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Türkiye's Sustainability Challenge: An Empirical ARDL Analysis of the Impact of Energy Consumption, Economic Growth, and Agricultural Growth on Carbon Dioxide Emissions

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Abstract

Global climate change, driven predominantly by carbon dioxide (CO₂) emissions, poses one of the most critical challenges to sustainability in the 21st century. As Türkiye continues to pursue economic expansion and agricultural development, the resulting rise in energy consumption has led to a substantial increase in CO₂ emissions. Given Türkiye's position as the world's 17th largest economy and its ranking as the 15th highest CO₂ emitter, understanding the country's exposure to climate risks is essential for informing policy efforts aimed at sustainable development. This study investigates the dynamic interplay between CO₂ emissions and their primary determinants in Türkiye, offering empirical insights into the pathways through which these factors influence environmental sustainability. Utilizing a 34-year time series and the Autoregressive Distributed Lag (ARDL) model, the findings reveal that both economic growth and energy consumption contribute significantly to rising CO₂ emissions, thereby exacerbating environmental degradation. Conversely, an increase in agricultural value added is associated with a reduction in CO₂ emissions, highlighting its potential role in improving environmental quality. The results underscore the urgent need for a comprehensive legal and institutional framework that supports technological innovation and accelerates the transition toward a low-carbon economy in Türkiye.



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1. Introduction

Energy has long been a cornerstone of human advancement, serving as a vital component of both daily life and economic development. Despite significant shifts in energy production and consumption patterns throughout history, fossil fuels remain the predominant energy source for both industrialized and emerging economies [1]. This dependency, particularly in sectors such as industry, transportation, agriculture, and tourism, continues to drive a global surge in energy demand and consequently carbon dioxide (CO₂) [2].

Recent technological progress has further intensified energy consumption, exacerbating pressure on finite energy resources and accelerating environmental degradation. Notably, global fossil fuel consumption rose by 5.8% in 2021, far exceeding the decade-long average of 0.9% [3]. As a result, CO₂ emissions estimated at 36.3 billion tons in 2021 have reached alarming levels, with electricity generation, industrial production, and transportation accounting for the largest shares [4]. These figures highlight the critical need for a sustainable energy transition, where economic development and environmental protection must be pursued in tandem.

As a result of these considerations, addressing global climate change with an approach that takes into account the environmental sustainability of economic growth is becoming increasingly important. Particularly, energy consumption, economic growth, and agricultural production activities are fundamental determinants of environmental degradation and play a critical role in the increase in CO₂ emissions on a global scale [5].

Figure 1 visualizes the reciprocal interactions among energy consumption, economic growth, and agricultural growth, as well as the impacts of these variables on CO₂ emissions. In the diagram, each variable is presented within rectangular boxes, and their relationships and interactions are represented by directional arrows.

