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How do energy consumption, natural resources, trade openness and FDI affect environmental quality in Algeria? Fresh insights from the novel DYNARDL simulations and KRLS approach

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Abstract. *This study investigates the impact of energy consumption, natural resource use, foreign direct investment (FDI), and trade openness on environmental degradation in Algeria over the period 1970–2022. To achieve this, we applied advanced econometric and machine learning approaches, including the Augmented ARDL model, the New DYARDL framework, and the Kernel Regularized Least Squares (KRLS) technique. The empirical results revealed divergent findings regarding the role of energy consumption: while traditional econometric models identified it as a primary driver of emissions, the dynamic specification attenuated its significance, reflecting the increasing reliance on relatively less polluting natural gas. Furthermore, the results provided evidence in support of the pollution haven hypothesis for trade openness and indicated that natural resource use contributes positively to environmental quality. In contrast, FDI exhibited no significant or consistent effect, as its scale remained insufficient to generate measurable environmental outcomes. Finally, the KRLS results confirmed the presence of complex and nonlinear interactions between economic and environmental factors.*

Keywords: environmental quality, energy consumption, natural resources, trade openness and FDI, DYARDL and KRLS.

JEL Classification: Q53, Q56, Q43, F21, C32.

1. Introduction

In recent years, the reduction of carbon dioxide emissions and the improvement of environmental quality have emerged as pressing global concerns. Environmental degradation transcends national borders, as its adverse effects are not confined to polluting countries alone but extend to the international community as a whole. This global interdependence has heightened interest in environmental health and positioned it as a central priority on the United Nations agenda. The pursuit of economic growth, development, and improved standards of living has been accompanied by intensified natural resource extraction and rising energy consumption, thereby accelerating environmental degradation (Opuala et al., 2023). Over the past few decades, the world has experienced profound climate change, primarily driven by greenhouse gas emissions from human activities, particularly industrialization. According to the International Energy Agency (2023), global carbon dioxide emissions from energy combustion and industrial processes increased dramatically, rising from 17.5 Gt in 1990 to 36.8 Gt in 2022.

Addressing and reducing environmental degradation is mainly related to identifying the factors causing it. Recently, the issue of identifying potential factors affecting carbon dioxide emissions and Ecological Footprint has occupied an important space in modern economic research. Researchers have presented several variables that can explain the quality of environmental quality, including economic growth (Gulistan et al, 2020), degree of urbanization (Islam et al, 2021), energy consumption (Shahzad, 2020; Udeagha & Ngepah, 2022), Natural resources abundance (Onifade et al, 2021; Shittu et al, 2021), trade openness (Tachie et al, 2020; Van Tran, 2020), institutional quality (Xaisongkham & Liu, 2022), degree of financial development (Al-Mulali et al , 2015), FDI flows (Opoku & Boachie, 2020; Khan & Ahmad, 2021), and globalization (Islam et al, 2021). Despite the successive and multiplicity of studies, how these factors influence and the degree of their influence is still a matter of controversy and debate.

Although China, the United States, the European Union (27 countries), India, Russia, and Japan are among the world's largest emitters of carbon dioxide together accounting for 67.8% of global fossil fuel-related emissions in 2021 (Crippa et al., 2022) the responsibility for addressing environmental degradation cannot be confined to these economies alone. The contributions of other countries, while relatively smaller in scale, remain significant in the aggregate. This underscores the necessity of collective international action and the intensification of global efforts to safeguard the environment and ensure long-term sustainability.

In this context, Algeria is classified among the developing countries with relatively high carbon emissions, contributing approximately 0.44% of global emissions and ranking third among the largest emitters in Africa. Carbon dioxide emissions in Algeria have shown a persistent upward trend, tripling from 62,936.9 kilotons in 1990 to 170,582 kilotons in 2019, before declining to 161,563 kilotons in 2020 due to the economic slowdown associated with the Covid-19 pandemic (World Bank Indicators, 2024). Algeria's economic and social development is heavily dependent on the hydrocarbons sector, reflecting its status as a rentier state. The country is endowed with significant natural resource wealth, ranking as the fifth-largest producer and fourth-largest exporter of natural

gas, as well as the third-largest producer and ninth-largest exporter of oil worldwide (Boukli Hacene et al., 2020). Hydrocarbons dominate Algeria's foreign trade, accounting for an average of 98% of exports during the period 2002–2014. Furthermore, the domestic energy supply required to sustain economic activity and meet rising societal demand is overwhelmingly derived from oil and gas. A substantial share of foreign direct investment flowing into Algeria is also concentrated in the hydrocarbons sector, further reinforcing the centrality of this industry to the national economy.

Thus, this research paper aims to study one of the most controversial issues in recent years, which is the impact of energy consumption, natural resources, trade openness, and foreign direct investment on environmental quality in one of the oil countries. Our study will focus on Algeria, as its continuing rise in carbon emissions makes it an interesting case study. In addition, we seek to present new evidence from a rentier state characterized by an abundance of natural resources and a continuous rise in demand for non-renewable energy, in addition to being a primary supplier of natural gas and oil in the world, and a destination for foreign direct investments in the hydrocarbons sector. We will focus on these four factors in particular as they are linked to the hydrocarbons sector, which represents the backbone of the economy and development in Algeria, and which may explain the state of environmental quality in Algeria.

The remainder of this study is structured as follows. Section 2 provides a review of the relevant literature. Section 3 outlines the data and methodological framework. Section 4 presents and discusses the empirical results. Finally, Section 5 concludes the study and offers policy recommendations.

2. Literature review

The environmental implications of energy consumption remain a subject of considerable debate. On one hand, proponents argue that economic growth necessitates the increased use of low-cost, non-renewable energy sources; on the other hand, critics emphasize that excessive reliance on such energy undermines environmental sustainability. Energy derived from oil, coal, and natural gas is particularly problematic, as it generates substantial emissions and contributes significantly to global environmental degradation. Empirical evidence supports this view. For instance, Gulistan et al. (2020), using data from 112 countries for the period 1995–2017, found that energy consumption exerts a detrimental effect on the environment. Similarly, Zhang et al. (2022), applying the CS-ARDL approach to a panel of 48 developing countries from 1990 to 2020, demonstrated that intensive reliance on carbon-based energy resources exacerbates environmental degradation. Opuala et al. (2023) reported comparable findings for West African countries between 1980 and 2017, highlighting the adverse role of energy consumption in environmental decline. Furthermore, Islam et al. (2021), employing a novel dynamic ARDL simulation approach for Bangladesh over the period 1972–2016, confirmed that energy use increases CO_2 emissions and environmental degradation in both the short and long run.

