability objectives.

4.4. Bounds Test for Cointegration

The ARDL bounds testing procedure was employed to determine whether a long-term equilibrium relationship exists among carbon emissions, economic growth, trade openness, and energy intensity in South Africa. The results reported in Table 4 indicate that the computed F-statistic of 36.488 exceeds the upper critical bound value at all conventional significance levels. Consequently, the null hypothesis of no cointegration is rejected, confirming the existence of a stable long-term relationship among the variables.

The existence of cointegration suggests that, although carbon emissions, economic growth, trade openness, and energy intensity may exhibit short-term fluctuations, they move together over time and converge towards a common long-term equilibrium path. This finding is particularly important because it implies that changes in economic activity, trade integration, and energy utilization have persistent long-term implications for environmental quality in South Africa. The result further indicates that deviations from equilibrium are

temporary and that the variables eventually adjust to restore their long-term relationship (Table 5).

Table 4. (a) ARDL bounds cointegration test. (b) Short-term ARDL coefficient estimates.

(a)				
Test Statistic			Value	
F-statistic			36.488	
<i>p</i> -value			0.000001	
Number of Regressors (k)			4	
Decision			Cointegration Exists	
(b)				
Variable	Coefficient	Std. Error	t-Statistic	<i>p</i> -Value
Constant	3.2507	1.3120	2.478	0.014 *
L(lnCO ₂ ,1)	0.0723	0.0690	1.048	0.296
lnGDP	−0.9911	0.4081	−2.428	0.016 *
lnGDP ²	0.0831	0.0307	2.704	0.007 ***
L(lnGDP ² ,1)	−0.0067	0.0037	−1.790	0.075
LnTrade	0.0535	0.0571	0.938	0.349
L(lnTrade,1)	−0.0203	0.0568	−0.357	0.722
L(lnTrade,2)	0.2281	0.0569	4.008	0.000 ***
lnEnergy	−0.0005	0.0614	−0.009	0.993
L(lnEnergy,1)	0.1640	0.0606	2.706	0.007 ***

Source: authors' computation using RStudio 2026.05 (2026). Note: * and *** indicate statistical significance at the 10% and 1% levels, respectively. Conclusion: The calculated F-statistic (36.488) exceeds the upper critical bound, confirming a long-term cointegrating relationship among the variables.

Table 5. (a) Error-Correction Model (ECM). (b) ECM statistics.

(a)				
Variable	Coefficient	Std. Error	t-Statistic	<i>p</i> -Value
Constant	3.2507	0.2386	13.623	0.000 ***
ΔlnGDP ²	0.0831	0.0062	13.473	0.000 ***
ΔlnTrade	0.0535	0.0509	1.050	0.295
ΔL(lnTrade,1)	−0.2281	0.0510	−4.468	0.000 ***
ΔlnEnergy	−0.0005	0.0533	−0.010	0.992
ECT(−1)	−0.9277	0.0680	−13.642	0.000 ***
(b)				
Statistic		Value		
R ²		0.5143		
Adjusted R ²		0.5024		
F-statistic		43.20		
Prob(F-statistic)		0.000		

Source: authors' computation using RStudio 2026.05 (2026). Note: *** indicate statistical significance at the 1% levels.

From a theoretical perspective, the cointegration result provides empirical support for the proposition that environmental outcomes are closely linked to macroeconomic and energy-related factors over the long term. This finding is consistent with the Environmental Kuznets Curve (EKC) framework, which assumes the existence of a stable long-term relationship between economic development and environmental degradation. The confirmation of cointegration, therefore, justifies the estimation of both long-term and short-term ARDL coefficients and supports further investigation of the nature of the growth–environment nexus.

The evidence of cointegration is consistent with numerous recent studies that have identified long-term relationships between carbon emissions, economic growth, trade openness, and energy-related variables. For example, a long-term equilibrium relationship between economic growth and carbon emissions in Croatia was reported using the ARDL framework [28]. Similarly, evidence of long-term interactions among economic growth, renewable energy consumption, and carbon emissions was found in Tunisia [37], while cointegration among economic growth, trade openness, foreign direct investment, and carbon emissions was confirmed in India using an ARDL model with structural breaks [29]. Related evidence has also been reported by studies [21,23,34] that documented persistent long-term relationships between economic activity, energy use, and environmental sustainability indicators.