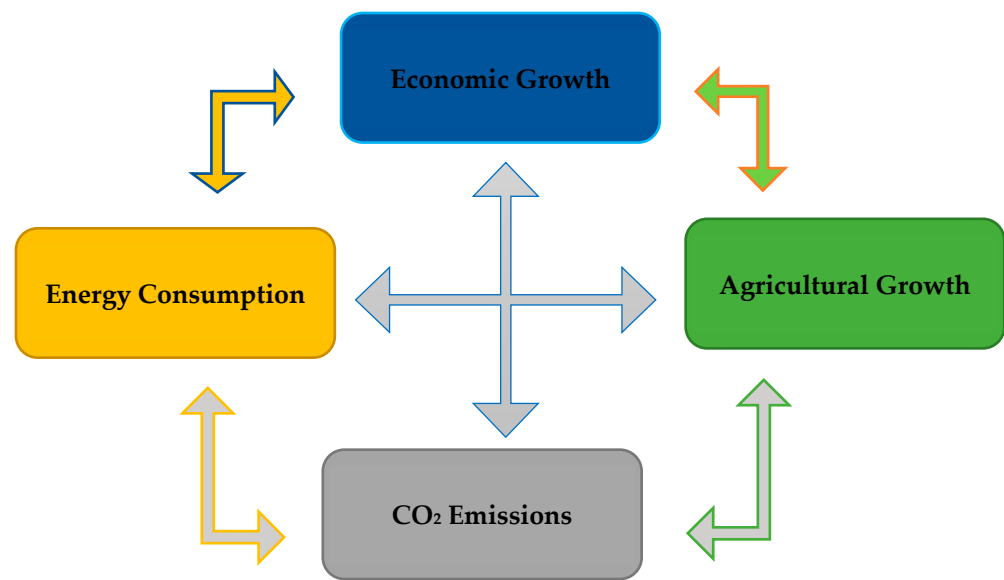


Figure 1. Interaction between energy consumption, economic growth, agricultural growth, and CO₂ emissions. Source: Presentation by the author.

Energy consumption holds a significant position in the system as both a cause and a consequence of economic growth. Economic growth increases energy demand through heightened production and consumption activities, while rising energy consumption supports the continuity and expansion of economic activities [6–8].

Similarly, there exists a bidirectional interaction between agricultural growth and economic growth. While agricultural production contributes to the economy, economic developments enhance investments in the agricultural sector and expand production capacity [9–12].

The relationship between energy consumption and agricultural growth is shaped particularly by the energy inputs utilized in modern agricultural techniques. Increasing energy use in the agricultural sector enhances production efficiency, while agricultural growth elevates energy demand. On the other hand, uncontrolled agricultural expansion is associated with deforestation, depletion of groundwater resources, and loss of biodiversity [13–15].

Each of these three fundamental factors contributes to the increase in CO₂ emissions through both direct and indirect pathways. In Figure 1, the directions of these effects are illustrated with arrows. Furthermore, the rise in CO₂ emissions may create a foundation for feedback mechanisms that can indirectly influence energy consumption and economic/agricultural activities. Therefore, addressing the system with a holistic and dynamic approach is crucial for environmental policy and sustainable development strategies. Indeed, in response to growing environmental concerns and the depletion of energy resources, many countries have begun to reassess their energy and climate policies.

For Türkiye, a country ranked as the world's 17th largest economy and the 15th highest CO₂ emitter in 2022, this issue is particularly urgent [16]. Although significant progress has been made in industrialization, the Turkish economy remains deeply rooted in agricultural production. Türkiye ranks 8th globally in terms of agricultural gross domestic product (GDP), with the sector contributing 6.2% to national GDP and employing approximately 30.7 million people in 2022 [16,17].

Türkiye has adopted a multidimensional approach to sustainable development, aligning national priorities with international climate commitments. Since 2012, the country has strengthened its legal frameworks to address climate change, including participation in key international agreements such as the United Nations Framework Convention on Climate Change, the Kyoto Protocol, and the Paris Agreement. With the ratification of the Paris Agreement in 2021 and the announcement of a 2053 net-zero emissions target, Türkiye has signaled its determination to transition toward a more sustainable, low-carbon economy [1,18].

Although many studies have explored the macroeconomic determinants of CO₂ emissions globally, there remains a relative paucity of empirical research focusing on Türkiye. This study aims to fill this gap by investigating the short- and long-run impacts of economic growth, energy consumption, and agricultural value added on CO₂ emissions using a 34-year time series and the Autoregressive Distributed Lag (ARDL) modeling framework.

By offering robust empirical evidence, this study seeks to inform sustainable development policies in Türkiye, particularly in light of the country's efforts to reconcile economic ambitions with environmental stewardship. The policy implications derived from the analysis are expected to guide strategic decision making in Türkiye's climate agenda and contribute to reducing its external energy dependency while supporting a sustainable future.

2. Literature Review

Table 1 summarizes several academic studies that examine the relationship between energy consumption, economic growth, agricultural growth, and carbon dioxide (CO₂) emissions. In this table, the variables examined in each study, the country or region covered, the method used, the key findings, and the relevant references are presented.