The relationship between FDI and the environment is still controversial and debated. Despite the many economic benefits that foreign direct investment brings to the host country, it has

many negatives, especially in terms of depleting the host country's natural resources and causing damage to the environment (Solarin & Al-Mulali, 2018). Theoretically, the theoretical literature linking FDI to the environment is focused on two hypotheses: the pollution haven hypothesis, which believes that foreign investment harms the environment, and the pollution halo hypothesis, which confirms that FDI enhances environmental quality. The pollution haven hypothesis suggests that as developing countries compete to attract foreign direct investment, they impose less stringent environmental standards on foreign firms. On the other hand, to escape the high costs of environmental compliance in developed countries and in order to maximize their profits, multinational companies are turning to these developing countries where they benefit from less stringent environmental laws. This means that FDI negatively affects the environment. In contrast, the pollution halo hypothesis argues that multinational companies, especially from developed countries, bring with them cleaner technology techniques, environmentally friendly production methods and better environmental management systems, which reflects positively on the work of local companies and on environmental standards in host developing countries (Seker et al, 2015; Solarin & Al-Mulali, 2018; Demena & Afesorgbor, 2020).

The theoretical literature suggests that foreign direct investment (FDI) influences environmental outcomes through three main channels: scale, structure, and technology. The scale effect implies that rising FDI inflows expand economic activity and energy consumption, thereby exerting a negative impact on the environment. The structural effect highlights that increased FDI can alter the industrial composition of the host economy, typically shifting it from an agrarian base toward a more energy-intensive industrial sector, and eventually, as development advances, toward a service-oriented economy with lower energy demands. Finally, the technological effect reflects the transfer of advanced production and management practices embedded in FDI, which may reduce energy consumption and enhance environmental quality (Christoforidis & Katrakilidis, 2022).

The topic of the impact of trade openness on the environment occupies an important space within current studies. Theoretically, the relationship between trade and environmental quality is usually explained by the environmental Kuznets curve (EKC), the pollution haven hypothesis and the endowment factor hypothesis. According to the EKC hypothesis, during the early stages of development, the main goal of developing countries is to drive economic growth, regardless of whether this growth may harm the environment, by encouraging industries that often cause pollution. However, as these countries develop, environmental awareness in society increases and governments set strict environmental standards. These countries stop producing some pollution-intensive goods and instead begin to import these goods from countries with less stringent environmental laws (Yu et al, 2019). While the pollution haven hypothesis indicates that foreign companies in developed countries with strict environmental regulations work to reduce their production costs by transferring their pollution-intensive industrial activities towards less developed countries, which are often characterized by relatively lenient environmental regulations. The endowment factor hypothesis also means that since specialization in production is based on the relative availability of production factors, and since pollution control is a low-cost factor in developing countries, the latter are more attractive for pollution-intensive production (Ssekibaala et al, 2022).

On the other hand, Antweiler et al (2001) divides the channels through which trade affects the environment into three: scale, composition, and technology. The scale means that trade openness is accompanied by the expansion of economic activities and increased demand for exported or imported products, which harms the environment due to increased energy consumption and depletion of natural resources. While composition refers to the structural composition of industrial production, trade openness can cause environmental degradation if the products and goods in trade are polluted. While technology indicates that with trade openness, the flow of advanced and cleaner technology and technologies increases towards developing countries, which may help them improve their environmental quality (Gulistan et al, 2020; Yu et al, 2019; Chang, 2015).

The relationship between natural resource extraction, resource depletion, and environmental quality has long been central to scholarly debate. Natural resources are widely recognized as a key driver of environmental degradation, primarily through their interaction with economic growth (Isiksal et al., 2022). In the early stages of development, rapid economic expansion is often the central objective of governments; however, such growth is typically accompanied by intensified exploitation of natural resources for energy production and industrial activities. The excessive reliance on and processing of non-renewable resources particularly fossil fuels and minerals has led to rising emissions and severe environmental consequences. Resource depletion has further contributed to biodiversity loss, deforestation, and widespread air and water pollution, thereby exacerbating climate change and accelerating environmental degradation (Huo & Peng, 2023).

Empirically, the majority of studies indicate that natural resources have a negative impact on the environment. The Aladejare (2022) study on the 5 richest African economies during the period 1990-2019, Li et al (2023) study on South Asian countries during the period 1990-2018, and Zhang et al (2024) study on a group of economies abundant in natural resources during The period 1990-2016, indicates that natural resources contributed to increasing environmental degradation (Aladejare, 2022; Li et al, 2023; Zhang et al, 2024).

Conversely, several studies have reported that natural resources and resource rents may have a positive effect on environmental quality. For instance, Khan, Hou, and Le (2021), analyzing data from the United States for the period 1971–2016, and Khan, Hou, Le, and Ali (2021), examining the top ten industrialized countries over 1970–2016, both found that natural resources are negatively associated with environmental degradation, suggesting that resource abundance can enhance environmental quality.

3. Methodology and data

3.1. Methodology

3.1.1. ARDL, Augmented ARDL and Dynamic NARDL approach

In light of the above discussions, the following two models are proposed:

$$CO2 = (EC, NAR, TRA, FDI) \quad (1)$$

$$LCF = (EC, NAR, TRA, FDI) \quad (2)$$

Through this study, we will attempt to study the impact of energy consumption (EC), natural resources (NAR), trade openness (TRA) and foreign direct investment (FDI) on environmental quality, which is the internal variable represented by carbon dioxide emissions (CO2) and the Load Capacity Factor (LCF) and each of them is expressed by two independent equations as follows:

$$CO2_t = \beta_0 + \beta_1 EC_t + \beta_2 NAR_t + \beta_3 TRA_t + \beta_4 FDI_t + \varepsilon_t \quad (3)$$

$$LCF_t = \delta_0 + \delta_1 EC_t + \delta_2 NAR_t + \gamma_3 TRA_t + \delta_4 FDI_t + \varepsilon_t \quad (4)$$

To detect the long-run relationship between the study variables, we use the ARDL bound testing approach developed by Pesaran et al (2001), and to clarify this approach, we will rely only on equation (1), which concerns carbon gas emissions. The long-run cointegration test is verified using the value of the F-state value significant at less than 5%. To perform this test, we rely on the following equation (5):

$$\begin{aligned}\Delta CO2_t = \theta + \rho_1 CO2_{t-1} + \rho_2 EC_{t-1} + \rho_3 NAR_{t-1} + \rho_4 TRA_{t-1} + \rho_5 FDI_{t-1} \\ + \sum_{i=1}^{q} \tau_1 \Delta CO2_{t-i} + \sum_{i=1}^{q} \tau_2 \Delta EC_{t-i} + \sum_{i=1}^{q} \tau_3 \Delta NAR_{t-i} \\ + \sum_{i=1}^{q} \tau_4 \Delta TRA_{t-i} + \sum_{i=1}^{q} \tau_5 \Delta FDI_{t-i} + \varepsilon_t \end{aligned} \quad (5)$$

In the framework of the Wald test to test hypothesis H_0, which states that "there is no cointegration between the variables in the model," where:

$$H_0: \quad \rho_1 = \rho_2 = \rho_3 = \rho_4 = \rho_5 = 0 \quad (6)$$

and

$$H_1: \quad \rho_1 \neq \rho_2 \neq \rho_3 \neq \rho_4 \neq \rho_5 \neq 0 \quad (7)$$

However, despite this, the cointegration method using the bound testing approach developed by (Pesaran & al, 2001) was not without some defects, especially since its tests were placed under a number of basic restrictions (Pata & Caglar, 2021).