The strong cointegration result obtained in this study suggests that environmental policies aimed at reducing carbon emissions cannot be implemented in isolation from broader economic and energy policies. Since economic growth, trade openness, and energy intensity are linked to carbon emissions in the long run, policymakers should adopt integrated strategies that simultaneously promote sustainable economic development, improve energy efficiency, encourage cleaner production technologies, and strengthen environmental governance. Such measures are essential for ensuring that economic progress is achieved without compromising environmental sustainability.

Overall, the ARDL bounds test confirms the presence of a stable long-term equilibrium relationship among the variables and provides a robust econometric foundation for estimating the long-term coefficients and error-correction dynamics presented in the subsequent sections.

4.5. Error-Correction Model (ECM)

The short-term dynamics of the relationship between carbon emissions, economic growth, trade openness, and energy intensity were examined using the Error-Correction Model (ECM). The estimated Error-Correction Term (ECT) is negative and highly statistically significant (-0.9277 , $p < 0.01$), satisfying the theoretical expectation for a valid long-term equilibrium relationship. The negative sign confirms the existence of cointegration among the variables and indicates that deviations from long-term equilibrium are corrected over time.

The magnitude of the ECT coefficient suggests that approximately 92.8% of any short-term disequilibrium is corrected within one period. This represents a relatively rapid speed of adjustment, implying that shocks affecting carbon emissions are largely transitory and that the system quickly returns to its long-term equilibrium path. The high adjustment rate reflects the strong interdependence between economic growth, trade openness, energy intensity, and environmental outcomes in South Africa. Similar evidence of rapid adjustment toward long-term equilibrium has been reported in recent ARDL-based environmental studies [28,29,37], which found that environmental and economic variables tend to converge relatively quickly following short-term disturbances.

With regard to the short-term coefficients, changes in the squared economic growth term exert a positive and statistically significant effect on carbon emissions. This finding suggests that periods of economic expansion are associated with increased environmental pressure in the short run, supporting the view that higher levels of production, industrial activity, and energy consumption contribute to rising carbon emissions. The result is consistent with studies that argue that economic growth continues to generate environmental costs in developing and emerging economies where production processes remain energy-intensive and heavily dependent on fossil fuels [21,24,33].

Lagged changes in trade openness exhibit a negative and statistically significant impact on carbon emissions in the short run. This result suggests that increased trade integration may contribute to environmental improvements through the transfer of cleaner technologies, greater production efficiency, and access to environmentally friendly goods and services. The finding supports the technology and efficiency effects of trade, which argue that openness can facilitate the adoption of cleaner production methods and reduce environmental degradation under the appropriate regulatory and institutional conditions. Similar evidence was reported in [12,15,16], showing that trade can contribute positively to environmental sustainability when accompanied by technological progress and effective governance mechanisms.

In contrast, energy intensity does not exert a statistically significant short-term effect on carbon emissions. This suggests that changes in energy efficiency may require a longer period before their environmental benefits become observable. Improvements in energy utilization often involve structural adjustments, technological investments, and behavioural changes that may not immediately translate into lower emissions. Consequently, the influence of energy intensity appears to be more relevant in the long run than in the short run. This finding is broadly consistent with the arguments advanced [9,25,34], which emphasize that energy-efficiency improvements typically generate environmental benefits over extended time horizons.

Overall, the ECM results indicate that although short-term shocks may temporarily affect carbon emissions, the adjustment mechanism is strong and effective, ensuring convergence toward long-term equilibrium. The findings further suggest that economic growth and trade openness play important roles in shaping short-term environmental outcomes, while the benefits of improved energy efficiency are more likely to materialize over the longer term. These results underscore the importance of integrating economic, trade, and energy policies within South Africa's broader environmental sustainability strategy.

4.6. Long-Term Coefficients

Table 6 presents the long-term coefficient estimates obtained from the ARDL model. The results indicate that economic growth exerts a statistically significant non-linear effect on carbon emissions in South Africa. Specifically, the coefficient of economic growth is negative, while the coefficient of the squared economic growth term is positive and statistically significant, confirming the existence of a U-shaped relationship between economic growth and carbon emissions. This finding implies that economic growth initially contributes to reductions in environmental degradation; however, beyond a certain income threshold, further economic expansion increases carbon emissions.

Table 6. Long-term ARDL coefficients.