Many studies confirm a long-run positive relationship between energy consumption, economic growth, and CO₂ emissions. This is evident in Türkiye [19], South Africa [20], 58 countries globally [21], African nations [22], Kuwait [23], MENA countries [24], OECD countries [25], and MINT countries [8]. These studies generally found that increases in energy use and economic growth drive up CO₂ emissions in both country-specific and cross-country contexts. An important subset of studies examined the Environmental Kuznets Curve (EKC) hypothesis. In Türkiye, an inverted U-shaped EKC relationship between economic growth and CO₂ emissions was detected [26], while in the OECD, the EKC model revealed that energy consumption and tourism increase emissions [27].

Table 1. Some selected literature summaries.

Study	Variables	Country/Region	Method	Findings
[19]	Energy consumption, economic growth, CO ₂ emissions	Türkiye	Cointegration, causality	Energy consumption and CO ₂ emissions are positively correlated in the long run.
[20]	Energy consumption, economic growth, CO ₂ emissions	South Africa	Cointegration, causality	Energy consumption and CO ₂ emissions are positively correlated in the long run.

Table 1. Cont.

Study	Variables	Country/Region	Method	Findings
[9]	Agriculture value added, natural resources, economic growth CO ₂ emissions	G7 countries	CS-ARDL	Economic growth and natural resources increase CO ₂ emissions. In contrast, agriculture decreases carbon emissions.
[21]	Energy consumption, economic growth, CO ₂ emissions	58 countries	Dynamic panel data (GMM)	Positive relationship between CO ₂ emissions, economic growth, and energy consumption.
[22]	Energy consumption, economic growth, CO ₂ emissions	African countries	Cointegration, causality	Energy consumption and economic growth positively affect CO ₂ emissions.
[26]	Energy consumption, CO ₂ emissions, per capita GSYİH	Türkiye	ARDL	Inverted U (EKC) relationship.
[27]	Energy consumption, real GDP, tourism, and trade CO ₂ emissions	OECD	Panel data, EKC model	Energy consumption and tourism increase CO ₂ emissions.
[11]	Per capita renewable energy consumption, agricultural value added, CO ₂ emissions	ASEAN-4 Indonesia, Malaysia, Philippines, Thailand	Granger causality	Renewable energy and agriculture decrease CO ₂ emissions.
[28]	Per capita renewable energy consumption, agricultural value added, CO ₂ emissions, real GDP	North African countries	Panel cointegration, Granger causality	GDP or in renewable energy consumption increases CO ₂ emissions, whereas an increase in agricultural value added reduces CO ₂ emissions.
[25]	Energy consumption, economic growth	OECD countries	Panel data	Positive relationship between economic growth and energy consumption.
[23]	Electric consumption, economic growth, CO ₂ emissions	Kuwait	VECM	Electric consumption and economic growth increase CO ₂ emissions.
[29]	Agricultural energy consumption, agricultural economic growth, agricultural CO ₂ emissions	China	ARDL, VECM, Granger causality	Agricultural energy consumption decreases CO ₂ emissions.
[24]	Energy consumption, economic growth, CO ₂ emissions	MENA countries	Granger causality	Energy conservation policies do not have an adverse effect on economic growth both in the short and intermediate run while their effects are negative in the long run.
[30]	Energy consumption, economic growth, natural resources, CO ₂ emissions	124 countries	Panel regression	Panel VAR analysis yielded different findings according to low-, middle-, and high-income country groups.
[8]	Energy consumption, economic growth, CO ₂ emissions, urbanization	MINT countries	Granger causality	All the MINT countries show a long-run relationship between economic growth, energy consumption, and CO ₂ emissions and urbanization.
[31]	Energy consumption, economic growth, agricultural value added, CO ₂ emissions	Vietnam	ARDL	Energy consumption and economic growth increase CO ₂ emissions while reducing agricultural value added.
[32]	Industrialization, economic growth, greenhouse gas, agricultural production	Türkiye	ARDL	Industrialization increases economic growth and greenhouse gas emissions, all of which positively affect agricultural production.

Table 1. Cont.

Study	Variables	Country/Region	Method	Findings
[33]	Economic growth, energy use, urbanization, tourism, agricultural value added, forested, CO ₂ emissions	Brazil	ARDL, FMOLS, Granger causality	All variables except for forest areas increase CO ₂ emissions.
[10]	Economic growth, renewable energy use, urbanization, industrialization, tourism, agriculture, forests, and carbon emissions	Türkiye	DOLS	Economic growth and energy consumption harm the environment. Agricultural productivity and forest areas are counterbalances.

