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Economic Growth, Trade Openness and Urbanization as Determinants of Carbon Dioxide Emissions in Algeria: An ARDL Approach, 1990–2025

Cherf Nassira

Abstract. *This study aims to analyze the determinants of carbon dioxide emissions in Algeria over the period 1990–2025,It examines the effects of economic growth, trade openness, and urbanization on CO_2 emissions,The Autoregressive Distributed Lag (ARDL) model is employed to investigate both short-run and long-run relationships,The results indicate the existence of a long-run relationship among the variables under study. Trade openness has a negative and statistically significant effect on CO_2 emissions,In contrast, urbanization has a positive and statistically significant effect, while economic growth has no significant long-run effect. These findings highlight the importance of integrated economic and environmental policies to promote sustainable growth and reduce CO_2 emissions. Industrial clusters show how spatial organization of economic activity affects environmental performance. To examine the determinants of CO_2 emissions in Algeria during 1990–2025, this study adopts the Fourier-ARDL approach to analyze both short-run dynamics and long-run relationships while accounting for smooth structural changes.*

Keywords: *CO_2 emissions, economic growth, trade openness, urbanization, ARDL, cointegration, Algeria*

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Əlcəzairdə karbon dioksid emissiyalarının müəyyənedici amilləri kimi iqtisadi artım, ticarətə açıqlıq və urbanizasiya: ARDL yanaşması (1990–2025)

Şerf Nassira

Xülasə. *Bu tədqiqat 1990–2025-ci illər ərzində Əlcəzairdə karbon dioksid (CO_2) emissiyalarının determinantlarını təhlil etməyi qarşıya məqsəd qoyur. Tədqiqat iqtisadi artımın, ticarət açıqlığının və şəhərləşmənin CO_2 emissiyalarına təsirini araşdırır. Dəyişənlər arasında həm qısamüddətli, həm də uzunmüddətli əlaqələri müəyyən etmək üçün Autoreqressiv Paylanmış Lag (ARDL) modelindən istifadə edilmişdir. Nəticələr tədqiq olunan dəyişənlər arasında uzunmüddətli əlaqənin mövcud olduğunu göstərir. Uzunmüddətli perspektivdə ticarət açıqlığı CO_2 emissiyalarına mənfi və statistik cəhətdən əhəmiyyətli təsir göstərir, şəhərləşmə isə müsbət və statistik cəhətdən əhəmiyyətli təsir göstərir. Bunun əksinə olaraq, iqtisadi artımın CO_2 emissiyalarına uzunmüddətli təsiri statistik cəhətdən əhəmiyyətli deyil. Bu nəticələr Əlcəzairdə davamlı iqtisadi inkişafı təşviq etmək və ətraf*

mühitə təzyiqləri və CO_2 emissiyalarını azaltmaq üçün inteqrasiya olunmuş iqtisadi və ekoloji siyasətlərin həyata keçirilməsinin vacibliyini vurğulayır. Sənaye klasterləri iqtisadi fəaliyyətin məkan təşkilinin ətraf mühitə təsirini nümayiş etdirir. Bu tədqiqat 1990–2025-ci illər ərzində Əlcəzairdə CO_2 emissiyalarının müəyyən edən amillərini araşdırmaq üçün həm qısamüddətli dinamikanı, həm də uzunmüddətli əlaqələri hamar struktural dəyişiklikləri nəzərə almaqla təhlil edən Fourier-ARDL yanaşmasından istifadə edir.

Açar sözlər: CO_2 emissiyaları, iqtisadi artım, ticarət açıqlığı, urbanizasiya, ARDL, kointeqrasiya, Əlcəzair

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Introduction

Climate change and environmental degradation have become among the most pressing challenges facing contemporary economies, particularly in light of the continuous increase in greenhouse gas emissions and the resulting economic, environmental, and social consequences (Loucks, 2021), Carbon dioxide (CO_2) emissions are among the most important indicators of environmental pressure due to their close association with fossil fuel use, industrial activity, and economic expansion. The growing emphasis on achieving sustainable development goals has shifted attention beyond the traditional view of economic growth as a standalone indicator of development toward examining whether economic growth can be achieved while reducing its adverse environmental consequences (Hickel, 2019).

This issue is particularly important in developing economies seeking to expand their productive base and diversify their economic activities. The expansion of production, investment, and industrialization may increase demand for energy and natural resources, as well as transportation and other economic activities, thereby intensifying environmental pressures. At the same time, technological progress, improvements in productive efficiency (Cantore, 2016), and the adoption of more sustainable practices may contribute to reducing emissions intensity. Therefore, the relationship between economic growth and environmental performance is not necessarily linear or stable, but may depend on the structural characteristics of the economy, the energy mix, the level of technological development, and the nature of industrial activity (Dogan, 2020).

In Algeria, this issue is particularly important given the historical dependence of the economy on the energy sector and natural resources, alongside ongoing efforts to develop the industrial base and diversify economic activity. Previous empirical studies have examined the relationship between economic growth, energy consumption, and CO_2 emissions in Algeria and have highlighted the importance of these variables in explaining environmental performance. Empirical evidence has also indicated that industrial activity constitutes an important factor in determining the evolution of emissions, making the study of industrial structure and organization increasingly relevant when analyzing the environmental determinants of the Algerian economy (Bouznit, 2016).

In this context, *industrialization and the spatial concentration of industrial activities* represent structural dimensions that deserve further investigation. Industrial clusters involve the concentration of interconnected firms and economic activities within a particular geographical or sectoral area, potentially generating economies of scale, knowledge and expertise sharing, common infrastructure,

greater efficiency, and innovation. In Algeria, increasing attention has been given to industrial clusters and agglomerations as potential mechanisms for supporting industrial development, strengthening firm competitiveness, and stimulating economic activity at both the local and national levels (Ferdj, 2024).

However, the environmental impact of industrial clusters does not necessarily follow a single direction. On the one hand, the concentration of industrial activity may increase production, energy consumption, transportation, and resource use, thereby raising CO_2 emissions. On the other hand, industrial concentration may generate benefits associated with shared infrastructure, more efficient resource utilization, knowledge and technology spillovers (Shen, 2023), and greater innovation, which may contribute to reducing emissions intensity. Accordingly, incorporating industrial clusters into the analysis of emission determinants makes it possible to move beyond examining the effect of *the scale of economic and industrial activity* toward investigating the effect of *the organization and spatial distribution of industrial activity* on environmental performance (Hu, 2022).