In the face of these shortcomings, (McNown & Al, 2018), (Sam & al, 2019) developed a new approach known as the Augmented ARDL Bounds Test, which incorporates additional and more precise tests to detect the presence of long-term equilibrium relationships. In addition to the overall F-test on the lagged dependent variable and independent variables, and the T-test on the lagged dependent variable introduced by (Pesaran & al, 2001), the Augmented ARDL Bounds Test includes an F-test on the lagged independent variables aimed primarily at detecting the possibility of a breakdown in the cointegration relationship, without the necessity for the dependent variable to be stationary at first differences (I(1)), as required by the traditional bounds test approach (Pesaran & al, 2001). As for the critical values specific to this test (Exogenous F-bounds test on legged independent variable), they are explained in the research paper provided by (Sam & al, 2019).

To investigate the existence of cointegration through this new approach, the following three tests are mandatory as follows (Caglar et al, 2024):

$$F_{overll}^{test} \quad H_0: \quad \rho_1 = \rho_2 = \rho_3 = \rho_4 = \rho_5 = 0 \quad (8)$$

$t_{DV}^{test} \quad H_0: \quad \rho_1 = 0 \qquad (9)$

$F_{IDV}^{test} \quad H_0: \quad \rho_2 = \rho_3 = \rho_4 = \rho_5 = 0 \qquad (10)$

If the values of all three test statistics exceed their respective upper limit critical values, it is inferred that there exists full cointegration among the variables.

The Dynamic ARDL (DYNARDL) approach, introduced by Jordan and Philips (2018), employs a uniform lag length for all variables in the analysis. This feature distinguishes it from the traditional ARDL model developed by Pesaran et al. (2001), which is characterized by greater complexity due to the inclusion of varying lag lengths across different variables (Kartal et al., 2023). An additional advantage of the DYNARDL framework is its ability to generate graphical simulations of counterfactual differences between variables. Specifically, the model illustrates how endogenous variables respond to shocks in exogenous variables, providing a dynamic visualization of causal relationships. These simulations plot the counterfactual reaction of an explanatory variable while holding all other explanatory variables constant, thereby isolating its effect on the dependent variable (Lin & Ullah, 2024). A fundamental requirement of the DYNARDL approach is that the dependent variable must be integrated of order one, I(1).

The dynamic ARDL algorithm conducts 5000 simulations utilizing a standard multivariate function for the vector parameter. Additionally, graphs are employed to verify the precise modification of regressors and their response to the response variable (Zhou et al, 2022).

The equation (4) includes a dependent variable integrated in zero order I(0), we will estimate it using the Augmented ARDL model, while the dynamic ARDL framework can only be presented for the equation (3) as follows:

$$\Delta CO2_t = \pi + \gamma_0\, CO2_{t-1} + \ \varphi_1\, \Delta EC_{t-1} + \gamma_1\, EC_{t-1} + \varphi_2\, \Delta NAR_{t-1} + \gamma_2\, NAR_{t-1} + \varphi_3\, \Delta TRA_{t-1} + \gamma_3\, TRA_{t-1} + \varphi_4\, \Delta FDI_{t-1} + \gamma_4\, FDI_{t-1} + \ \partial\, ECT_{t-1} + \epsilon_t \qquad (11)$$

In Eq. (11), $\varphi_1, \varphi_2, \varphi_3, \varphi_4$ capture the short-term estimates of the designated variables, whereas and γ_1 , $\gamma_2, \gamma_3, \gamma_4$ are long-term estimates of the selected variables, which is applicable to model (1), ϵ_t denotes an error term and ECT_{t-1} representes error correction term.

3.1.2. The KRLS approach

The KRLS model at first was designed by Hainmueller and Hazlett (2014) primarily for social science researchers to conduct regression analysis and inference without any prior assumptions of linear (Sarkodie, 2021). After estimating and examining the DYNARDL model, we employ these methode (KRLS), an algorithm in machine learning that uses pointwise derivatives to investigate the causal-effect relationship (Sarkodie & Owusu, 2020). This methodology is applied to verify the results of DYNARDL simulations (Kartal, 2023). The KRLS method proves to be fitting for application in social science research due to its nonlinear nature, utilization of radially basis functions to determine the most suitable surface, facilitation of acquiring marginal effects, evasion of rigid parametric assumptions, and facilitation of interpreting intricate relationships (Kartal et al; 2023). The KRLS estimator exhibits all the sought-after statistical properties, being unbiased and consistent.

It asymptotically adheres to the normal distribution under mild regularity conditions. Remarkably, its efficiency is not significantly lower than that of the OLS estimator, even in scenarios where the data exhibit a linear patterni (Dmitraki& Emmanouilidis, 2023).

3.2. Data sources and variables

This study estimates an econometric modeling technique to address the effect of energy consumption (EC), natural resources (NAR), trade openness (TRA) and foreign direct investment (FDI) on environmental quality which is the endogenous variable presented by Carbon Dioxide emissions (CO2) & Load Capacity Factor (LCF) and each of them is expressed in an independent model. Our analysis uses annual data from 1970 to 2022 (see table 1):

Table 1. *Definition of variables and data sources*

Symbols (sign)	Variables: Descripion (units)	Expected sign		Sources
		On CO_2	On LCF	
CO_2	Carbon Dioxide emissios CO2 emissions (kt)	N/A		WDI
LCF	Load Capacity Factor: Biocapacity is expressed in terms of global hectares per capita (gha)	N/A		Global Footprint Network
NAR	Natural resources abundance (% of GDP)	-	-	WDI
FDI	FDI net inflows (% of GDP)	+	-	WDI
EC	Energy consumption (% of total final energy consumption)	+	-	EIA
TRA	Trade openness index measured by the sum of exports and imports of goods and services % of GDP	+ or -	+ or -	WDI

Expected sign: N/A: indicates the dependent variable. **-** Negative, + Positve, + **or -** Negative or Positive
Source: Authors' own compilation.