The role of agriculture and renewable energy has been another focus. In G7 countries, agriculture was found to reduce CO₂ emissions, while natural resources and economic growth increased them [9]. In ASEAN-4 nations, both renewable energy use and agriculture reduced emissions [11]. Similar findings emerged in North African countries where an increase in agricultural value added reduced emissions, whereas GDP and renewable energy use increased them [28]. In China, agricultural energy consumption was found to lower agricultural CO₂ emissions [29], while in Vietnam, increased agricultural value added reduced overall emissions [31]. When considering broader variables, studies in Brazil indicated that economic growth, energy use, urbanization, tourism, and agricultural value added all increased CO₂ emissions, while forest areas had the opposite effect [33]. In Türkiye, agricultural productivity and forest areas were found to counterbalance the environmental damage from economic growth and energy use [10]. Urbanization was also studied, with results indicating that in MINT countries, there is a long-run relationship between economic growth, energy consumption, and CO₂ emissions and urbanization [8]. Finally, industrialization has been shown to simultaneously increase both economic growth and greenhouse gas emissions but also to positively affect agricultural production in Türkiye [32].

3. Materials and Methods

This study created a time-series dataset for Türkiye from 1990 to 2023 using statistics from the World Bank and the International Energy Agency [2,16]. All variables were logarithmically transformed to achieve normality. Table 2 shows these logarithmic representations along with their units and sources.

Table 2. Definitions of variables used in the analysis.

Variables and Symbol	Descriptions	Unit Data	Sources
LCO ₂	Carbon dioxide emissions	Kilo tons	[16]
LGDP	Economic growth	USD	[16]
LEU	Energy use	Kg per capita oil equivalent	[2]
LAGDP	Agricultural GDP	Percentage	[16]

“L” stands for logarithmic transformation.

Additionally, the annual changes in the variables used in this study for Türkiye are presented in Figure 2. Except for agricultural GDP, energy use and GDP exhibit an increasing trend. On the other hand, CO₂ emission levels in Türkiye showed a continuous increase until 2017, after which they started to decrease and stabilized. This shift coincides with the rise in renewable energy use in Türkiye, reflecting a global trend where the rate of increase in carbon emissions has slowed. Indeed, in 2008, electricity produced from renewable energy sources accounted for 17.7% of total production in Türkiye, and this share increased to 35.7% in 2021 and 40% in 2022 [34].