Trade openness is another important factor in explaining the evolution of carbon emissions. On the one hand, the expansion of international trade may increase production, transportation, energy consumption, and resource use, thereby intensifying environmental pressures. On the other hand, greater trade openness may facilitate the transfer of modern technologies, improve productive efficiency, and provide access to more energy-efficient and environmentally friendly technologies and equipment. Consequently, the net effect of trade openness on carbon emissions remains an empirical question that depends on the nature of the production and trade structure and the technological conditions of the economy under investigation (Wang & Zhang, 2023).

Urbanization also represents an important structural transformation that can influence environmental performance through changes in consumption, housing, transportation, and energy-use patterns. The increasing share of the population living in urban areas may raise demand for electricity, transportation, services, and infrastructure, potentially increasing emissions. Conversely, effective urban planning, improved public transportation systems (Yao, 2021), more efficient infrastructure, and economies of scale in service provision may mitigate some of the environmental consequences associated with urbanization. Therefore, the effect of urbanization on CO_2 emissions may vary depending on the characteristics of cities, the quality of urban planning, and the level of infrastructure development (Singh, 2024).

1.Research Hypotheses

Based on the research objectives and questions, the study proposes the following hypotheses:

H1: There is a cointegration relationship between carbon dioxide (CO_2) emissions and the explanatory variables, namely economic growth (GDP), trade openness (TO), and urbanization (URB), in Algeria during the period 1990–2025.

H2: There is a statistically significant effect of the explanatory variables, namely economic growth (GDP), trade openness (TO), and urbanization (URB), on carbon dioxide (CO_2) emissions in Algeria during the period 1990–2025.

Methods

This section presents the econometric methodology adopted to examine the determinants of carbon dioxide (CO_2) emissions in Algeria over the period 1990–2025. The analysis focuses on the effects of economic growth, trade openness, and urbanization. To capture both short-run dynamics and long-run relationships while accounting for potential smooth structural changes, the study employs the Fourier-ARDL approach.

2.1.Mathematical Specification of the Model:

Based on the objective of the study, which is to analyze the effects of economic growth, industrial clusters, trade openness, and urbanization on carbon dioxide emissions in Algeria over the period 1990–2025, the general economic model can be specified as follows:

$$CO2_t = f(GDP_t, TO_t, URB_t)$$

Carbon dioxide emissions *(CO2)* represent the dependent variable, while the explanatory variables include *economic growth (GDP)*, measured by the actual year-on-year growth rate; *trade openness (TO)*, measured as the ratio of the sum of exports and imports to gross domestic product (GDP); and *urbanization (URB),* which represents the share of the population residing in urban areas relative to the total population. Collectively, these variables are intended to explain the determinants of carbon dioxide emissions in Algeria over the period 1990–2025.

Accordingly, the proposed model equation, expressed in its explicit and linear form, can be specified as follows:

$$\Delta CO2_t = \alpha_0 + \Sigma_{i=1}^{p-1} \alpha_i \Delta CO2_{t-i} + \Sigma_{j=0}^{q1-1} \beta_j \Delta GDP_{t-j} + \Sigma_{j=0}^{q2-1} \gamma_j \Delta URB_{t-j} + \Sigma_{j=0}^{q3-1} \delta_j \Delta TO_{t-j} + \lambda_1 CO2_{t-1} + \lambda_2 GDP_{t-1} + \lambda_3 URB_{t-1} + \lambda_4 TO_{t-1} + \varepsilon_t$$

Where:

- Δ : denotes the first difference operator..
- Pq **:**represent the maximum lag orders for the dependent and explanatory variables in the model..
- $\lambda 1, \lambda 2, \lambda 3, \lambda 4,$ Level coefficients: These are the coefficients of the variables in levels and are used to test for the existence of a long-run relationship.
- $.\alpha 1, \alpha 2, \alpha 3, \alpha 4$: represent the coefficients of the long − run relationship
- *CO2* : represents carbon dioxide ***(CO2)*** emissions
- *GDP* : Economic Growth
- *URB* : represents urbanization.
- *TO* : represents trade openness.
- *T* denotes the number of observations.
- ε_t represents the random error term.

2.2. Study Data:

This study relies on annual data for Algeria covering the period *1990–2025*, with the aim of analyzing the determinants of carbon dioxide emissions, with particular emphasis on *economic growth, urbanization, and trade openness***.** The data were obtained from the *World Bank (World Development Indicators – WDI),* as it is a reliable international source that provides consistent and comparable time-series data.

The study variables include *carbon dioxide emissions (CO_2)***,** *economic growth***,** measured as the percentage change in real gross domestic product (GDP) from one year to the next, *urbanization (URB)***, *and* *trade openness (TO)*.** The following table presents the study variables.

Table1

Research variables

Variable Type	Variable	Measurement Method	Symbol
Dependent Variable	Carbon Dioxide Emissions	Total CO_2 emissions	CO_2
Independent Variable	Economic Growth	Percentage change in real GDP from one year to the next	GDP
Independent Variable	Urbanization	Percentage of the population residing in urban areas relative to the total population (%)	URB

Independent Variable	Trade Openness	((Exports + Imports) / GDP) × 100	TO

2.3. Descriptive and exploratory analysis of the data

The descriptive statistics presented in the table indicate variation in the characteristics of the study variables over the study period, which comprises 36 observations. The arithmetic mean of GDP was approximately 2.66%, with values ranging from −5% to 6.50% and a standard deviation of 2.29, reflecting fluctuations in economic growth rates over the study period.

The TO variable recorded a mean of 54.17, with values ranging from 38.98 to 71.03 and a standard deviation of 8.43. Meanwhile, the mean value of URB was approximately 64.90, with a minimum of 52.95, a maximum of 75.27, and a standard deviation of 7.47.

Regarding the distributional characteristics, GDP exhibited negative skewness of −1.29, whereas the skewness coefficients for TO and URB were relatively close to zero, at 0.083 and −0.187, respectively.

Based on the Jarque–Bera test, the probability value for GDP was approximately 0.0002, which is below the 5% significance level, indicating rejection of the null hypothesis of normality for this variable. In contrast, the probability values for TO and URB were 0.617 and 0.221, respectively, both exceeding the 5% significance level. Therefore, the null hypothesis of normality is not rejected for these two variables.