4. Results and discussions

4.1. Descriptive statistics and correlation matrix

Table 2. represents the results of descriptive statistics. In our case, all series is characterized by a lower degree of dispersion this is confirmed by low values of standard deviations where all the data are located around their mean therefore they are homogeneous. Skewness statistics indicate that CO2, EC, NAR & TRA are negatively skewed in other words left-skewed however LCF & FDI are exhibit a right-skewed distribution. The sample data is normally distributed therefore we accept the null hypothesis of normality except LCF & EC where the Jarque-Bera' probability is lower than the critical value 5%.

Table 2. *Descriptive statistics*

Variables	CO_2	LCF	EC	NAR	TRA	FDI
Mean	11.21444	0.805449	9.189075	2.957367	4.041064	0.693346
Median	11.24426	0.734976	9.334632	3.012232	4.061573	0.702589
Std. dev.	0.547072	0.19358	0.472673	0.394131	0.194625	0.674673
J-B	5.320995	20.24174	26.84711	3.268159	3.586872	4.733169
Prob (J-B)	0.069913	0.00004	0.000001	0.195132	0.166387	0.093801

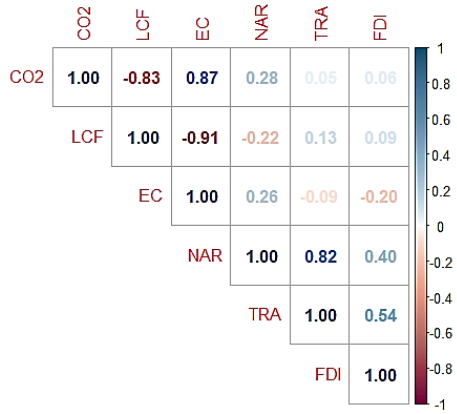
Source: Authors' own computations using EViews 13 software.

4.2. Matrix of correlation

The findings of the correlation matrix, as illustrated in Fig. 1, show carbon dioxide emissions (CO_2) a strong positive correlation with energy consumption (EC), suggesting

that higher fossil-fuel-based energy use conduct leads to increased emissions. Concerning natural resources (NAR), the correlation is weakly positive with CO_2 and feebly negative with LCF, suggesting that resource exploitation contributes only marginally to environmental degradation. Trade openness (TRA) and foreign direct investment (FDI) demonstrate very weak correlations with both CO_2 and LCF (Load Capacity Factor), suggesting that their role in forming environmental quality in Algeria stays relatively limited. Generally, these results emphasize that energy consumption is the most influential driver of environmental degradation, while the other variables exert secondary.

Figure 1. *Results of Pair-wise correlation*



Source: Authors' own computations using R studio.

4.3. Unit Root without a Structural Breakpoint and with a Structural Breakpoint

Tables 3 present the results of a unit root test in the presence of structural breaks (L-S) as follows:

Table 3. *Lee and Strazicich (2003) Unit Root Test With two Structural Break*

Variables	At level			At first difference			Results
	t-stat	DT_{1t}	DT_{2t}	t-stat	DT_{1t}	DT_{2t}	
CO_2	-5.943	1988	2012	-6.832 *	1983	2011	**I(1)**
LCF	-6.330 **	1983	2002	-8.194 *	2002	2012	**I(0)**
EC	-6.335 **	1991	1996	-5.471	1981	1998	**I(0)**
TRA	-5.878	1984	2005	-7.961 *	1985	2000	**I(1)**
NAR	-5.128	1984	2004	-8.563 *	1984	1995	**I(1)**
FDI	-5.627	1987	2000	-10.017 *	1980	1989	**I(1)**

Note: *, ** and *** indicate significance at 10%, 5% and 1% level, respectively.
DT_{1t} and DT_{2t} refer to the first and second break dates, respectively.
Source: Authors' own computations using EViews 13 software.

To decide the degree of integration of all-time series and determine their order we relied more on the results of the unit root test of Lee and Strazicich (2003) with two structural breaks. The results show that LCF and CE are constant at the level, while CO2, TRA, NAR and FDI are constant at the first difference. Since all the definite variables are integrated in either I(0) or I(1). Hence, the novel dynamic ARDL simulation approach proves to be suitable for implementation on such time series variables.

4.4. Bound tests

For the first model, the upper part of table 4 reports the results of the bounds testing procedure. For both models and according to Pesaran et al. (2001) the computed F-test statistic is found to be exceeding the upper limit, additionally, the calculated t-test statistic is greater than the asymptotic upper bound in absolute values. In these terms, we accept the alternative hypothesis, so there is strong evidence of cointegration. Next, we report the summary of outcomes in the lower part of table 4 using the Augmented ARDL bounds testing approach. It is clear that test statistics are big than the critical value at a 1% level of significance, suggesting the long-run association between load capacity factor, natural resources, energy consumption trade openness and FDI.

Table 4. *Bounds test results: Pesaran, Shin, and Smith bounds testing*

K		10%		5%		1%		p	value
		I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
Model 1: $CO2_t$ The ARDL bounds test									
F	**16.560** *	1.930	3.310	2.369	3.952	3.432	5.486	0.000 *	0.000 *
t	**-6.986** *	-1.589	-3.355	1.965	-3.797	2.713	-4.688	0.000 *	0.000 *
Model 2: LCF_t - The augmented ARDL bounds test (AARDL)									
F	**8.667** *	1.9	3.01	2.26	3.48	3.07	4.44	--	--
t_{DEP}	**-6.537** *	-1.62	-3.26	-1.95	-3.6	-2.58	-4.23	--	--
F_{IND}	**10.434** *	2.09	3.65	2.61	4.36	3.84	6.12	--	--

Note: I(0) and I(1) denote the lower and upper band critical values at 10%, 5%, and 1% significance level of Pesaran, Shin, and Smith bounds test (PSS); P-values are Kripfganz & Schneider critical values and approximate P-values; * indicates the presence of cointegration at the 1% significance level.
Source: Authors' own computations using STATA 17 software.

4.5. ARDL and AARDL estimation

We summarize the findings of long run estimation in Panel A: firstly, the energy consumption and FDI affect CO_2 emissions positively implying that any increase in EC (FDI) by 1% boost CO_2 with 0.699% (0.281%), whereas they reduce LCF with 0.886% (0.030%). Juxtaposing, trade openness index has a positive impact on both CO_2 & LCF while natural resources abundance affect CO_2 & LCF negatively. All these results are significant at 1% level, except FDI coefficient in AARDL model, which is significant at 10%.