Variable	Coefficient	Std. Error	t-Statistic	p-Value
Constant	3.5042	1.3885	2.524	0.012 *
lnGDP	−1.0684	0.4331	−2.467	0.014 *
lnGDP ²	0.0823	0.0331	2.488	0.014 *
lnTrade	0.2817	0.0781	3.609	0.000 ***
lnEnergy	0.1762	0.0647	2.725	0.007 ***

Source: authors' computation using RStudio 2026.05 (2026). Note: * and *** indicate statistical significance at the 10% and 1% levels, respectively.

The observed U-shaped relationship contrasts with the conventional Environmental Kuznets Curve (EKC) hypothesis, which predicts an inverted U-shaped relationship whereby environmental degradation rises during the early stages of economic development before declining at higher income levels. The rejection of the traditional EKC

hypothesis suggests that South Africa's economic growth path remains strongly associated with carbon-intensive production structures and fossil-fuel-based energy consumption. Although economic development may initially be accompanied by improvements in efficiency and environmental management, these gains appear insufficient to offset the environmental pressures generated by sustained economic expansion.

This finding is consistent with the growing body of literature questioning the universality of the EKC hypothesis and emphasizing the importance of country-specific economic, technological, and institutional factors in shaping environmental outcomes. Similar conclusions have been reported by studies that highlights the complex relationship between income and environmental quality [24,35], and demonstrated that environmental transitions may not necessarily follow the traditional EKC pattern [17]. Likewise, technological progress and environmental innovation are critical determinants of whether economic growth ultimately leads to environmental improvement [33,36].

Trade openness exhibits a positive and statistically significant long-term effect on carbon emissions. This finding suggests that increased integration into global markets contributes to higher environmental degradation over time. One possible explanation is that trade expansion stimulates industrial production, transportation activities, and energy demand, thereby increasing carbon emissions. The result supports the scale effect hypothesis, which argues that greater economic activity resulting from trade liberalization may increase environmental pressure unless accompanied by cleaner technologies and stricter environmental regulations. This finding is consistent with the empirical evidence in the literature [12,14,15,18], which found that trade openness may increase carbon emissions in countries where economic growth remains dependent on energy-intensive production processes.

Energy intensity also exhibits a positive and statistically significant long-term effect on carbon emissions. This result indicates that increases in energy use relative to economic output contribute to environmental degradation in South Africa. The finding reflects the country's continued reliance on fossil fuels, particularly coal, as the dominant source of energy generation. Consequently, improvements in energy efficiency and reductions in energy intensity are likely to play a crucial role in mitigating carbon emissions and promoting sustainable development. Similar literature [9,25,31,32,34] found that energy intensity and fossil-fuel dependence are major drivers of environmental degradation in developing and emerging economies.

From a policy perspective, the long-term results suggest that economic growth alone is insufficient to guarantee environmental sustainability. The findings highlight the need for stronger environmental regulations, accelerated investment in renewable energy technologies, improved energy efficiency, and the adoption of cleaner production methods. Furthermore, trade policies should be accompanied by measures that encourage green technologies and environmentally sustainable production practices. Without such interventions, continued economic expansion and trade integration may exacerbate environmental degradation and undermine South Africa's commitments to climate-change-mitigation and sustainable development objectives.

Overall, the long-term estimates confirm that economic growth, trade openness, and energy intensity are important determinants of carbon emissions in South Africa. The results provide evidence that environmental sustainability requires a comprehensive policy framework that simultaneously promotes economic development, energy transition, and environmental protection.

4.7. Granger Causality Results

Table 7 reports the results of the pairwise Granger causality tests conducted to examine the direction of predictive relationships among economic growth, trade openness, energy intensity, and carbon emissions. It is important to note that Granger causality does not imply true economic causation; rather, it assesses whether past values of one variable contain useful information for predicting future movements in another variable.

Table 7. (a) Granger causality results. (b) Environmental Kuznets Curve (EKC) turning point.

(a)			
Null Hypothesis	F-Statistic	p-Value	Decision
lnGDP does not have a Granger causal effect on lnCO ₂	0.398	0.672	Fail to reject
lnCO ₂ does not have a Granger causal effect on lnGDP	0.321	0.726	Fail to reject
lnTrade does not have a Granger causal effect on lnCO ₂	7.059	0.001 ***	Reject
lnEnergy does not have a Granger causal effect on lnCO ₂	0.455	0.635	Fail to reject
lnGDP ² does not have a Granger causal effect on lnCO ₂	0.437	0.646	Fail to reject
(b)			
Measure		Value	
Turning Point (GDP)		389.93	

Source: authors' computation using STATA 18 (2026). Note: *** indicate statistical significance at the 1% levels.