Overall, these results indicate differences in the behavior of the study variables, as well as variation in their statistical distributional characteristics over the period under analysis.

Table 2

Descriptive statistics of the study variables

	GDP	TO	URB
Mean	2.661543	54.16595	64.90425
Median	3.150000	54.04975	65.72250
Maximum	6.500000	71.02850	75.26800
Minimum	-5.000000	38.97890	52.95000
Std. Dev.	2.289736	8.284280	7.472397
Skewness	-1.294201	0.082826	-0.187322
Kurtosis	5.133225	2.215033	1.631550
Jarque-Bera	16.87572	0.965422	3.019518
Probability	0.000217	0.617108	0.220963
Sum	95.81555	1949.974	2336.553
Sum Sq. Dev.	183.5012	2402.025	1954.285
Observations	36	36	36

Source. Prepared by the researcher based on EViews 13 outputs.

2.4. Correlation Matrix of the Study Variables

The simple correlation matrix indicates relatively weak linear relationships among the explanatory variables of the model. The correlation coefficient between *Gross Domestic Product (GDP) and Trade Openness (TO)* was approximately *0.330544***,** indicating a weak to moderate positive relationship. Meanwhile, the correlation between *Gross Domestic Product (GDP)* and *Urbanization (URB)* was *0.119971***,** representing a very weak positive relationship.

The correlation between *Trade Openness (TO)* and *Urbanization (URB)* was *−0.113824*, indicating a very weak negative relationship. Overall, the results reveal relatively low correlation coefficients among the explanatory variables, with the absolute value of the highest correlation coefficient not exceeding *0.331*. This provides preliminary evidence that there is no strong linear correlation problem among the independent variables. However, this should be further confirmed using the *Variance Inflation Factor (VIF)* test.

Ordinary correlations:

	GDP	TO	URB
GDP	1.000000		
TO	0.330544	1.000000	
URB	0.119971	-0.113824	1.000000

Figure 3
Correlation Matrix of the Study Variables

Source. Prepared by the researcher based on EViews 13 outputs.

2.5. Multicollinearity Test
The table presents the results of the *Variance Inflation Factor (VIF)* test for the explanatory variables, namely *economic growth (GDP), trade openness (TO), and urbanization (URB)*. *The VIF* value for *GDP* was *1.155297*, while the VIF value for *TO* was *1.153615*, and *URB* recorded a value of *1.042577*.

These values are very low and close to one, and are well below the commonly used threshold values for detecting multicollinearity. The results therefore indicate that there is *no substantial multicollinearity problem among the explanatory variables*, suggesting that the degree of linear dependence among them is limited. This supports their simultaneous inclusion in the econometric model and enhances the reliability of the estimated coefficients of the ARDL model.

Table 4
Results of the Variance Inflation Factor (VIF) multicollinearity test

Variable	VIF
GDP	1.155297
TO	1.153615
URB	1.042577

Source. Prepared by the researcher based on R 4.6.0 outputs.

2.6. Time-Series Trend Analysis of the Study Variables in Algeria, 1990–2025
The figure 2 illustrates the historical trends of the study variables, namely *carbon dioxide emissions (CO_2), economic growth (GDP), trade openness (TO), and urbanization (URB)* in Algeria over the period 1990–2025. The time series reveal clear differences in the patterns of evolution of these variables, reflecting the economic and structural changes experienced by the Algerian economy during the study period.

The figure shows a *general upward trend* in carbon dioxide emissions. Emissions increased gradually from approximately 76 at the beginning of the period to more than 200 toward the end. Despite some fluctuations and temporary declines, particularly during certain years in the 1990s and early 2000s, the long-term trend remained clearly upward. This pattern indicates increasing environmental pressure associated with economic activity, energy consumption, and urbanization.

This variable is characterized by considerable fluctuations compared with the other variables. It recorded alternating positive and negative growth rates during the 1990s and early 2000s, followed by periods of relatively high growth during the first decade of the 2000s. A sharp decline in economic growth can also be observed around *2020***,** coinciding with the global economic shock associated with the COVID-19 pandemic, followed by a *clear recovery in subsequent years***.** Overall, the series indicates that economic growth in Algeria was characterized by a relatively high degree of volatility throughout the study period.

Trade openness exhibits a more volatile pattern. It increased from approximately 48 at the beginning of the period to levels exceeding 60 during the mid-2000s, reaching a peak of approximately 70 toward the end of that decade. Thereafter, it generally followed a downward trajectory, with some temporary rebounds, reaching approximately 39 at the end of the study period. This pattern suggests a relative decline in the degree of trade openness during the latter part of the study period compared with the levels recorded during the mid-2000s.

Urbanization displays the most stable trend compared with the other variables. It increased almost continuously from approximately *53% in 1990* to more than *75% in the final years of the study period***,** although the rate of increase slowed somewhat during certain periods. This trend reflects the continuation of the urbanization process in Algeria and the increasing concentration of the population in urban areas.