Panel B presents the short-run estimates. The coefficients for FDI, trade openness, and natural resource abundance are consistent with the long-run specifications; however, they are statistically insignificant, except for natural resource abundance in Model 1. Energy consumption exhibits a negative effect on CO_2 emissions and a positive effect on LCF, but these coefficients are insignificant and contradict the results reported in Panel A.

For the ARDL model, the error correction term (ECT) is negative and highly significant at the 1% level, indicating the speed of adjustment toward long-run equilibrium. The estimated coefficient of –0.630 suggests that approximately 63% of the disequilibrium from the previous period is corrected in the short run. Similarly, in the Augmented ARDL (AARDL) model, the ECT is also negative (–0.859) and statistically significant at the 1% level, confirming the existence of a cointegrating relationship. This result indicates that about 85.9% of the disequilibrium is corrected in the subsequent period, implying a faster speed of adjustment compared to the CO_2 model.

The determination coefficient of the first model is 85.6%, implying that is 85.6% of CO_2 emissions variations are explained by EC, TRA, NAR and FDI while the rest of the variation is explained by other factors that are not mentioned in the model. Concerning the second model, the value of R^2 means that 66.9% of LCF variations can be explained by the same exogenous variables and 33.1% are determined by other variables.

Table 5. *ARDL and Augmented ARDL results estimation*

Model 1 : $ARDL(1,4,3,4,4)$				**Model 2:** $Augmented\ ARDL(1,4,2,3,0)$		
Parameters	**Coefcients**	**t**	**p values**	**Coefcients**	**t**	**p values**
Panel A: Long run coeffcients						
EC	0.699	7.44	0.000	-0.886	-5.288	0.000
TRA	2.005	7.21	0.000	2.571	7.483	0.000
NAR	-1.179	-7.50	0.000	-0.660	-4.216	0.002
FDI	0.281	4.29	0.000	-0.030	-2.029	0.050
Panel B: Short run coeffcients						
ECM(-1)	-0.630	-6.99	0.000	-0.859	-6.982	0.000
ΔEC	-0.320	-1.11	0.278	1.032	0.975	0.336
ΔEC(-1)	0.416	1.43	0.165	0.919	0.748	0.459
ΔEC(-2)	-0.268	-1.01	0.323	0.274	0.234	0.816
ΔEC(-3)	-0.766	-2.59	0.016	-3.949	-3.473	0.001
ΔTRA	0.179	0.85	0.403	0.419	1.153	0.257
ΔTRA(-1)	-1.098	-5.61	0.000	-1.021	-2.525	0.016
ΔTRA(-2)	-0.844	-3.10	0.005	--	--	--
ΔNAR	-0.293	-3.30	0.003	-0.037	-0.377	0.708
ΔNAR(-1)	0.512	5.33	0.000	0.569	4.685	0.000
ΔNAR(-2)	0.233	2.41	0.024	0.320	3.478	0.001
ΔNAR(-3)	-0.144	-2.29	0.031	--	--	--
ΔFDI	0.051	1.69	0.104	--	--	--
ΔFDI(-1)	-0.131	-3.18	0.004	--	--	--
ΔFDI(-2)	-0.108	-3.13	0.004	--	--	--
ΔFDI(-3)	-0.093	-3.86	0.001	--	--	--
D1	0.142	2.56	0.017	--	--	--
D2	--	--	--	-0.145	-6.615	0.000
R-squ	0.856			0.669		
Adj R-squ	0.735			0.578		
P-value F s	0.000			0.000		

Source: Authors' own computations using STATA 17 software.

Table 6 explicates the findings of this model diagnostic tests on the time series dataset. We applied the Breusch-Godfrey LM test to discover any potential serial correlation in the two model. The results indicated that did not exhibit any concerns regarding serial autocorrelation In both proposed econometrics models. The White's heteroscedasticity test is also applied to confirm the homoscedasticity of two our models.

Table 6. *Model diagnostic test*

Panel A: Breusch–Godfrey LM test for autocorrelation				
	Model 1 : $CO2_t$		**Model 2 :** LCF_t	
Lags (P)	**F-statistic**	**df**	**F-statistic**	**df**
1	1.001 [0.3271]	(1, 24)	0.252 [0.6194]	(1, 30)
2	0.967 [0.3950]	(1, 23)	1.969 [0.1578]	(2, 29)
Panel B: White's test (Cameron & Trivedi's decomposition of IM-test)				
Source	**Chi-square**	**df**	**Chi-square**	**df**
Heteroskedasticity	46.00 [0.4306]	45	46.00 [0.4306]	45
Skewness	9.23 [0.9873]	21	13.19 [0.5873]	15
Kurtosis	0.22 [0.6379]	1	0.24 [0.6227]	1
Total	55.45 [0.8421]	67	59.44 [0.5328]	61

Note: For autocorrelation, H_0: No serial correlation. P-values in [ ]
Source: Authors' own computations using STATA 17 software.

Figure 2. *Parameter stability plots: Cum sum test using OLS CUSUM plot for parameter stability*

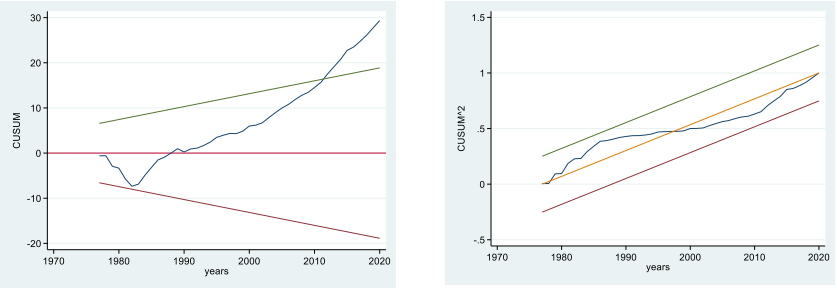
Panel A: Model 1: $CO2_t$ **Panel B: Model 2: LCF_t**



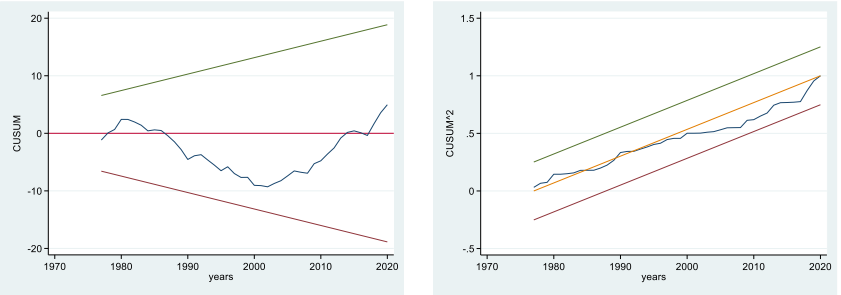
Source: Authors' own computations using STATA 17 software.

