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Can Sustainable Economic Development Curtail Carbon Dioxide Emissions? Insights from Algeria's Industry

Czy zrównoważony rozwój gospodarczy może ograniczyć emisję dwutlenku węgla? Spostrzeżenia dotyczące przemysłu Algierii

Abstract

Historically, Algeria's industry has significantly driven the country's economic growth but has also become a notable contributor to carbon dioxide emissions. In an era where climate change threatens our world, understanding the role of sustainable economic development in mitigating environmental impacts is paramount. This study investigates the efficacy of sustainable economic development strategies in reducing CO_2 emissions within Algeria's industrial sector. Utilising an autoregressive distributed lag (ARDL) model to analyse data spanning 1990 to 2021, we explore the dynamic relationship between GDP per capita, industry value added, energy consumption, labour productivity, exports, and CO_2 emissions. Our findings reveal that sustainable economic practices significantly reduce CO_2 emissions in both the short and long term. The results advocate for a redefined approach to industrial policies, emphasising the potential of sustainable economic strategies to achieve a balance between economic growth and environmental preservation in Algeria and similar contexts globally.

Keywords:
carbon dioxide emissions, Algeria, industrial sector, ARDL approach, sustainable economic development

JEL classification codes:
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Streszczenie

Rozwój algierskiego sektora przemysłowego, który historycznie był czynnikiem napędzającym wzrost gospodarczy kraju, przyczynił się do zwiększenia emisji dwutlenku węgla. Zrozumienie roli zrównoważonego rozwoju gospodarczego w łagodzeniu wpływu zmiany klimatu na środowisko ma ogromne znaczenie w momencie, gdy zagraża ona naszej planecie. W niniejszym badaniu przeanalizowano skuteczność strategii zrównoważonego rozwoju gospodarczego w ograniczaniu emisji CO_2 w sektorze przemysłowym Algierii. Wykorzystując model ARDL do analizy danych obejmujących lata 1990–2021, badamy dynamiczny związek między PKB na mieszkańca, wartością dodaną w przemyśle, zużyciem energii, wydajnością pracy, eksportem i emisjami CO_2. Nasze wyniki ujawniają, że zrównoważone praktyki gospodarcze znacznie zmniejszają emisje CO_2 w krótkim i długim okresie. Wyniki te dowodzą konieczności zmiany polityki przemysłowej i wskazują na potencjał zrównoważonych strategii gospodarczych, które umożliwiają osiągnięcie równowagi między wzrostem gospodarczym a ochroną środowiska zarówno w Algierii, jak i na całym świecie.

Słowa kluczowe:
emisja dwutlenku węgla, Algieria, sektor przemysłowy, metoda ARDL, zrównoważony rozwój gospodarczy

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Introduction

António Guterres, the Secretary-General of the United Nations, once said, "The era of global warming has ended; the era of global boiling has arrived" Clifford [2023]. This proclamation underscored that the threat of climate change has reached a critical juncture, marking a turning point in the global dialogue on climate action. Evidence from the United Nations indicates that global emissions of fossil carbon dioxide rebounded to pre-pandemic levels in 2021, after a decline of 5.4% in 2020 as a result of extensive closures [Stuart et al., 2022]. This means that the world is not on track to meet the ambitious goals of the Paris Agreement, which aims to limit global warming to well below 2ºC above pre-industrial levels. According to the International Monetary Fund (IMF), in order to attain carbon neutrality by 2050, it is imperative for the global community to reduce greenhouse gas emissions by a minimum of 25% by the end of this decade [Parry et al., 2021].

Africa, hosting 17% of the global population [Statista, 2023], contributes merely 4% to worldwide CO_2 emissions [Statista, 2023], emphasising its minor role in global warming causes. Despite this low contribution, the continent is disproportionately affected by climate change impacts, facing severe vulnerabilities due to its geographical and socio-economic conditions. According to the IPCC's Special Report, Africa is experiencing increasing temperatures at a rate faster than the global average, significantly impacting its ecosystems, economies, and communities [IPCC, 2021]. The continent's vulnerability is further exacerbated by its dependence on agriculture, which employs around 60% of its population and is highly susceptible to climate variability [Mapanje et al., 2023]. This situation is aggravated by existing challenges such as poverty, with the World Bank indicating that over 40% of people in Sub-Saharan Africa live below the poverty line, limiting their capacity to adapt to climate change. Moreover, the United Nations Environment Programme (UNEP) highlights that Africa's adaptation costs could rise to $ 50 billion per year by 2050 if global warming exceeds 2ºC. This stark contrast underscores the urgent need for targeted climate resilience and adaptation strategies within African nations, particularly in countries such as Algeria, Africa, and Egypt, which are among Africa's top carbon emitters.

In light of these challenges, sustainable economic development has emerged as a promising solution and defining feature of the modern economy, offering a model to promote economic progress while considering the environmental impact. Nonetheless, there is no agreement on how sustainable economic development principles can fight climate change. Based on [Hammer, Pivo, 2017; Anzolin, Lebdioui, 2021; Raihan, Tuspekova, 2022; Sadiq et al., 2023], the adoption of sustainable economic development practices may promote a carbon dioxide reduction over time. However, while there is a general consensus on the importance of combating climate change, [Li, Lin 2015; Xu, Lin, 2015; Khan, Majeed 2023] argue that the connections between sustainable economic development principles and the reduction of CO_2 emissions are not straightforward. They contend that the links are subtle and not well-defined, making it challenging to draw clear conclusions about the effectiveness of these principles in reducing carbon emissions.