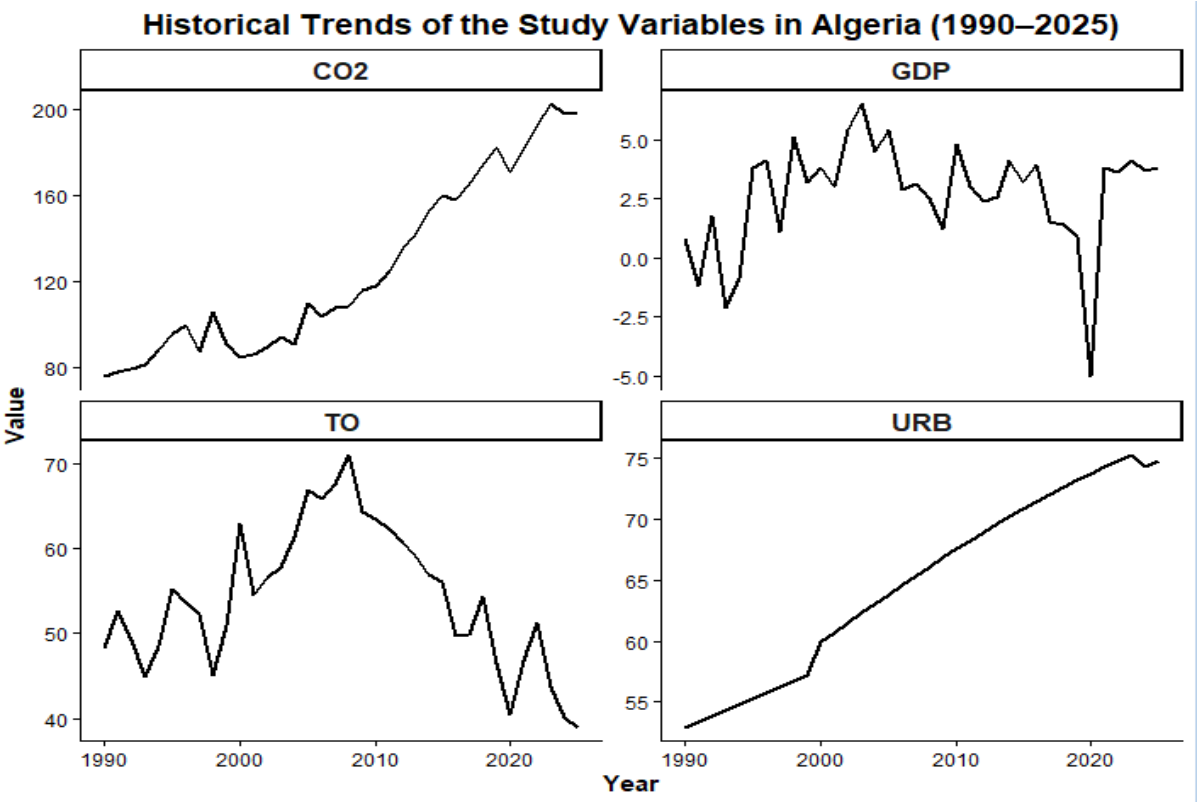


Figure 2

Trends of the study variables

Source. Prepared by the researcher based on R 4.6.0 outputs.

2.7 Analysis of the Relationship between CO_2 Emissions and Economic Variables in Algeria

The figure 3 illustrates the graphical relationships between *carbon dioxide emissions (CO_2)* and the explanatory variables, namely *Gross Domestic Product (GDP), Trade Openness (TO), and Urbanization (URB)* in Algeria over the period *1990–2025***.**

The figure indicates a *weak positive linear relationship* between CO_2 emissions and GDP, while a *negative relationship* is observed between CO_2 emissions and trade openness (TO). In contrast, the relationship between CO_2 emissions and urbanization (URB) exhibits *a strong positive pattern***,** with emission levels increasing as the degree of urbanization rises.

These descriptive patterns indicate differences in both the direction and strength of the relationships between the dependent variable and the explanatory variables. However, graphical relationships alone are insufficient to establish causality or statistical significance. Therefore, these relationships need to be further examined using the econometric tests and estimation results of the *ARDL model***.**

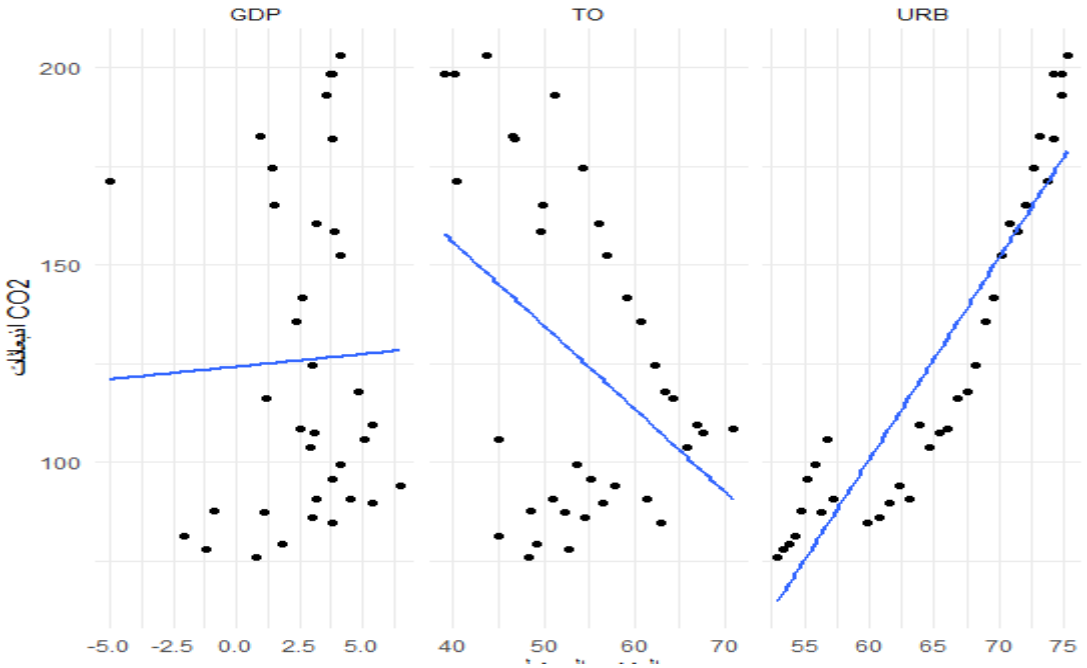


Figure 3

Analysis of the relationship between CO_2 emissions and economic variables in Algeria

Source. Prepared by the researcher based on R 4.6.0 outputs.

Results

3.1. Stationarity Test of the Time Series

The stationarity of a time series is assessed by determining whether it contains a *unit root***.** The presence of a unit root indicates that the series is non-stationary, which may lead to *spurious regression results* and consequently affect the reliability of econometric analysis.