Figure 3. *Cumulative sum and cumulative sum squares plots for two models estimated*

Panel A: Model 1: $CO2_t$



Panel B: Model 2: LCF_t



Source: Authors' own computations using STATA 17 software.

4.6. Dynamic ARDL simulations estimation

Table 7 shows the findings of the novel Dynamic ARDL simulations as follow. The results showed that in the short term, the abundance of natural resources had a negative and significant effect on CO_2 emissions, and that energy consumption had a negative but insignificant effect, while the effect of trade openness and foreign direct investment was positive but insignificant.

In the long term, the results showed a positive and insignificant effect of energy consumption on CO_2 emissions. The results indicate that increase in energy consumption leads to an increase in CO_2 emissions. This means that energy consumption in Algeria has caused further environmental degradation. This is because power generation in Algeria relies heavily on non-renewable sources, such as coal and natural gas, which are the main sources of carbon and greenhouse gases, and thus ecosystem degradation. These results are consistent with the work of Bélaïd & Youssef (2017) who found that the effect of renewable and non-renewable electricity consumption on CO_2 emissions in Algeria was positive but insignificant. These results support the work of Adedoyin et al. (2021) who found that non-renewable energy consumption caused an increase in emissions levels in sub-Saharan Africa, and Islam et al. (2022) who concluded that energy use negatively affected the ecological footprint and caused environmental degradation in Bangladesh.

While trade openness showed a positive and significant effect on CO_2 emissions in the long run, which means that trade openness harmed environmental quality in Algeria. A 1% increase in trade openness leads to an increase in CO_2 emissions by 0.403%. These results are logical in a country like Algeria, where hydrocarbon exports constitute the main component of exports. Algeria is the fifth largest producer and fourth largest exporter of natural gas, and the third largest producer and ninth largest exporter of oil in the world (Boukli Hacene et al, 2020). These results are consistent with those presented by Hakimi & Hamdi (2016) and Yu et al (2019). Khan et al. (2019) concluded that trade has contributed to increased environmental degradation in Pakistan, noting that the negative impact of trade openness on the environment is due to developed countries shifting their polluting production processes to developing countries.

The results also revealed that the abundance of natural resources had a negative and significant impact on carbon dioxide emissions in the long run, as a 1% increase in natural resources results in a 0.235% decrease in CO_2 emissions. This means that natural resources contribute to improving environmental quality. This can be explained by the fact that companies use environmentally safe technologies to extract natural resources, which reduces the amount of carbon dioxide emitted into the environment. It can also be explained by the fact that Algeria, despite its abundance of natural resources, does not exploit these resources efficiently in the industrial sector, which is still not developed enough to allow it to use this abundance intensively in production processes. These results are consistent with those presented by Khan et al (2021), Majeed et al (2021), Huo & Peng (2023). However, these results conflict with the works of Bekun et al. (2019) and Guo et al. (2023), who revealed that natural resource rents are a source of environmental degradation in the long run.

The results further indicate that FDI exerts a positive but statistically insignificant effect on CO_2 emissions in the long run, implying that increases in FDI are associated with higher emissions. This outcome is plausible in the Algerian context, where FDI is predominantly resource-seeking and concentrated in the extractive industries sector. Such findings lend support to the pollution haven hypothesis in Algeria, which posits that firms from developed countries—facing stringent environmental regulations and higher compliance costs—relocate their production activities to developing economies with more lenient

regulatory frameworks. These results are in line with Mukiyen Avcı (2023), who demonstrated that Turkey functions as a pollution haven for advanced economies. Similarly, Khan et al. (2019) found that FDI had a positive but insignificant effect on environmental degradation in Pakistan in the long run, emphasizing that much of the FDI flowing from developed to developing economies is directed toward manufacturing, mining, and electricity generation, sectors that contribute substantially to environmental degradation.

ECT refers to the error correction term, which measures the speed of adjustment toward long-run equilibrium. The results show that the estimated ECT has a negative and statistically significant value, indicating that the imbalance will be corrected by approximately 19% in the long run. Moreover, the R^2 value suggests that the independent variables explain around 67% of the total variation in the dependent variable. The estimated p-value of the F-statistic further confirms that the model provides a good overall fit.

The new dynamic ARDL simulation model proves effective in automatically generating graphs and predicting the future values of the dependent variable in response to changes in the explanatory variables while holding other factors constant. In this study, we predicted the variation in CO_2 emissions in response to a positive or negative 1% change in the explanatory variables, namely energy consumption, trade openness, natural resource abundance, and foreign direct investment.

Table 7. *Estimates of DYARDL simulations model*

Parm	Coef	SE	t	P-value	Min 95	Max 95
Long-run analysis						
EC_{t-1}	0.135	0.143	0.94	0.354	-0.155	0.425
TRA_{t-1}	0.403	0.131	3.07	0.004	0.137	0.667
NAR_{t-1}	-0.235	0.091	-2.58	0.014	-0.420	-0.050
FDI_{t-1}	0.021	0.060	0.36	0.721	-0.099	0.143
Short-run analysis						
ECM(-1)	-0.189	0.108	-1.75	0.087	-0.408	0.029
ΔFDI	0.032	0.046	0.70	0.488	-0.060	0.125
ΔEC	-0.143	0.441	-0.32	0.747	-1.036	0.749
ΔTRA	0.289	0.275	1.05	0.300	-0.266	0.844
ΔNAR	-0.245	0.129	-1.90	0.065	-0.507	0.016
D_1	-0.232	0.146	-1.59	0.121	-0.527	0.063
Model characteristics						
R^2	0.67	Prob > F	0.026			
Adj R-squa	0.51					
Num of obs.	50	Simulations	5000			

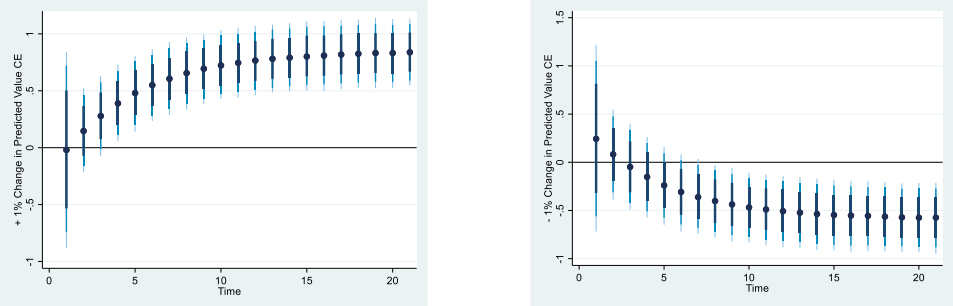
Notes: The table show the estimation results of the DYNARDL simulation and the associated diagnostic checks. ECM(-1) indicates the error correction term coefficient. D_1 dummy variable symbolizing the structural changes detected in the model. SE is the standard error.