The results reveal no statistically significant causal relationship between economic growth and carbon emissions in either direction. Specifically, economic growth does not have a Granger causal effect on carbon emissions, and carbon emissions do not have a Granger causal effect on economic growth. This finding suggests that, although economic growth is significantly associated with carbon emissions in the ARDL framework, past changes in GDP do not provide additional predictive information regarding future carbon emissions beyond that already contained in the emissions series itself. Similarly, changes in carbon emissions do not appear to influence future economic growth. The absence of causality may reflect the influence of other intervening factors, such as technological change, energy structure, environmental policies, and institutional conditions, which mediate the relationship between economic activity and environmental outcomes. Similar mixed evidence regarding the growth–environment causality nexus has been reported in recent studies examining the Environmental Kuznets Curve (EKC) hypothesis [21,28] (Table 8).

Table 8. Diagnostic tests.

Test	Statistic	p-Value	Decision
Ljung–Box serial correlation	$\chi^2 = 0.449$	0.503	No autocorrelation
Breusch–Pagan heteroskedasticity	BP = 3.963	0.914	Homoskedastic residuals
Jarque–Bera normality	JB = 4.622	0.099	Residuals approximately normal

Source: authors' computation using STATA 18 (2026).

In contrast, trade openness was found to have a Granger causal effect on carbon emissions at the 1% significance level, indicating that past changes in trade activities contain valuable information for predicting future movements in carbon emissions. This result suggests that increasing integration into international markets may influence environmental outcomes through changes in production patterns, industrial activity, transportation demand, and energy consumption. The finding is consistent with the long-term ARDL results, which identified trade openness as an important determinant of carbon emissions. It also supports the view that trade-related activities play a significant role in shaping environmental performance in developing economies. Similar evidence has been docu-

mented in the literature [12,14,15,18], which reported that trade openness can significantly influence environmental quality through both scale and composition effects.

The results further indicate the absence of a statistically significant causal relationship between energy intensity and carbon emissions. This finding suggests that short-term fluctuations in energy intensity do not possess sufficient predictive power to explain future variations in carbon emissions. One possible explanation is that the environmental effects of changes in energy efficiency emerge gradually over time and are therefore more evident in long-term relationships than in short-term predictive dynamics. This interpretation is consistent with the ARDL and ECM findings, which indicate that energy-related factors exert a stronger influence on environmental outcomes over extended periods. Similar conclusions have been reached by previous studies [9,25,34], who emphasize that improvements in energy efficiency often generate environmental benefits that materialize over longer horizons.

Overall, the Granger causality results highlight the importance of trade openness as a key predictor of carbon emissions in South Africa, while suggesting that the relationships involving economic growth and energy intensity are more complex and may operate through indirect or long-term channels. These findings reinforce the need for policymakers to consider the environmental implications of trade policies and international economic integration when designing strategies aimed at reducing carbon emissions and promoting sustainable development.

4.8. Diagnostic Tests

Several post-estimation diagnostic tests were conducted to assess the reliability and robustness of the model. The Box-Ljung test failed to reject the null hypothesis of no serial correlation, indicating that the residuals are independently distributed. The Breusch–Pagan test further confirmed the absence of heteroskedasticity.

In addition, the Jarque–Bera test indicates that the residuals are approximately normally distributed. Collectively, these diagnostic results confirm that the estimated ARDL-ECM model is statistically stable and reliable for inference.

Overall, the findings establish the presence of a long-term relationship among carbon emissions, economic growth, trade openness, and energy intensity. The study does not support the traditional Environmental Kuznets Curve hypothesis; instead, it reveals a U-shaped relationship between economic growth and environmental degradation.

Furthermore, trade openness and energy intensity contribute positively to carbon emissions in the long run, while the error correction mechanism confirms rapid adjustment toward equilibrium following short-term disturbances.

5. Conclusions, Policy Recommendations and Limitations of the Study

5.1. Conclusions

This study examined the relationship between economic growth, trade openness, energy intensity, and carbon emissions in South Africa over the period 1970–2022 within an Environmental Kuznets Curve (EKC) framework using the ARDL approach. The empirical results confirm the existence of a stable long-term relationship among the variables, indicating that economic activity, trade integration, and energy use remain important determinants of environmental outcomes in South Africa.