Several tests can be used to examine the stationarity of time series, including the *Augmented Dickey–Fuller (ADF) test***.** In this study, the appropriate lag length was determined to examine the stationarity of the series using *EViews 13***.**

Table 5
ADF test for the stationarity of the study time series

Variable	Specification	At Level: t-Statistic	Prob.	Stationarity Result	Critical Values	At First Difference: t-Statistic	Prob.	Stationarity Result	Critical Values	Order of Integration
GDP	Trend and Intercept	-2.89	0.17	Non-s	At 5% level	-4.41	0.00	Stationary	At 5% level	I(1)
	Intercept	1.59	0.99	Non-s	At 5% level	-2.18	0.02	Stationary	At 5% level	
	None	6.86	0.99	Non-s	At 5% level	-2.18	0.02	Stationary	At 5% level	
CO_2	Trend and Intercept	-1.93	0.61	Non-s	At 5% level	-7.71	0.00	Stationary	At 5% level	I(1)
	Intercept	0.21	0.97	Non-s	At 5% level	-7.56	0.00	Stationary	At 5% level	
	None	2.61	0.99	Non-s	At 5% level	-6.09	0.00	Stationary	At 5% level	
TO	Trend and Intercept	-0.55	0.97	Non-s	At 5% level	-6.29	0.00	Stationary	At 5% level	I(1)
	Intercept	-1.36	0.58	Non-s	At 5% level	-6.15	0.00	Stationary	At 5% level	
	None	-0.51	0.48	Non-s	At 5% level	-6.20	0.00	Stationary	At 5% level	
URB	Trend and Intercept	-0.14	0.99	Non-s	At 5% level	-5.30	0.00	Stationary	At 5% level	I(1)
	Intercept	-1.64	0.44	Non-s	At 5% level	-5.06	0.00	Stationary	At 5% level	
	None	7.27	0.99	Non-stationary	At 5% level	-2.50	0.01	Stationary	At 5% level	

Source. Prepared by the researcher based on EViews 13 outputs.

The results of the Augmented Dickey-Fuller (ADF) test presented in Table (02) indicate that the time series of the study variables do not exhibit stationarity at level, as the statistical probability values (Prob.) indicate that the null hypothesis of a unit root cannot be rejected at the 5% significance level. In other words, the variables GDP, CO_2, TO, and URB are non-stationary at level.

Upon moving to the First Difference, the ADF test statistics generally decline, while the probability values reach 0.00 for most specifications, which are below the 5% significance level. This allows the null hypothesis to be rejected and the alternative hypothesis of stationarity to be accepted. Accordingly, the variables GDP, CO_2, TO, and URB become stationary after first differencing, indicating that they are integrated of order one, I(1).

These results indicate that all variables included in the estimated model are integrated of order I(1) under the adopted specification, and the results provide no evidence of any variable being integrated of order two, I(2). This finding is econometrically important because it satisfies one of the fundamental conditions for applying the ARDL methodology, which allows for the analysis of variables with mixed orders of integration, namely I(0) and I(1), provided that none of the variables is integrated of order I(2).

3.2. Optimal lag length selection test

Based on the *Akaike Information Criterion (AIC)***,** the optimal lag lengths were determined. The results indicate that the *ARDL (1,1,2,2)* model is the optimal specification, as shown in the following figure.

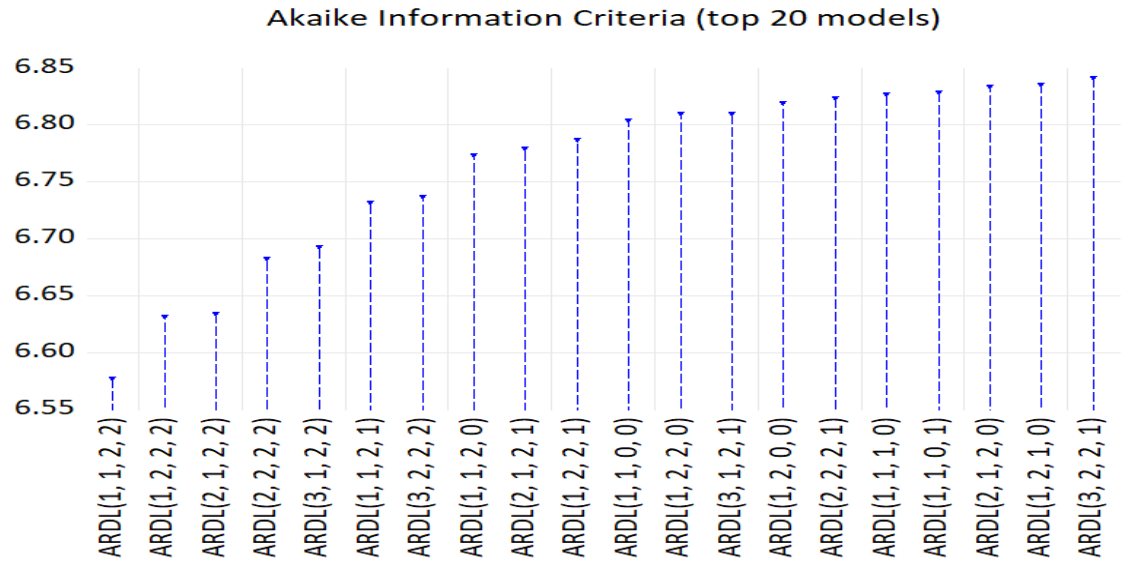


Figure 4

Results of the optimal lag length selection test for the ARDL model

Source. Prepared by the researcher based on EViews 13 outputs.

The results of the ARDL model selection test for the period 1990–2025, based on 34 observations, indicate that the optimal model is ARDL(1,1,2,2), which was selected based on the statistical information criteria. This model recorded the lowest value of the Akaike Information Criterion (AIC), at 6.576699, the lowest value of the Schwarz/Bayesian Information Criterion (BIC), at 7.030186, and the lowest value of the Hannan–Quinn Information Criterion (HQ), at 6.729284. Furthermore, the model achieved the highest Adjusted R^2 value of 0.979889, indicating a high explanatory power in accounting for variations in carbon dioxide emissions. These results confirm that the ARDL(1,1,2,2) model provides an appropriate specification compared with the alternative models presented. Therefore, it can be adopted as the basis for conducting the bounds test for cointegration, estimating the long-run and short-run coefficients, and examining the error correction mechanism.

3.3. Bounds Test for Cointegration

The results of the F-Bounds Test for the ARDL(1,1,2,2) model indicate that the calculated F-statistic is 3.557619, while the number of explanatory variables is k = 3, with an effective sample size of 34 observations. Based on the critical values for the finite sample (n = 35), the calculated F-statistic exceeds the upper bound I(1) at the 10% significance level, where the lower and upper bounds are 2.618 and 3.532, respectively. This allows the null hypothesis of no levels relationship to be rejected at this significance level.

In contrast, the calculated F-statistic falls between the lower and upper bounds at the 5% significance level, where the bounds are 3.164 and 4.194, respectively. Therefore, the result is inconclusive at the 5% significance level. Moreover, the calculated F-statistic does not exceed the lower bound at the 1% significance level.

Accordingly, the bounds test provides evidence of the existence of a long-run relationship among the study variables at the 10% significance level, while caution should be exercised when interpreting the long-run relationship at stricter significance levels.