Keeping other things constant, Fig. 4 shows that positive shock of energy consumption increase the propagation of CO_2 emissions, while a -1% changes in energy consumption reduce the effect of CO_2, therefore the irrational utilization of energy provoke the CO_2 emissions. Likewise, in Fig. 5, a 1% counterfactual shocks in trade openness have a positive effect on CO_2 emissions, whereas, the negative changes have a negative effect (decrease) on the dependent variable. In contrast, positive (negative) shock of natural resources abundance reduce (improve) the CO_2 emissions. Finally, Fig. 7 illustrates that +1% changes

in FDI increase the CO_2 emissions, but -1% changes have a slight positive effect on the endognenous variable. According to the results of DYARDL diagrams, only natural resources abundance that can decline CO_2 emissions & improve the environmental quality in Algeria.

The DARDL model stands out for its ability to aid in visually representing, modeling, and of counterfactual alterations in a dependent variable caused by a shock in an explanatory variable (Hassan et al, 2024).

Figure 4. *Effects of ±1% Counterfactual Shocks in EC on the CO_2*



Notes: dot (●) Dots represent average predicted value while dark blue to light blue lines stands for 75, 90 and 95% confidence interval by +1% and − 1% shock in EC.

Figure 5. *Effects of ±1% Counterfactual Shocks in TRA on the CO_2*

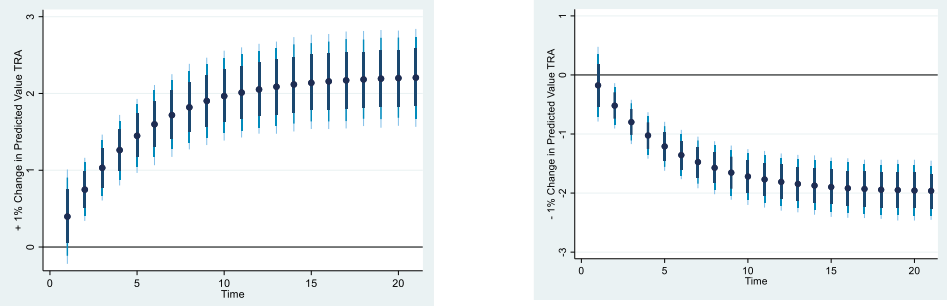


Figure 6. *Effects of ±1% Counterfactual Shocks in NAR on the CO_2*

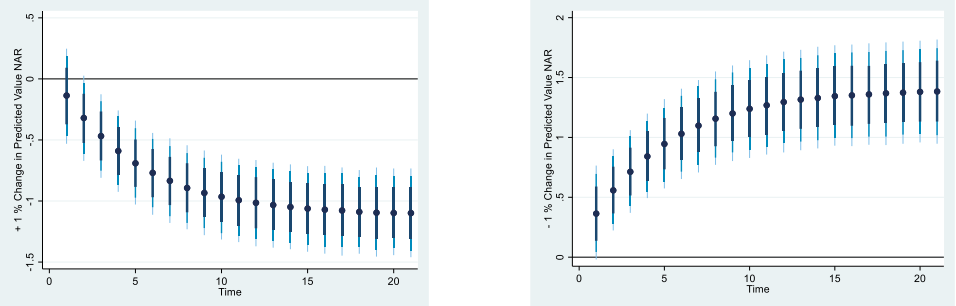
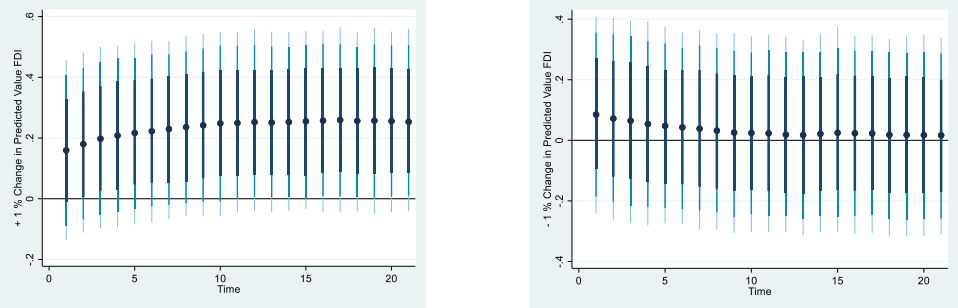


Figure 7. *Effects of ±1% Counterfactual Shocks in FDI on the CO_2*



Source: Authors' own computations using STATA 17 software.

4.7. KRLS estimation

The KRLS approach is executed to research, with the help of pointwise derivatives, the link between CO_2 and the independent parameters. The KRLS results for CO_2 emissions is appear in Table 8. The KRLS approach is applied to check the results of the DYNARDL simulations. Table 8. presents the KRLS approach results as follow:

Table 8. *Pointwise derivatives using KRLS*

CO_2	Avg.	SE	t	P>t	P25	P50	P75
EC	0.808	0.053	15.077	0.000	0.329	0.997	1.198
TRA	0.103	0.133	0.775	0.442	-0.356	0.136	0.630
NAR	-0.212	0.071	-2.968	0.005	-0.483	-0.260	0.068
FDI	0.167	0.024	6.930	0.000	-0.030	0.174	0.355
D1	0.254	0.043	5.868	0.000	0.066	0.240	0.422
Diagnostics							
Lambda	0.061	Sigma	5	R2	98.1	obs	51
Tolerance	0.051	Eff. df	25.09	Looloss	7.352		

Notes: Where Avg. is the average marginal effect; SE is the standard error; P-25, P-50, and P-75 represent 25th, 50th, and 75th percentile.
Source: Authors' own computations using STATA 17 software.

Table 8 presents, the predictive power of the KRLS model is 98.1 implying that the explanatory variables explain 98.1% of the variation in the CO_2 emissions in the Algeria. According to the results, the mean pointwise marginal effects for natural resources, FDI, Energy consumption and trade openness are 0.808, 0.103, -0.212, 0.167 and 0.254 respectively. However, only natural resources, FDI, Energy consumption and dummy variable found to be statistically significant at all examined levels. It is clear that the positive sign of the energy consumption coefficient, trade openness and also FDI is consistent with the results obtained from the DARDL model. Also, Table 8 gives percentiles at the 25th, 50th, and 75th levels for an analysis of various marginal effects using regressor derivatives. Specifically, at the first quartile, a unit increase in energy consumption causes a 0.329% increase in CO2, at 50% and 75% the effect is still positive but it increases with higher degrees (0.997%, 1.198% respectively).