The findings reveal that economic growth exerts a non-linear effect on carbon emissions. Contrary to the conventional EKC hypothesis, the results indicate a statistically significant U-shaped relationship, whereby economic growth initially contributes to lower carbon emissions but subsequently increases environmental degradation beyond a certain income threshold. This suggests that South Africa has not yet achieved a sustainable

growth path capable of decoupling economic expansion from environmental pressures. As economic activity continues to expand, the environmental costs associated with production and energy consumption remain significant.

The study further finds that trade openness contributes positively to carbon emissions in the long run, although short-term effects indicate some environmental benefits arising from technological diffusion and efficiency gains. These results suggest that the scale effects associated with increased production and trade activities outweigh the environmental benefits derived from technology transfer and improved production processes over time. Similarly, energy intensity exerts a positive and significant influence on carbon emissions, confirming that South Africa's continued reliance on energy-intensive production structures and fossil-fuel-based energy sources remains a major contributor to environmental degradation.

The error correction mechanism indicates a rapid adjustment towards long-term equilibrium following short-term shocks, demonstrating the stability of the estimated relationships. Furthermore, the Granger causality analysis reveals that trade openness predicts future carbon emissions, highlighting the importance of trade-related policies in shaping environmental outcomes.

Overall, the findings suggest that economic growth alone is insufficient to improve environmental quality in South Africa. Achieving sustainable development will require coordinated policy interventions aimed at improving energy efficiency, accelerating the transition towards renewable energy sources, promoting cleaner production technologies, and integrating environmental considerations into trade and industrial policies. Such measures are essential if South Africa is to reduce carbon emissions while maintaining long-term economic growth and fulfilling its climate-change-mitigation commitments.

5.2. Policy Recommendations

The findings suggest that economic growth in South Africa has a non-linear relationship with carbon emissions, whereby higher levels of economic expansion eventually contribute to increased environmental degradation. Policymakers should therefore pursue a green growth strategy that promotes low-carbon industrialization, sustainable infrastructure development, and the adoption of cleaner production technologies. Greater investments in environmentally friendly technologies and stronger environmental regulations are necessary to ensure that future economic growth is achieved without increasing carbon emissions.

The results further indicate that trade openness contributes positively to carbon emissions in the long run, despite generating short-term environmental benefits through efficiency gains and technology transfer. Consequently, trade policies should be aligned with environmental objectives by encouraging the importation of cleaner technologies, promoting environmentally sustainable exports, and enforcing environmental standards in export-oriented industries. Such measures would enable South Africa to benefit from international trade while reducing its environmental impact.

Energy intensity was found to have a positive and significant effect on carbon emissions, highlighting the importance of energy efficiency in achieving environmental sustainability. Policy interventions should therefore focus on reducing energy intensity through technological innovation, improved energy management practices, and investments in energy-efficient production systems. In addition, accelerating the transition towards renewable energy sources such as solar and wind power would reduce reliance on fossil fuels and contribute to long-term emissions reductions.

Given that carbon emissions remain closely linked to economic growth, trade activities, and energy intensity, South Africa should strengthen its climate mitigation efforts

through comprehensive carbon reduction strategies. These should include expanding renewable energy capacity, promoting cleaner production methods, encouraging energy efficiency improvements, and supporting sustainable economic activities that reduce environmental degradation while maintaining economic competitiveness. Such interventions would contribute to achieving sustainable development and meeting national climate change commitments.

5.3. Limitations of the Study

Despite providing important insights into the relationship between economic growth, trade openness, energy intensity, and carbon emissions in South Africa, this study is subject to several limitations that should be considered when interpreting the findings.

First, although the use of quarterly data spanning the period 1970–2022 provides a comprehensive basis for examining the long-term and short-term dynamics of carbon emissions, the analysis is conducted at the aggregate national level. Consequently, the study does not account for sector-specific heterogeneity in environmental performance. Different sectors of the South African economy, including mining, manufacturing, transport, agriculture, and services, may exhibit distinct patterns of energy consumption, carbon emissions, and environmental responses to economic growth. As a result, the aggregate framework may conceal important sectoral differences that could influence the overall growth–environment relationship.