Table 7

Bounds test for cointegration

F-Bounds Test		Null Hypothesis: No levels relationship		
Test Statistic	Value	Signif.	I(0)	I(1)
		Asymptotic: n=1000		
F-statistic	3.557619	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	34	Finite Sample: n=35		
		10%	2.618	3.532
		5%	3.164	4.194
		1%	4.428	5.816

Source. Prepared by the researcher based on EViews 13 outputs.

3.4. Diagnostic Tests for the ARDL(1,1,2,2) Model

The results of the diagnostic tests presented in the table indicate that the *ARDL model* exhibits acceptable statistical and diagnostic properties, as the tests reveal no major problems that could affect the validity of the model. Regarding serial correlation, the *Breusch–Godfrey LM test* yielded a probability value of *0.9239***,** which is greater than the 5% significance level. Therefore, the null hypothesis of no serial correlation in the residuals up to the second order cannot be rejected. Accordingly, there is no evidence of an autocorrelation problem in the model errors.

The *Breusch–Pagan–Godfrey test* recorded a probability value of *0.7181***,** which is also greater than 0.05. This indicates that the null hypothesis of homoskedasticity cannot be rejected, and hence there is no evidence of *heteroskedasticity* in the model residuals. This result is consistent with the *ARCH test***,** which recorded a probability value of *0.6228***,** confirming the absence of ARCH effects or systematic conditional changes in the error variance.

Regarding the adequacy of model specification, the *Ramsey RESET test* yielded a probability value of *0.0732***,** which is above the 5% significance level. Thus, the null hypothesis cannot be rejected, and there is insufficient statistical evidence of a major model specification error or the omission of an important nonlinear form in the specification at this significance level.

Finally, the *Jarque–Bera statistic* was approximately *1.70*, with a probability value of *0.42*, which is greater than 0.05. Therefore, the null hypothesis of normality of the residuals cannot be rejected. Accordingly, there is no statistical evidence that the residuals deviate from a normal distribution.

Overall, these results indicate that the model does not suffer from serial correlation, heteroskedasticity, or ARCH effects. Moreover, its residuals exhibit an acceptable normal distribution, and there is insufficient evidence at the 5% significance level of model specification error. Therefore, the diagnostic tests provide statistical support for the adequacy of the estimated model and the validity of the inferences derived from it.

Table 8
Diagnostic tests for the ARDL(1,1,2,2) model

Diagnostic Test	Statistic	Prob.	Decision at 5%	Conclusion
Breusch–Godfrey LM	F = 0.079476	0.9239	Do not reject H_0	No serial correlation up to the second order
Breusch–Pagan–Godfrey	F = 0.681399	0.7181	Do not reject H_0	No evidence of heteroskedasticity
ARCH	F = 0.246885	0.6228	Do not reject H_0	No ARCH effects
Ramsey RESET	F = 3.523890	0.0732	Do not reject H_0	No sufficient evidence of model specification error
Jarque–Bera	JB = 1.700000	0.4200	Do not reject H_0	Residuals are normally distributed

Source. Prepared by the researcher based on EViews 13 outputs.

3.5. Analysis of the CUSUM/CUSUMSQ Structural Stability Tests for the ARDL(1,1,2,2) Model
The graphs present the results of the *CUSUM and CUSUMSQ tests* for assessing the structural stability of the model. The first graph, corresponding to the *CUSUMSQ test*, shows that the cumulative path of the squared residuals remains within the critical bounds at the *5% significance level* throughout the study period, despite some noticeable fluctuations during the middle of the sample period.

Similarly, the second graph, corresponding to the *CUSUM test*, indicates that the cumulative path of the residuals remains within the critical bounds throughout the sample period, without exceeding them at any point in time.

Accordingly, *there is no statistical evidence of structural changes or instability in the model coefficients during the study period*. This indicates that the model coefficients are stable and that its estimates can be relied upon to interpret the long-run and short-run relationships among the variables. These findings further support the adequacy and stability of the *ARDL model*.

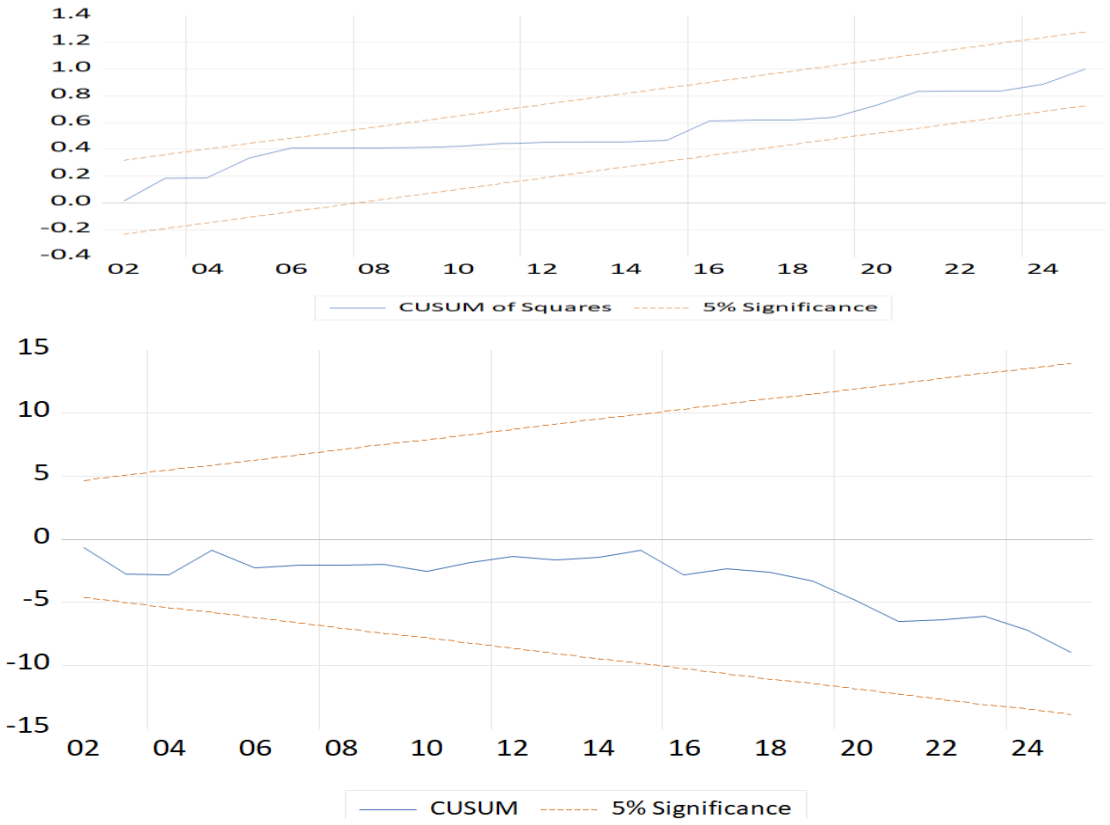


Figure 5

Structural stability of the model

Source. Prepared by the researcher based on R 4.6 outputs.