Based on this knowledge, the primary inquiry of this study is the correlation between sustainable economic development and the mitigation of carbon dioxide emissions within Algeria's industrial sector. Specifically, the study examines the temporal dynamics of this relationship in both the short and long term. The objective is to understand methods for enhancing efficiency and sustainability in industrial expansion, rather than diminishing the sector's economic contribution. Therefore, the study addresses the fundamental question: Can sustainable economic development practices in the Algerian industrial sector reduce carbon dioxide emissions? The central hypotheses are as follows: Hypothesis 1: Sustainable economic development practices and principles do not have a notable effect on CO_2 emissions in the Algerian industrial sector; Hypothesis 2: There is a notable effect of sustainable economic development practices and principles on CO_2 emissions in Algeria's industrial sector.

The main aim of this study is to explore the effectiveness of sustainable economic development strategies in reducing carbon dioxide emissions in Algeria's industrial sector. By analysing data from 1990 to 2021 using the autoregressive distributed lag (ARDL) model, the research seeks to understand the relationship between economic growth indicators and the environmental impact. This investigation is crucial for devising policies that can balance economic advancement with ecological preservation. In addition, Algeria was chosen for this study due to its unique economic and environmental profile. The country has a significant dependency on fossil fuels, is a major player in the global energy market, and faces pressing sustainability challenges. Its industrial sector offers a pivotal case for examining the interplay between economic development and environmental impact, offering valuable insights applicable to both developing and developed nations. These countries often grapple with similar issues as they seek to benefit from their energy resources while facing the imperative of transitioning to greener practices and combating the harmful effects of climate change.

The importance of this study lies, first, in that it provides fresh evidence on the relationship between sustainable economic development practices and CO_2 emissions in Algeria's industrial sector, emphasising the role of low-carbon exports, energy efficiency, and the transition to cleaner energy sources. Second, the study enriches the current body of literature by demonstrating that sustainable development measures can lead to significant reductions in emissions, thus contributing to the global discourse on environmental sustainability. Additionally, by employing the autoregressive distributed lag (ARDL) methodology, the study examines the short-term and long-term dynamics of the relationship between economic development and CO_2 emissions. This methodological approach allows for a more comprehensive understanding of the temporal aspects of this relationship, adding depth to the analysis that is not commonly found in existing literature. Moreover, the study's focus on Algeria is particularly valuable given the country's significant dependency on fossil fuels and the challenges it faces in transitioning to more sustainable economic practices. By providing insights specific to Algeria, this research fills a critical gap in the literature on emerging economies and their pathways to sustainable development.

The following section offers a concise literature review. Then, the methodology and data collection techniques are outlined. After that, the results related to the research question are discussed. The paper concludes by summarising key findings and proposing recommendations based on the results.

Literature review

Since its introduction in the 1987 Brundtland report entitled "Our Common Future", the notion of sustainable development has garnered extensive recognition as an essential element in addressing the phenomenon of climate change and the depletion of natural resources [**UN, 1988**]. Subsequent to that, the idea of sustainability was introduced to economic development policies, establishing sustainable economic development as a generally embraced objective for the 21st century. Nevertheless, despite its widespread appeal, the task of formulating an exact and widely acknowledged definition of sustainable economic growth has significant analytical difficulties. Frequently, the pursuit of acceptability takes precedence over accuracy. But in this study, we anchor our discussion in the framework articulated by **Kruja** [**2013**], who characterises sustainable economic development as a set of methodologies that not only bolster long-term economic growth but also address the ecological crises induced by the industrial exploitation of resources and subsequent environmental degradation. This perspective aligns with our focus on balancing economic development and environmental sustainability. Further examination of definitional nuances may reveal additional insights, but we have adopted this well-established conceptualisation to underpin our current study. Although sustainable economic development is carefully defined, scholars continue to debate whether its principles and strategies can effectively lead to substantial reductions in carbon dioxide emissions.

Numerous empirical studies have investigated this relationship with mixed and sometimes contradictory conclusions. Some research provides evidence that sustainable economic development principles can successfully reduce emissions. For instance, **Zhixin and Qiao** [**2011**] examined the linkage between low-carbon transition in industry and the path of China's sustainable development, using a linear regression model from

1996–2009, with carbon dioxide emissions per unit of output as the dependent variable. They argue that as China's development mode shifts away from a standard growth model towards a sustainable model, there has been a corresponding decrease in carbon emissions. In 2012, [Adom et al.] used the ARDL method to investigate the short- and long-term relationship between CO_2 emissions and industrial structure in Senegal, Ghana, and Morocco from 1971 to 2007. The researchers used real GDP, technical efficiency, industry value added to GDP, and carbon dioxide emissions. The evidence suggests that industrial structures using sustainable economic development principles can be a powerful tool for achieving a carbon emission reduction. A further study by Dong et al. [2020] sheds light on how to achieve a beneficial balance between economic progress and carbon emissions by exploring the dynamic relationship between industrial structure upgrading, sustainable economic development, and carbon emissions reductions. The authors used VAR models and vector error correction models (VECM) in China from 1978 to 2017. The results show that industrial structure upgrading is negatively correlated with carbon emissions, leading to reduced emissions.