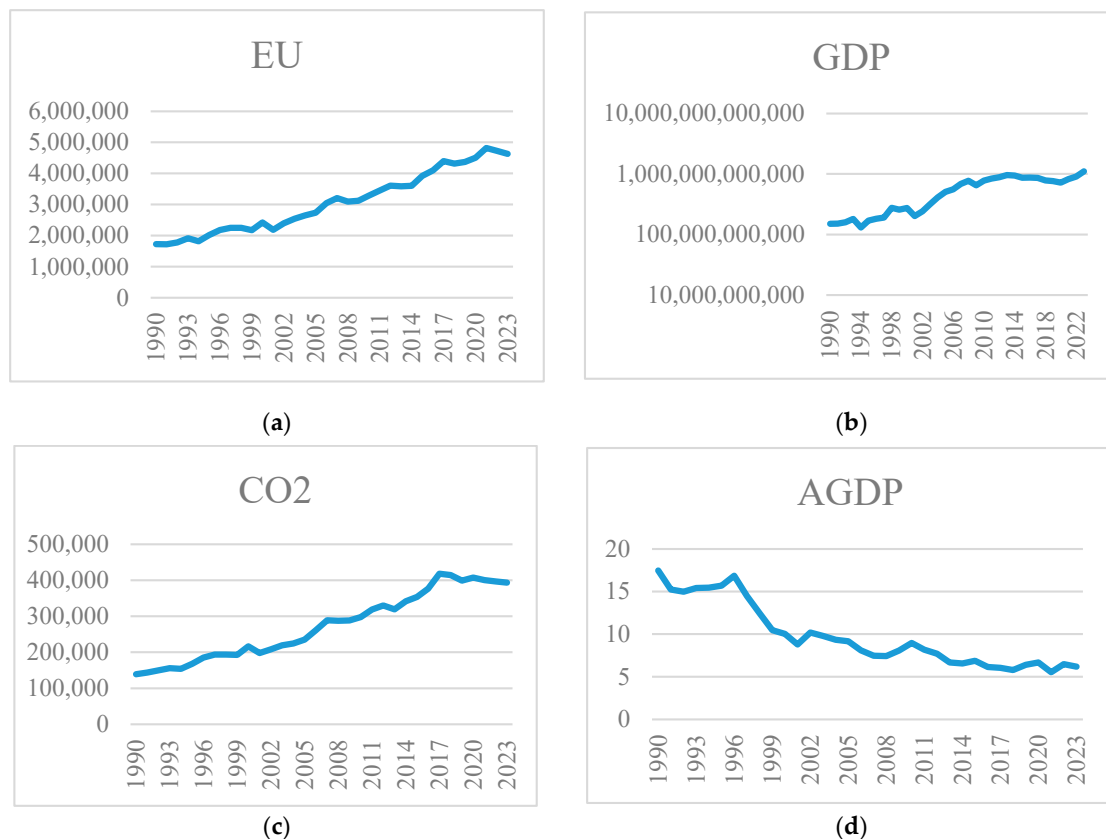


Figure 2. Annual changes in study data (Türkiye). (a) Energy use in Türkiye (kg per capita oil equivalent); (b) economic growth in Türkiye (USD); (c) carbon dioxide emissions in Türkiye (kilotons); (d) agricultural growth in Türkiye (percentage).

Numerous studies have demonstrated that economic growth and energy consumption are generally related to CO₂ emissions. This relationship can be defined at any time using a closed function [35].

$$CO_{2t} = f(GDP_t; EU_t) \quad (1)$$

On the other hand, as explained in detail in the introduction, the agricultural sector is closely linked to CO₂ emissions and contributes to both economic growth and environmental degradation. For this reason, agricultural growth at time t (AGDP _{t}) has been added as a third independent variable to Equation (1). The other independent variables, GDP _{t} and EU _{t} , represent economic growth and energy use at time t , respectively. The dependent variable CO_{2 t} remains as the carbon dioxide emissions at time t (Equation (2)).

$$CO_{2t} = f(GDP_t; EU_t; AGDP_t) \quad (2)$$

When the intercept (τ_0), error term (ε_t), and the coefficients for the variables (τ_1 , τ_2 , and τ_3) are added to Equation (2), Equation (3) can be written.

$$CO_{2t} = \tau_0 + \tau_1 GDP_t + \tau_2 EU_t + \tau_3 AGDP_t + \varepsilon_t \quad (3)$$

Finally, Equation (4), which expresses the logarithmic transformation of the variables at time t , can be written as follows.

$$LCO_{2t} = \tau_0 + LGDP_t + \tau_2 LEU_t + \tau_3 LAGDP_t + \varepsilon_t \quad (4)$$

Before estimating the relevant equation in this study, certain tests need to be conducted. Unit root tests should be performed separately for each of the variables used. This way, it can be determined whether the series are stationary. Following this, it should be investigated whether there is a cointegration relationship between the variables [36]. In this research, two of the most commonly used tests to identify autoregressive unit roots have been selected. These tests are the Augmented Dickey–Fuller (ADF) test and the Phillips–Perron (PP) test [37,38]. The Autoregressive Distributed Lag (ARDL) bounds testing approach has been used for cointegration. This test has various advantages over traditional methods. It can be applied particularly to series with different integration degrees in terms of stationarity criteria [39]. It is more reliable with small sample sizes. It is especially effective in accurately estimating long-run relationships between series. Furthermore, the ARDL bounds testing approach can be used regardless of whether the series are integrated of order I(2), I(0), or I(1), which is a significant advantage. The formula for the ARDL bounds test is given in Equation (5).