3.6. Estimation of the Parameters of the Proposed ARDL(1,1,2,2) Model for the Dependent Variable CO_2

A. Short-Run Results

The short-run dynamics of the estimated ARDL model are presented through the Error Correction Model (ECM), which captures the immediate and lagged effects of the explanatory variables on changes in CO_2 emissions. The results show that economic growth has a positive and statistically significant short-run effect on CO_2 emissions. The coefficient of D(GDP) is estimated at 0.8708, with a probability value of 0.0451, indicating statistical significance at the 5% level. This finding suggests that increases in economic activity are accompanied by higher CO_2 emissions in the short run, potentially reflecting increased production, energy consumption, and related economic activities.

Trade openness exhibits a dynamic short-run relationship with CO_2 emissions. The coefficient of D(TO) is negative (−0.4342) and statistically significant at the 10% level ($p = 0.0683$), indicating an initial reduction in emissions following an increase in trade openness. However, the first lag, D(TO(−1)), has a positive and statistically significant coefficient of 0.8374 ($p = 0.0024$), significant at the 1% level. This reversal in the sign across periods indicates that the short-run effect of trade openness varies over time, with an immediate negative association followed by a positive lagged effect.

Urbanization also displays a negative short-run association with CO_2 emissions. The contemporaneous coefficient of D(URB) is −3.9371, with a probability value of 0.0899, indicating significance at the 10% level. Similarly, D(URB(−1)) has a negative coefficient of −5.9498 and is statistically significant at the 5% level ($p = 0.0258$). The persistence of the negative coefficient across the current and lagged periods suggests that increases in urbanization are associated with reductions

in CO_2 emissions in the short run. This relationship may reflect, among other factors, changes in urban economic structures, resource allocation, or energy-use patterns accompanying urban development.

The error correction term, CointEq(−1), is negative and statistically significant, with an estimated coefficient of −0.5001 and a probability value of 0.0001, significant at the 1% level. The negative sign and statistical significance indicate the presence of an adjustment mechanism through which short-run deviations are corrected toward the estimated long-run equilibrium path. The coefficient implies that approximately 50% of the disequilibrium from the preceding period is corrected within one period. Thus, the model exhibits a relatively substantial adjustment speed toward long-run equilibrium, indicating that deviations from the equilibrium relationship tend to be partially corrected in the subsequent period.

Table 9

ARDL(1,1,2,2) model estimation results

ARDL Error Correction Regression
Dependent Variable: D(CO2)
Selected Model: ARDL(1, 1, 2, 2)
Case 2: Restricted Constant and No Trend
Date: 09/21/26 Time: 13:56
Sample: 1990 2025
Included observations: 34

ECM Regression
Case 2: Restricted Constant and No Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(GDP)	0.870814	0.411928	2.113999	0.0451
D(TO)	-0.434157	0.227425	-1.909013	0.0683
D(TO(-1))	0.837394	0.247292	3.386258	0.0024
D(URB)	-3.937054	2.227676	-1.767337	0.0899
D(URB(-1))	-5.949781	2.502860	-2.377193	0.0258
CointEq(-1)*	-0.500069	0.109772	-4.555522	0.0001

R-squared	0.580730	Mean dependent var	3.536098
Adjusted R-squared	0.505860	S.D. dependent var	7.818351
S.E. of regression	5.495916	Akaike info criterion	6.404673
Sum squared resid	845.7425	Schwarz criterion	6.674030
Log likelihood	-102.8794	Hannan-Quinn criter.	6.496531
Durbin-Watson stat	1.991695		

* p-value incompatible with t-Bounds distribution.

Source. Prepared by the researcher based on eviews 13

B Long-Run Results

Table 10 presents the estimated long-run coefficients of the ARDL(1,1,2,2) model, providing evidence on the equilibrium associations between the explanatory variables and CO_2 emissions in Algeria over the period 1990–2025. The estimated coefficient of economic growth is negative (−1.1170), indicating an inverse long-run association between GDP and CO_2 emissions; however, the corresponding probability value of 0.3969 indicates that this effect is statistically insignificant at the 10%, 5%, and 1% levels. Thus, the empirical results do not provide sufficient statistical evidence to establish a significant long-run relationship between economic growth and CO_2 emissions. In contrast, trade openness records a negative coefficient of −1.1166 and is statistically significant at the 1% level ($p = 0.0070$). This finding indicates that, ceteris paribus, higher trade openness is associated with lower CO_2 emissions in the long run. This negative association may be related to greater access to environmentally efficient technologies, improvements in production processes, or more efficient energy use associated with international economic integration, although these potential mechanisms cannot be established directly from the estimated model. Urbanization exhibits a positive and highly

significant coefficient of 5.2669 (p = 0.0000; t = 14.9443), indicating a strong positive long-run association between urbanization and CO_2 emissions. This result suggests that increasing urbanization is accompanied by higher emissions, potentially reflecting greater energy demand, transportation activity, and expansion of economic and infrastructure activities in urban areas. Finally, the constant term is estimated at −133.5337 and is statistically significant at the 1% level (p = 0.0002). Nevertheless, its economic interpretation remains limited because it represents the intercept of the estimated equation rather than the effect of any explanatory variable. Overall, the long-run estimates reveal differentiated relationships, with trade openness associated with lower CO_2 emissions, urbanization associated with higher emissions, and economic growth showing no statistically significant long-run effect**.**

Table 10
ARDL (1,1,2,2) model estimation results

Levels Equation
Case 2: Restricted Constant and No Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
GDP	-1.116959	1.294964	-0.862541	0.3969
TO	-1.116599	0.378253	-2.951990	0.0070
URB	5.266893	0.352434	14.94433	0.0000
C	-133.5337	30.62422	-4.360396	0.0002

EC = CO2 - (-1.1170*GDP -1.1166*TO + 5.2669*URB -133.5337)

Source. Prepared by the researcher based on eviews 13

4. Hypothesis Testing
Based on the estimation results of the ARDL(1,1,2,2) model, the study hypotheses are tested using the bounds test for cointegration, the short-run and long-run coefficient estimates, and the error correction mechanism. The results are summarized as follows.