Conversely, other studies present conflicting evidence on the magnitude and viability of sustainable economic development policies for emission mitigation. The study by Jin et al. [2014] conducted research to investigate the impact of technical advancements on carbon dioxide emissions in the industrial sector, specifically focusing on the potential reduction achieved via improvements in energy efficiency. The researchers used panel data from 35 sub-industrial sectors in China, covering the period 1999 to 2011. The researchers conducted a focused examination of the gross domestic product (GDP) and carbon dioxide emissions within each sector, with the aim of analysing the correlation between economic progress and emissions. The findings suggest that the implementation of sustainable economic development principles has not yet succeeded in fully mitigating industrial CO_2 emissions.

In the context of examining the Environmental Kuznets Curve (EKC) hypothesis, Jalil and Mahmud [2009] explored the long-term dynamics between CO_2 emissions, energy consumption, income, and foreign trade in China from 1975 to 2005. They investigate the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shaped relationship between environmental degradation (measured through CO_2 emissions) and income per capita. Using the Auto Regressive Distributed Lag (ARDL) approach, they confirm an EKC relationship, finding that economic growth initially increases CO_2 emissions until reaching a tipping point where further growth leads to environmental improvement. Their analysis also reveals that economic growth and energy consumption are the primary long-term determinants of CO_2 emissions, while trade shows a positive but insignificant effect. Moreover, the study by Jungho [2015] on Arctic countries provides valuable insights. Baek's research, which explored the relationship between economic development, energy consumption, and CO_2 emissions using an Autoregressive Distributed Lag (ARDL) approach, reveals limited evidence for the EKC hypothesis in Arctic countries. While previous findings indicate a mixed impact of economic growth on environmental outcomes across Arctic countries, with energy consumption generally exacerbating emissions, our research aims to elucidate how Algeria's industrial practices and sustainable development strategies contribute to this dynamic. The nuanced understanding of these relationships can offer valuable insights for policy formulation aimed at balancing economic growth with environmental sustainability. The study by Jani et al. [2017] presents a comprehensive overview of the sustainability challenges and opportunities facing the steel re-rolling industry, and they discuss a number of sustainability initiatives that have been implemented in the industry, such as energy efficiency improvements, air pollution control technologies and waste minimisation. They argue that the industry needs to continue to invest in sustainability initiatives and rely on other methods in order to reduce its environmental impact and improve its long-term competitiveness.

Analysing the Environmental Kuznets Curve (EKC) for carbon dioxide (CO_2) emissions and economic growth in Algeria, Touitou and Langarita [2021] found that there exists a positive long-term relationship between CO_2 emissions and real GDP. They also determined that the direction of this relationship goes from economic growth to CO_2 emissions according to Granger causality tests. For a developing country such as Algeria, it was concluded that economic growth determines the level of emissions, which means that an energy policy favouring the environment could be implemented without negatively affecting economic growth. Additionally, the ARDL regression supported the EKC's hypothesis, indicating that in the first phase, economic growth leads to higher levels of CO_2 emissions, but once a specific threshold (inflection point) is reached, these emissions begin to decline. The paper by **Abdulraheem and Alrikabi** [**2023**] provides a comprehensive overview of the challenges and opportunities facing industrial cities in a way that minimises their environmental impact, and it discusses a number of strategies that can be used to make them more sustainable. They argue that the principles of sustainable economic development are not enough to reduce the impact of industries CO_2 emissions.

The existing body of literature extensively examines the relationship between sustainable economic development and carbon dioxide emissions. However, the conclusions drawn from these studies are inconclusive, highlighting a divergence in the perceived efficacy of sustainable practices in mitigating emissions within various industries and geographic contexts. Moreover, a significant portion of the existing research about this subject matter has been concentrated on industrialised nations. In contrast, studies have yet to be conducted in emerging countries such as Algeria. The current body of research about the causal pathways via which sustainable economic development strategies might effectively mitigate carbon dioxide emissions within Algeria's industrial sector is limited. Hence, this study extended the analysis beyond the use of gross domestic product (GDP) as a proxy for sustainable economic growth, given the inherent limits associated with GDP. According to **Dabbous and Tarhini** [**2021**], the use of GDP per capita as a metric for sustainable development is more complete due to its consideration of both economic growth and wealth distribution. In addition to these factors, the scholars also took into account other indicators that might be used to assess the extent of sustainable economic growth within Algeria's industrial sector. These supplementary measures included industry-specific value added, energy consumption patterns within industry, labour productivity levels within the sector, and the volume of exports originating from industry. This work represents a novel contribution as it is the first to use these variables and employ the ARDL approach in order to evaluate the impact of critical factors for sustainable economic growth on carbon dioxide (CO_2) emissions. By focusing on Algeria, the study aims to contribute valuable insights to the global discourse on how countries with significant natural resources and economic dependence on fossil fuels can effectively implement sustainable development strategies.