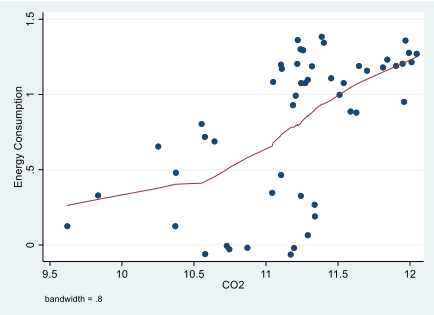
As for trade openness (TRA), its impact was small, at 0.103, and statistically insignificant. However, the percentiles reveal that its value is negative (P25 = -0.356) at the lower

quintiles, while it takes positive values (P50 = 0.136, P75 = 0.630) at the middle and upper quintiles. This can be explained by the fact that at the beginning of trade liberalization, under certain conditions, it may have a positive or neutral impact on the environment through the transfer of clean technology. However, under other conditions, with the increase in trade volume in polluting industries, its impact on the environment becomes negative through the increase in CO_2.

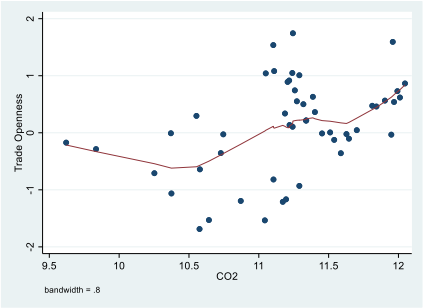
We also find that natural resources contribute to improving environmental quality by reducing CO_2 emissions. The positive environmental impact appears stronger in the lower and middle quintiles but weakens in the upper quintile. This pattern may reflect a substitution effect, whereby less polluting natural gas replaces more carbon-intensive energy sources, or it may indicate that revenues generated from oil exports are being used to finance cleaner technologies and environmentally friendly infrastructure.

Contrary to the DYNARDL results, the KRLS technique reveals a significant negative impact of FDI on the environment, starting close to zero in the lower quintile and increasing in the upper quintiles. The high elasticity of the KRLS enables it to capture nonlinear effects. This result could support the "pollution haven" hypothesis and emphasizes the importance of investment quality, not just quantity.

Figure 8. *Pointwise marginal effects of the energy consumption, natural resources and trade openness on the CO_2 emissions*

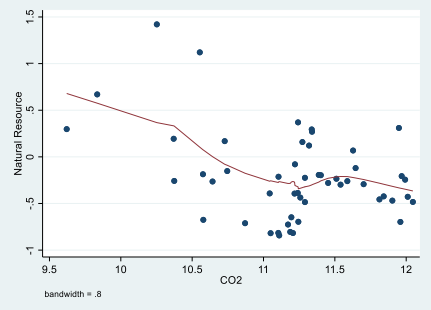


A. Pointwise Marginal Effect of the Energy Consumption on the CO_2 Emissions



B. Pointwise Marginal Effect of the Trade openness on the CO_2 Emissions

C.



D. Pointwise Marginal Effect of the Natural Resource on the CO_2 Emissions

5. Conclusion and policy implications

This paper would contribute to the existing literature on the determinants of environmental quality by providing empirical evidence that can inform policy aimed at reducing environmental degradation. Specifically, the study examines the impact of energy consumption, natural resources, foreign direct investment (FDI), and trade openness on CO_2 emissions and the Load Capacity Factor (LCF) in Algeria over the period 1970–2022.

Preliminary results reveal that, when estimating the first model using the ARDL methodology and the second model through the Augmented ARDL method, energy consumption exerts a statistically significant and positive long-run effect on emissions. This confirms that reliance on conventional energy sources is the primary driver of carbon emissions and a key determinant of environmental degradation. In contrast, estimates from the dynamic DYARDL model suggest that, in the long run, energy consumption does not significantly influence environmental quality in Algeria. One possible explanation is that the effect of energy consumption is subsumed within other, more influential variables such as trade openness and natural resources. Moreover, Algeria's energy profile—dominated by natural gas—may produce different environmental outcomes compared to economies more reliant on coal or other highly polluting sources.

The econometric results further indicate that trade openness is associated with a deterioration in environmental quality. This finding lends support to the pollution haven hypothesis, which argues that trade liberalization in developing economies, such as Algeria, tends to attract pollution-intensive investments and industrial activities relocated from advanced economies with stricter environmental standards. Consequently, these results highlight the necessity of complementing trade liberalization with stringent environmental regulations and effective monitoring mechanisms, in order to mitigate the ecological costs of openness while still reaping its economic benefits.

In contrast, natural resources show a positive impact on environmental quality, possibly reflecting the use of oil and gas to improve environmental infrastructure. It also reflects the reliance on natural gas (dominant in Algeria) for power generation, which is less polluting than other energy sources. Foreign direct investment, however, has no clear impact on environmental quality in the case of Algeria, particularly since its size is not large enough to have a significant impact compared to trade openness and natural resources.

To support the study's findings, we used the KRLS technique. The results indicate that energy consumption is the most important generator of carbon dioxide emissions in Algeria, exhibiting a positive and significant marginal effect that increases across percentiles and increases at higher levels of emissions. Meanwhile, the relationship between trade, foreign direct investment, and carbon emissions appears nonlinear, with their effects varying depending on the sample distribution and economic situation. This supports the importance of adopting a nonlinear approach to understanding complex environmental-economic relationships. In contrast, the natural resource effect confirms that increasing natural rents can be used to improve environmental quality. Hence, it can be said that the results of KRLS confirmed and deepened the results of DYNARDL, as they showed non-linear details that must be taken into account when setting environmental policies in Algeria.

In conclusion, the findings suggest that environmental policies in Algeria should prioritize the following directions:

- Accelerating the energy transition by expanding the deployment of renewable energy sources and enforcing strict energy efficiency standards;
- Improving energy efficiency to maximize both economic and environmental benefits, rather than concentrating exclusively on reducing consumption volumes;
- Integrating carbon clauses and environmental standards into trade agreements, while incentivizing the development of low-emission value chains to mitigate the environmental risks associated with trade expansion;
- Earmarking a share of hydrocarbon revenues for the establishment of an environmental sovereign fund dedicated to financing the energy transition and green infrastructure projects;
- Adopting a selective investment policy that provides strong incentives for environmentally responsible projects, restricts highly polluting investments, and promotes the localization of low-carbon industries.

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