Hypothesis 1
H1: There is a cointegration relationship between CO_2 emissions and the explanatory variables (GDP, TO, and URB).
To test this hypothesis, the ARDL bounds test was employed. The results show that the calculated F-statistic is *3.557619***,** which exceeds the upper bound I(1) critical value of *3.532 at the 10% significance level.* Accordingly, the null hypothesis of no levels relationship is rejected at the 10% level, providing evidence of a long-run cointegration relationship between CO_2 emissions and the explanatory variables. However, at the 5% significance level, the calculated F-statistic lies between the lower bound I(0) of *3.164* and the upper bound I(1) of *4.194***,** making the result inconclusive at this level. Therefore, the first hypothesis is *supported at the 10% significance level***,** indicating the existence of a long-run relationship among the study variables.

Hypothesis 2
H2: There is a statistically significant effect of the explanatory variables (GDP, TO, and URB) on CO_2 emissions.
The estimation results of the ARDL model provide partial support for this hypothesis. In the short run, economic growth has a positive and statistically significant effect on CO_2 emissions, with a coefficient of *0.8708* and a probability value of *0.0451***.** Trade openness exhibits dynamic effects, with a negative contemporaneous effect significant at the 10% level and a positive lagged effect

significant at the 1% level. Urbanization also shows statistically significant negative short-run effects. In the long run, trade openness has a negative and statistically significant effect on CO_2 emissions ***(−1.1166; p = 0.0070),*** while urbanization has a positive and statistically significant effect ***(5.2669; p = 0.0000).*** In contrast, the long-run effect of economic growth is statistically insignificant ***(−1.1170; p = 0.3969).*** Accordingly, the second hypothesis is *partially supported,* as the explanatory variables do not all exert statistically significant effects in the same direction or over the same time horizon.

Discussion

The empirical findings provide several important insights into the determinants of CO_2 emissions in Algeria over the period 1990–2025. The results indicate that the effects of economic growth, trade openness, and urbanization vary across the short and long run, suggesting that the relationship between economic activity and environmental pressure is dynamic rather than uniform over time.

The positive and statistically significant short-run effect of economic growth on CO_2 emissions suggests that increases in economic activity may initially be accompanied by higher environmental pressure. This relationship can be associated with increased energy consumption, production activity, transportation, and reliance on carbon-intensive energy sources. However, the statistically insignificant long-run coefficient of economic growth indicates that the initial increase in emissions associated with economic expansion does not necessarily persist over the long term. This difference between the short- and long-run effects suggests that the environmental consequences of economic growth may depend on structural changes in production, energy use, and technological conditions over time.

Trade openness presents a different pattern. Its negative and statistically significant long-run coefficient indicates that greater integration into international trade is associated with lower CO_2 emissions in the long run. One possible interpretation is that greater openness may facilitate access to cleaner technologies, more energy-efficient production methods, and environmental standards embodied in imported capital goods. Trade integration may also encourage structural changes toward less emission-intensive activities. However, the mixed short-run coefficients indicate that the environmental effects of trade openness are not immediate or uniform across different lag periods. This finding suggests that the environmental consequences of trade may depend on the time required for technological diffusion and structural adjustment.

Urbanization emerges as an important determinant of CO_2 emissions in the long run. The positive and statistically significant long-run coefficient indicates that higher urbanization is associated with greater CO_2 emissions. This result may reflect the increasing demand for electricity, transportation, housing, infrastructure, and other energy-intensive urban services accompanying the expansion of urban populations. In the Algerian context, continued urban expansion may therefore generate additional environmental pressures unless urban development is accompanied by improvements in public transportation, energy efficiency, urban planning, and the use of lower-carbon energy sources.

The error-correction mechanism further indicates a relatively substantial speed of adjustment toward the long-run equilibrium, with approximately 50% of short-run deviations being corrected within one period. This finding suggests that shocks affecting CO_2 emissions and their determinants do not permanently disconnect the variables from their underlying equilibrium relationship. Instead, the system gradually adjusts following short-run disturbances.

The diagnostic and stability results strengthen the reliability of the estimated specification. The absence of evidence of serial correlation, heteroskedasticity, and ARCH effects indicates that the

residuals satisfy important diagnostic requirements. In addition, the CUSUM and CUSUMSQ results indicate parameter stability over the study period. These findings support the use of the estimated model for interpreting the dynamic relationship among the variables.

Taken together, the findings suggest that reducing CO_2 emissions in Algeria requires attention not only to economic growth but also to the structural dimensions of development, particularly urbanization and trade. The positive long-run association between urbanization and emissions highlights the importance of integrating environmental considerations into urban development and infrastructure planning. At the same time, the negative long-run association between trade openness and emissions suggests that international economic integration may be compatible with environmental improvement when it facilitates technological upgrading and more efficient production. These interpretations should nevertheless be considered in light of the bounds-test evidence, which establishes a long-run relationship at the 10% significance level but remains inconclusive at the 5% level.

Conclusion

The theoretical literature identifies CO_2 emissions as the result of interactions among economic growth, urbanization, trade openness, energy use, and technological progress.Economic growth may increase environmental pressure through higher production and energy consumption, particularly during the early stages of development. However, technological innovation and improvements in energy efficiency can gradually reduce the environmental costs of economic expansion.Urbanization may contribute to higher emissions through increased transportation, construction, and energy demand.Effective urban planning and sustainable infrastructure can nevertheless limit these environmental pressures.

Trade openness may have either positive or negative effects on environmental quality depending on production structures and environmental regulations.

International trade can also facilitate the transfer of cleaner technologies and more efficient production methods, These theoretical mechanisms are particularly relevant to Algeria given its economic structure and continuing urban expansion.

Therefore, sustainable development requires integrating economic growth with cleaner technologies, energy efficiency and environmentally responsible trade.
This theoretical framework provides a basis for empirically examining the determinants of CO_2 emissions in Algeria over the study period.

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