Methodology

Over the past 30 years, the industrial sector has been the number one contributor to the economy, and also the largest contributor to CO_2 emissions. Besides, the hydrocarbon industry stands as the dominant force in the industrial landscape, surpassing all other business sectors. The industrial sector in Algeria is classified into 11 main branches according to the National Statistics Office (ONS). These are energy; hydrocarbons; mines and quarries; iron, steel and mechanical products; construction materials; petrochemicals; agro-industry; textiles; leather and shoes; and wood, cork and paper [**ONS, 2021**]. Notably, the hydrocarbon and energy sectors are the principal contributors to CO_2 emissions, reflecting their significant environmental footprint alongside their economic importance.

Thus, we were interested in testing the following hypotheses:

Hypothesis 1: Sustainable economic development practices and principles do not have a notable effect on CO_2 emissions in the industrial sector of Algeria.

Hypothesis 2: There is notable effect of sustainable economic development practices and principles on CO_2 emissions in the industrial sector of Algeria.

This study employed the autoregressive distributed lag (ARDL) method introduced by **Pesaran and Shin** [**1998**], **Pesaran et al.** [**2001**]. The ARDL approach was chosen because it has several advantages, including the ability to be used regardless of whether the time series variables are I(0), I(1), or frictionally integrated by [**Shrestha, Bhatta, 2018**]. Additionally, this method is commensurate with the data available and with the objectives of the research by [**Kripfganz, Schneider, 2016**].

Variables and data

The data used in this research were retrieved from the World Bank database (WDI), Our World in Data, Office National Statistical (ONS), and Statista. Annual data were utilised, covering the period from 1990 to 2021. The methodology of the study justifies the use of different types of variables by employing an autoregressive distributed lag (ARDL) model to explore the relationship between various explanatory variables and CO_2 emissions. The explanatory variables are specified as indicators such as GDP per capita, industry value added, energy consumption, labour productivity, and exports. The aim is to quantify their impact on CO_2 emissions, the dependent variable, which is measured in original units (millions of tons). This distinction is justified by the nature of the ARDL model, which is designed to capture both short-term and long-term effects of these variables on CO_2 emissions. The use of indicators for explanatory variables allows for a nuanced analysis of how different aspects of economic development and industrial activity contribute to emissions, while measuring CO_2 emissions in its original scale provides a direct assessment of the environmental impact.

Table 1. Details of the variables used in the study

Variables	Description of the variables	Measurement unit	Source
Dependent variable			
$CO2_{industry}$	Emission of carbon dioxide from industry	million t	Our World in Data
Independent variables			
GDP_{capita}	Gross domestic product per capita	Constant (2015) dollar prices US$	World Development Indicators, World Bank
$VA_{industry}$	Industry value added (% of GDP)	Million dollars US$	OECD.Stat
$EC_{industry}$	Industry energy consumption, % of total energy consumption	annual growth (%)	authors' calculations
$LP_{industry}$	Labour productivity in industry	annual growth (%)	authors' calculations
$X_{industry}$	Export of industry sector	Million dollars US$	National Bureau of Statistics in Algeria-ONS

Source: Authors' own elaboration.

As shown in Table 1, the study's dependent variable was carbon dioxide (CO_2) emissions from industry. Meanwhile, the five independent variables examined as potential drivers were gross domestic product (GDP/ per capita); industry value added (% of GDP); industry energy consumption growth; labour productivity growth in industry, reflecting the efficiency of labour in producing industrial goods; and technological advancements in industrial processes. These independent variables were chosen based on their potential to influence CO_2 emissions directly or indirectly through changes in industrial practices and outputs. This study contributes to the understanding of how economic growth and industrial activity relate to environmental outcomes, particularly in developing contexts where industrial expansion is often seen as a pathway to economic development but comes with considerable environmental trade-offs.

These indicators provide a standardised way to measure and compare the effects of these dimensions on CO_2 emissions, which is crucial for understanding the multifaceted nature of sustainable economic development. Besides, the ARDL model requires that the dependent variable be measured in a form that accurately reflects the outcome of interest. Since the study focuses on CO_2 emissions, presenting this variable in its original form ensures that the findings are directly relevant and easily interpretable in the context of environmental policy and industrial regulation. Although individual indicators are useful for comparative analysis across countries or regions, the study's focus on Algeria specifically allows for a more in-depth analysis of its internal dynamics. By using original data for the dependent variable, the research provides insights that are directly applicable to Algeria's industrial sector and its sustainability challenges.