Second, the empirical model is based on an augmented Environmental Kuznets Curve (EKC) framework and therefore focuses on a selected set of explanatory variables, namely economic growth, trade openness, and energy intensity. While these variables are theoretically and empirically relevant, other important determinants of environmental degradation were not explicitly incorporated into the analysis. Variables such as renewable energy consumption, technological innovation, foreign direct investment, urbanization, institutional quality, environmental regulations, climate policies, and financial development may also influence carbon emission dynamics. The omission of these factors may limit the comprehensiveness of the estimated relationships.

Third, the study employs the conventional Autoregressive Distributed Lag (ARDL) bounds-testing approach to estimate the long-term and short-term relationships among the variables. Although the ARDL methodology is appropriate for the study objectives and remains widely applied in environmental economics research, it assumes symmetric adjustment processes and does not explicitly capture non-linear or asymmetric responses. In practice, the effects of increases and decreases in economic growth, trade openness, or energy intensity may differ, implying that important asymmetric relationships may remain unexplored within the present framework.

Fourth, stationarity was assessed using the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests. While these tests are widely accepted and sufficient for the implementation of the ARDL framework, additional robustness checks such as the Dickey–Fuller Generalised Least Squares (DF-GLS), Kwiatkowski–Phillips–Schmidt–Shin (KPSS), and Zivot–Andrews unit root tests with endogenous structural breaks were not undertaken. Given South Africa’s experience of major economic reforms, energy supply disruptions, policy transitions, and global economic shocks during the study period, the presence of structural breaks cannot be completely ruled out. Similarly, although the ARDL bounds-testing approach provides a reliable framework for examining long-term relationships, alternative cointegration procedures such as the Bayer–Hanck combined cointegration test could provide additional evidence regarding the robustness and stability of the estimated relationships.

Fifth, the analysis assumes parameter stability throughout the sample period and does not explicitly model structural regime shifts or time-varying relationships. Consequently, potential changes in the growth–environment nexus associated with economic restructuring, technological progress, energy transitions, or environmental policy reforms may not be fully captured. The estimated coefficients therefore represent average relationships over the sample period rather than potentially evolving dynamics.

Finally, the study primarily focuses on hypothesis testing and policy-oriented econometric analysis rather than prediction and forecasting. Consequently, advanced artificial intelligence (AI), machine learning (ML), and deep learning techniques capable of identifying highly complex non-linear relationships and generating long-term forecasts were not incorporated. Although traditional econometric approaches remain appropriate for testing the Environmental Kuznets Curve hypothesis and evaluating policy implications, AI-based methods may provide complementary insights into future carbon emission trajectories and environmental sustainability scenarios.

Future research may extend the present study by incorporating additional environmental, institutional, technological, and macroeconomic variables; undertaking sector-specific analyses; employing non-linear and asymmetric frameworks such as the Non-linear Autoregressive Distributed Lag (NARDL) model; incorporating structural break methodologies including Zivot–Andrews and Bai–Perron tests; applying Bayer–Hanck cointegration procedures as robustness checks; exploring time-varying parameter and threshold models; and integrating machine learning techniques to enhance forecasting accuracy and scenario analysis. Such extensions would contribute to a more comprehensive understanding of the growth–environment nexus and sustainable development challenges in South Africa.

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Abbreviations

The following abbreviations are used in this manuscript:

ADF	Augmented Dickey–Fuller Test
AIC	Akaike Information Criterion
ARDL	Autoregressive Distributed Lag
CO ₂	Carbon Dioxide Emissions
CUSUM	Cumulative Sum of Recursive Residuals
CUSUMSQ	Cumulative Sum of Squares of Recursive Residuals
CTS	Composite Trade Share (proxy for trade openness)
ECM	Error-Correction Model
ECT	Error-Correction Term
EI	Energy Intensity

EKC	Environmental Kuznets Curve
GDP	Gross Domestic Product
GDP ²	Squared Gross Domestic Product
GDP _{pc}	Gross Domestic Product per capita
GMM	Generalized Method of Moments
I(0)	Integrated of order zero
I(1)	Integrated of order one
I(2)	Integrated of order two
LCO ₂	Log of Carbon Emissions
LEI	Log of Energy Intensity
LGDP	Log of GDP per capita
LGDP ²	Log of squared GDP per capita
LTO	Log of Trade Openness
LogL	Log-Likelihood
PP	Phillips–Perron Test
SIC	Schwarz Information Criterion
TO	Trade Openness
TTS	Traditional Trade Share (proxy for trade openness)

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