Model specification

The functional form of the model, as expressed in Equation 1, posits CO_2 emissions from industry as the response variable, with the following predictors: GDP per capita, industry value added (as a percentage of GDP), industry energy consumption growth, labour productivity growth in industry, and other industry-specific technological advancements. The equation is presented as follows:

$$CO2_{industry} = \beta_0 + \beta_1 GDP_{capita} + \beta_2 VA_{industry} + \beta_3 EC_{industry} + \beta_4 LP_{industry} + \beta_5 X_{ndustry} + \varepsilon_i \quad (1)$$

Here, β_0, β_1, β_2, β_3, β_4, and β_5 represent the long-term effects, with the lagged values capturing the short-run dynamics affecting $CO2_{industry}$. ε_i is the error term, indicating the discrepancy between predicted and actual values. The general form of an Autoregressive Distributed Lag [ARDL] equation is as follows:

$$\begin{aligned}\Delta(CO2_{industry})_t = \beta_0 + \sum_{i=1}^{n}\phi_i \Delta(CO2_{industry})_{t-i} + \sum_{i=0}^{P_1}\gamma_i \Delta(GDP_{capita})_{t-i} + \sum_{i=0}^{P_2}\theta_i \Delta(VA_{industry})_{t-i} \\ + \sum_{i=0}^{P_3}\delta_i \Delta(EC_{industry})_{t-i} + \sum_{i=0}^{P_4}\varphi_i \Delta(LP_{industry})_{t-i} + \sum_{i=0}^{P_5}\sigma_i \Delta(X_{industry})_{t-i} \\ + \alpha_1(GDP_{capita})_{t-1} + \alpha_2(VA_{industry})_{t-1} + \alpha_3(EC_{industry})_{t-1} + \alpha_4(LP_{industry})_{t-1} + \alpha_5(X_{industry})_{t-1} + \varepsilon_t\end{aligned} \quad (2)$$

The first-difference operator Δ is used to denote the difference between two consecutive observations of a variable. The noise residuals ε_t are random shocks that cannot be explained by the model. The long-run coefficients α_1, α_2, α_3, α_4, and α_5 are the coefficients that describe the long-run relationship between CO_2 emissions and the other variables in the study.

If the variables in a model are found to have a long-run relationship, the short-run estimates using the error correction term (ECT) can be used to determine how the variables adjust to any deviations from the long-run equilibrium. The error correction term serves the purpose of determining the significance of a long-term association and offers an insight into the temporal duration required for short-term variances to achieve equilibrium in the long run [**Bölükbaş, 2019**].

$$\begin{aligned}\Delta(CO2_{industry})_t = \beta_0 + \sum_{i=1}^{n}\beta_i \Delta(CO2_{industry})_{t-i} + \sum_{i=0}^{P_1}\gamma_i \Delta(GDP_{capita})_{t-i} \\ + \sum_{i=0}^{P_2}\theta_i \Delta(VA_{industry})_{t-i} + \sum_{i=0}^{P_3}\delta_i \Delta(EC_{industry})_{t-i} + \sum_{i=0}^{P_4}\varphi_i \Delta(LP_{industry})_{t-i} \\ + \sum_{i=0}^{P_5}\sigma_i \Delta(X_{industry})_{t-i} + \lambda(ECM_{t-1}) + \varepsilon_t\end{aligned} \quad (3)$$

The ARDL approach allows us to differentiate between short-term and long-term impacts by incorporating both first-differenced variables to capture immediate effects and lagged levels of the variables to assess long-term relationships. This specification includes an error correction term (ECT_{t-1}).

Findings and discussion

Findings

In this section, we delve into the core findings of our study, focusing on the impact of various economic and environmental factors on CO_2 emissions within Algeria's industrial sector. We examine the findings that emerged from our study, which systematically analysed the complex interrelationship between numerous key economic and environmental factors and their collective impact on carbon dioxide emissions stemming from industrial activities across Algeria over the past decade.

Table 2. Descriptive statistics of variables

	$CO2_{industry}$	GDP_{capita}	$VA_{industry}$	$EC_{industry}$	$LP_{industry}$	$X_{industry}$
Mean	5.6259	3125.938	46677.6	19.2206	0.0045969	0.1217
Maximum	9.9	5611	59297.99	21.79	0.0301	3.1423
Minimum	2.29	1420	34185.09	16.05	−0.0251	−0.6959
Std. Dev.	2.4640	1437.934	10106.51	1.5303	0.0184682	0.6212
Variance	6.071464	2067653	1.02e+08	2.342039	0.000341	0.385916
Skewness	0.385568	0.305427	0.0753977	− .322425	−0.0652138	0.246005
Kurtosis	1.715692	1.692971	1.3000	2.494806	1.535933	1.30536
Obs	32	32	32	32	32	32

Source: Authors' own elaboration.

Table 2 presents descriptive statistics for the variables used in the study. The values in the table indicate that the data is not widely dispersed over time. This suggests that the variables are relatively stable, with no major outliers.

First, checking for stationarity is a fundamental step in time series analysis. Two powerful diagnostic tools are the Augmented Dickey–Fuller (ADF Test) of stationarity and the Phillips–Perron (PP) unit root test. If a series is stationary in its initial form, it is considered to be integrated of order zero I (0). Conversely, if a series is non-stationary in its initial form but becomes stationary after taking the first difference, it is integrated of order one I (1) [Nkoro, Uko, 2016].

Table 3. Augmented Dickey–Fuller [ADF] and Phillips–Perron (PP) tests

	ADF at level		ADF at first difference		Phillips – Perron at level		Phillips – Perron at first difference		Order
	Test statistic	p-value	Test statistic	p-value	Test statistic	p-value	Test statistic	p-value	
$CO2_{industry}$	−0.534	0.8852	−5.024	0.000*	−0.734	0.8378	−5.752	0.000*	**I (1)**
GDP_{capita}	−1.152	0.6937	−3.737	0.003*	−1.281	0.6379	−5.037	0.000*	**I (1)**
$VA_{industry}$	−0.671	0.8540	−2.610	0.025*	−0.388	0.3993	−3.091	0.027*	**I (1)**
$EC_{industry}$	−1.934	0.3162	−3.180	0.021*	−1.619	0.4733	−5.501	0.000*	**I (1)**
$LP_{industry}$	−1.740	0.4105	−4.131	0.000*	−1.762	0.3993	−5.700	0.000*	**I (1)**
$X_{industry}$	−4.234	0.0006	–	–	−6.862	0.000*	–	–	**I (0)**

Source: Authors' own elaboration.

The findings of the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests at the level and first difference are summarised in Table 3. The test findings indicate that all variables exhibit stationarity either at the common level or when subjected to first difference. Due to this rationale, we employed the co-integration test in order to ascertain the presence or absence of a long-term association between the variables. When performing cointegration tests, it is essential to select the optimal number of lags to use in the analysis [Asumadu-Sarkodie, Owusu, 2016]. Next, selecting an appropriate lag order is crucial to obtain accurate and reliable cointegration test results.

Table 4. Results of optimal lag selection

Lag	LL	LR	Df	P	FPE	AIC	HQIC	SBIC
0	−507.712				3.5e+08	36.6937	36.781	36.9792
1	−388.269	238.89	36	0.000	956655	30.7335	31.3444	32.7318
2	−344.184	88.17	36	0.000	798462	30.156	31.2905	33.8671
3	1349.77	3220.3*	36	0.000	1.6e-42*	−85.6979*	−83.5161*	−78.5611*

* Optimal Lag

Source: Authors' own elaboration.

The lag-order selection criteria for various lag lengths [0 to 3] for the given variables, namely $CO2_{industry}$, GDP_{capita}, $VA_{industry}$, $EC_{industry}$, $X_{industry}$, and $VA_{industry}$, are presented in Table 4. The ideal lag duration, indicated by an asterisk (*), is chosen based on the criterion that offers the most accurate fit for the model. The ideal lag duration in this example is determined to be 3, since it produces the highest log likelihood, the highest likelihood ratio test statistic, and the lowest values for the AIC, HQIC and SBIC criterion.

Then, cointegration testing is a critical step in determining whether a model exhibits important long-run relationships. If cointegration is not found, it is necessary to work with the variables in differences, which will discard long-run information [**Rehman et al., 2021**].

Table 5. Results of cointegration test

Estimated Equation: Equation (2)			
Selected Optimal Lags/AIC Lags: 3			
Test Statistic	Value	k*****	Conclusion
F-statistic	4.441**	5	
Critical Value Bounds*			**The F-statistic is significant at the 5% level Cointegration exists**
Significance	I (0) Bound	I (1) Bound	
10%	2.26	3.35	
5%	2.62	3.79	
1%	2.96	4.18	

Note: * Pesaran Critical Values
The number of independent variables for the explained variable in the ARDL model is denoted by (k=5).
The lower critical bound value for the Pesaran bounds test is denoted by I (0), while the upper critical bound value is denoted by I (1).
Source: Authors' own elaboration.

The cointegration test findings presented in Table 5 indicate that the F-statistic exceeds both the lower and upper bound values in a statistically significant manner. The available statistical evidence suggests that there exists a long-term link between the variables. Hence, there exists support for the existence of a sustained association between the dependent variable and the independent factors. This conclusion provides support for the utilisation of the Autoregressive Distributed Lag (ARDL) model in estimating the dynamics in both the long and short term. It confirms that the variables are interconnected and not merely correlated.

In order to estimate the short-run dynamics and the adjustment process toward the long-run equilibrium, the Akaike Information Criterion (AIC) and Schwarz Information Criterion (SC) were utilized. Both criteria serve as measures to determine the model fit, with the optimal lag length being identified by the minimisation of these values. In line with [**Abbasi et al., 2022**], the lag length in this study was selected based on achieving the lowest AIC value. Consequently, the ARDL (1,1,1,1,0,2) model was deemed appropriate for estimating the long-run cointegrating relationship, as dictated by the Akaike Information Criteria.

Table 6. ARDL estimations for short and long run

Model: ARDL lags (1 1 1 1 0 2) **Dependent Variable:** $CO2_{industry}$				
	Coefficient	Std.err	t-statistic	Prob
ECM	−0.491713	0.1643109	−2.99	0.008
long-run estimates				
GDP_{capita}	0.000047	0.000453	0.11	0.000
$VA_{industry}$	−0.035521	0.252916	−0.14	0.001
$EC_{industry}$	1.893873	0.302016	6.27	0.003
$LP_{industry}$	−0.766328	0.425975	−1.80	0.186
$X_{industry}$	0.000221	0.000056	3.91	0.000

short-run estimates				
$d(GDP_{capita})$	−0.0003127	0.000022	−1.38	0.185
$d(VA_{industry})$	−0.0001229	0.000146	−0.84	0.411
$ld(VA_{industry})$	0.0002601	0.000096	2.71	0.014
$d(EC_{industry})$	0.1158026	0.142102	0.81	0.348
$d(LP_{industry})$	1.000108	11.97728	0.08	0.322
$d(X_{industry})$	−0.3768141	0.148696	−2.53	0.507
Constant	−1.682005	2.483966	−0.68	0.021
R-squared	0.9802			
Adj R-squared	0.9681			
Prob>F	0.0000			

Source: Authors' own elaboration.

In the ARDL model, Table 6 presents the associations between industrial carbon dioxide (CO_2) emissions and other parameters, including GDP per capita, industry value, energy consumption, productivity, and exports. The ECM phrase suggests that these variables are interconnected and undergo adjustments to achieve long-term equilibrium, resulting in an annual adjustment of nearly half of the deviation toward equilibrium. The long-term relationship between GDP and emissions exhibits a slight rise, which is consistent with the environmental Kuznets curve theory. However, the impact of industrial value remains uncertain. Increased energy consumption has a substantial impact on emissions, but higher productivity, although not substantial, tends to decrease them. Exports, which have a positive correlation with emissions, underscore their significance in the context of short-term emission reduction policies. The impact of short-term value-added and exports on emissions is substantial, but the impacts of GDP, industrial value and energy are inconsequential, highlighting the direct importance of exports on emissions.

Based on the results of the ARDL model, we are able to evaluate the stated hypotheses. The findings support Hypothesis 2, which posits that sustainable economic development practices have a significant impact on CO_2 emissions within Algeria's industrial sector. Consequently, we can reject Hypothesis 1, asserting that sustainable economic development principles and practices do not have a noticeable impact on CO_2 emissions in this sector. Additionally, to ensure the reliability of these findings, diagnostic tests were conducted to assess the robustness of the model.

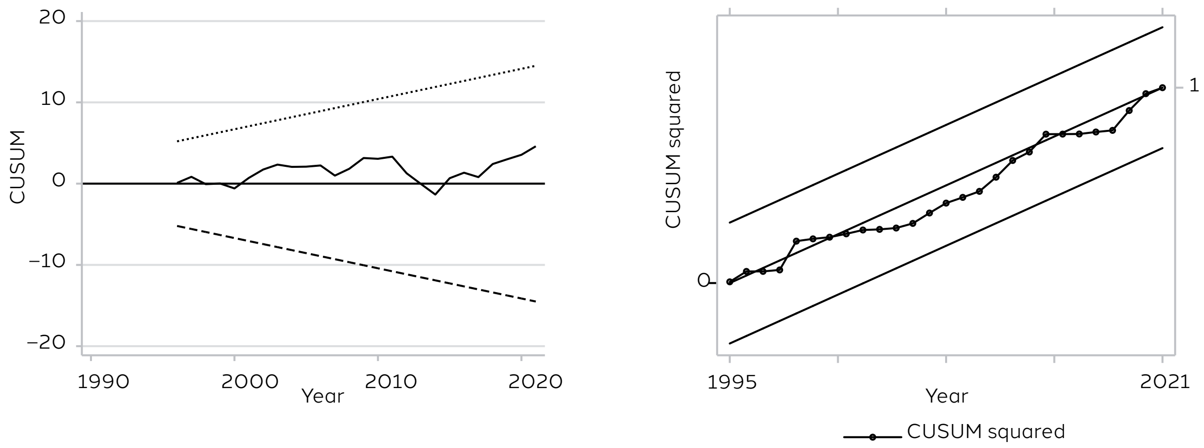
Table 7. Summary of diagnostic test results

	statistics	Prob
Chi-square Test for Normality	3.323	0.208
Jarque–Bera (JB)	0.921	0.489
Skewness and Kurtosis tests	kurtosis (2.867), skewness (0.0001)	0.01565
The Breusch–Godfrey (BG) test	0.941	0.489
Heteroskedasticity (ARCH) test	0.262	0.612
Ramsey (RESET) test	0.98	0.1865

Source: Authors' own elaboration.

Table 7 provides a comprehensive summary of the results obtained from the diagnostic tests. According to the results of the Chi-square Test for Normality, Jarque – Bera test, and Breusch – Godfrey test, the data exhibits a normal distribution, as indicated by the non-significant p-values (> 0.05). The data does not exhibit heteroskedasticity, as shown by the results of the heteroskedasticity (ARCH) test, which produced a p-value (> 0.05). The absence of autocorrelation is indicated by the p-value of the Ramsey (RESET) test, which exceeds the threshold of 0.05. The obtained findings suggest that the data follows a normal distribution and does not exhibit any significant issues related to autocorrelation or heteroskedasticity.

Figure 1. CUSUM and CUSUMSQ plots of the residuals



Source: Authors' own elaboration.

According to Figure 1, the cumulative total (CUSUM) plot remains within the critical value boundaries, suggesting that the parameters remain stable throughout the duration of the research. The cumulative sum of the squared residuals (CUSUMSQ) plot consistently falls inside the crucial boundaries, providing additional evidence for the stability of the coefficients.

Discussion

The long-run estimates from the ARDL model indicate a positive relationship between GDP per capita and industrial CO_2 emissions. This relationship is consistent with the initial stages of the Environmental Kuznets Curve (EKC) hypothesis, which posits that environmental degradation initially increases with economic growth, before it decreases after reaching a certain level of income. The EKC theory posits that, in early development, emissions increase with income growth up to a certain turning point, after which the relationship becomes negative. This has been shown by studies such as [Leitão, 2013; Destek et al., 2020; Ridzuan et al., 2020]. The finding matches the small long-run elasticity found in the model. Prior studies on Algeria [Kais, Ben Mbarek, 2017; Gorus, Aslan, 2019; Espoir, Sunge, 2021] have similarly provided empirical support for the EKC model. In addition, the statistically significant positive link between industry energy consumption and CO_2 emissions conforms to expectations from environmental economics models of pollution emissions. The long-run elasticity of 1.89 is reasonably high, reflecting Algeria's continued dependence on fossil fuels such as oil and natural gas. This finding reinforces previous work emphasising the importance of energy efficiency and renewable energy to decouple energy use and emissions [Engo, 2021; Chikhi et al., 2022]. Moreover, energy consumption was found to have the largest positive and highly significant effect on emissions in the long run. This aligns with expectations, as greater energy use leads to higher CO_2 releases holding other factors constant. A number of previous studies, such as [Chekouri et al., 2020, 2021] and [Touitou, Langarita, 2021], have found a positive relationship between energy consumption and CO_2 emissions in Algeria.

The short-run dynamics highlight the importance of exports and industry value added as drivers of year-to-year changes in emissions. The error correction term was negative and significant, confirming cointegration. The coefficient value indicates that around 49% of any disequilibrium is corrected annually. Studies have found that industry value added can have a negative or positive impact on CO_2 emissions. For example, [Alam, 2015] and [Jebli et al., 2020] found that an increase in value added in the industrial sector leads to an increase in CO_2 emissions. However, a study by [Huang et al., 2023] found that an increase in value added in industry does not necessarily lead to an increase in CO_2 emissions.

The ARDL model reveals that factors related to sustainable development – such as energy efficiency, exports, and industry value added – have statistically significant effects on industrial CO_2 emissions, both in the short and long term. This provides robust evidence of the link between sustainable growth and CO_2 emissions in Algeria's industrial sector. The analysis suggests that promoting low-carbon exports, enhancing efficiency, and transitioning to cleaner energy sources could significantly reduce emissions.

Conclusions and recommendations

In recent years, the topic of climate change has garnered significant attention and recognition in the realms of politics, economics and the environment. The prevailing scientific consensus strongly supports the notion that the substantial release of carbon dioxide from human activities is a primary driver of climate change. This research aimed to examine the impact of sustainable economic development practices on reducing carbon dioxide emissions in Algeria's industrial sector. In the research, an autoregressive distributed lag (ARDL) methodology was used to examine the interrelationships among the variables under investigation during the period spanning from 1990 to 2021, including both short- and long-term dynamics.

The findings suggest that, over an extended period, the impact of GDP per capita growth on emissions is minimal. However, industrial energy use and trade competitiveness are the main factors influencing rising emissions. Nevertheless, implementing sustainable development concepts that effectively separate emissions from economic growth has the potential to alleviate this issue gradually. The findings of the short-term analysis indicate a positive correlation between industrial exports and industrial CO_2 emissions. This suggests that making changes to this particular component might benefit industrial carbon dioxide emissions in the short term.

In summary, the study reveals complex interrelationships among sustainable economic progress, industrial operations, and CO_2 emissions. The study results underscore the significance of adopting the concepts and values of sustainable economic development to effectively mitigate carbon dioxide emissions in Algeria's industrial sector. Nevertheless, attaining this change will require considerable effort and unwavering dedication. Through the planned and prudent use of its resources, Algeria can steer its industries towards a more environmentally sustainable trajectory, marked by a reduction in carbon emissions. However, the country's reliance on hydrocarbons necessitates ongoing governmental initiatives to enable a sustainable transition towards environmentally acceptable alternatives. The findings provide more support for the notion that the course of Algeria's economic expansion will have a significant impact on its environmental prospects. Implementing strategic measures that prioritise efficiency may successfully align economic development goals with the hopes of reducing emissions.

We consider confronting climate change not optional but necessary. We propose a set of recommendations to encourage carbon reductions and maintain ecologically sustainable economic growth within the Algerian industrial sector. These include: (1) Creating a pragmatic, realistic national plan with a defined vision aligned with sustainable economic development values; (2) Investing in agriculture and renewable power sources. These areas offer prospects for job creation, export generation, and attracting foreign capital without causing CO_2 emissions; (3) Increasing work productivity in the industry through the modernisation of tools and equipment, boosting efficiency and output. This would make the industrial sector more efficient and productive; (4) Expanding the diversity of the economy to increase revenue streams, improve employment opportunities, and avoid dependence on oil and gas exports.

Our research has some limitations in scope that provide opportunities for further investigation. Specifically, this study focused on one sector (the industrial sector) and was conducted in one country (Algeria). These limitations provide a strong foundation for future research, which could be expanded to include other sectors or even make a comprehensive comparison among countries. These approaches would allow for richer insights into the research questions.

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