$$\Delta LCO2_t = \tau_0 + \tau_1 LCO2_{t-1} + \tau_2 LGDP_{t-1} + \tau_3 LEU_{t-1} + \tau_4 LAGDP_{t-1} + \sum_{i=1}^q \gamma_1 \Delta LCO2_{t-i} + \sum_{i=1}^q \gamma_2 \Delta LGDP_{t-i} + \sum_{i=1}^q \gamma_3 \Delta LEU_{t-i} + \sum_{i=1}^q \gamma_4 \Delta LAGDP_{t-i} + \varepsilon_t \quad (5)$$

The aim here is to determine the existence of a long-run relationship between the variables. To accomplish this, the calculated F statistics are compared with the critical values of [39]. If the F statistic exceeds the upper critical value, the null hypothesis (H0) is rejected, indicating that there is a long-run relationship. Conversely, if the F statistics fall below the lower critical value, the null hypothesis is accepted. This suggests that there is no cointegration relationship among the regressors. In this study, the ARDL approach was used to uncover both long-run and short-run relationships between the variables. After the cointegration relationship has been established, the long-run coefficients were estimated according to Equation (5). Following this, the error correction model (ECM) developed by Engle and Granger [38] was implemented. This model examines the convergence to equilibrium in the long run and identifies the short-run coefficients. As shown in Equation (6), it has been integrated into the ARDL approach.

$$\Delta LCO2_t = \tau_0 + \tau_1 LCO2_{t-1} + \tau_2 LGDP_{t-1} + \tau_3 LEU_{t-1} + \tau_4 LAGDP_{t-1} + \sum_{i=1}^q \gamma_1 \Delta LCO2_{t-i} + \sum_{i=1}^q \gamma_2 \Delta LGDP_{t-i} + \sum_{i=1}^q \gamma_3 \Delta LEU_{t-i} + \sum_{i=1}^q \gamma_4 \Delta LAGDP_{t-i} + \varnothing ECM_{t-1} + \varepsilon_t \quad (6)$$

A comprehensive evaluation was undertaken to ensure the robustness of our cointegration analysis, underscoring its reliability and value in our findings.

4. Results

In this section, firstly, descriptive statistics of each series are summarized in Table 3. According to the number of observations, values such as the mean, minimum, and maximum values and standard deviations of the series were calculated. In addition, according to the Jarque–Bera test statistics calculated according to the kurtosis and skewness values, it is seen that all of the series meet the normal distribution criteria.

The descriptive statistics reveal that the average value of carbon dioxide emissions (LCO₂) is 12.46, with a standard deviation of 0.36, indicating relatively low variability across the observations. The mean value of gross domestic product (LGDP) is 26.81, with a standard deviation of 0.72, reflecting moderate variation in economic performance. Energy use (LEU) has an average value of 14.89 and a standard deviation of 0.33, showing relatively stable energy consumption levels. In contrast, the agricultural value added (LAGDP)

demonstrates the highest dispersion, with a mean of 9.74 and a standard deviation of 3.71. Regarding the distribution characteristics, the skewness values indicate that LCO₂, LGDP, and LEU are slightly negatively skewed, while LAGDP is positively skewed. Kurtosis values for all variables are below 3, suggesting a platykurtic distribution. The Jarque–Bera test results indicate that none of the variables significantly deviate from normality at the 5% significance level, as all probability values exceed 0.05. In total, the dataset consists of 34 observations for each variable (Table 3).

Table 3. Descriptive statistics of each variable.

	LCO ₂	LGDP	LEU	LAGDP
Mean	12.45550	26.80696	14.88624	9.736079
Median	12.52027	27.12256	14.93660	8.480997
Standard Deviation	0.357796	0.716816	0.330472	3.714826
Minimum	11.84365	25.59579	14.35904	5.533753
Maximum	12.94347	27.73360	15.38828	17.47623
Kurtosis	1.691427	1.477226	1.713017	2.214999
Skewness	−0.162880	−0.357235	−0.052392	0.401240
Jarque–Bera	2.576184	4.008187	2.362016	4.510906
Probability	0.275796	0.134782	0.306969	0.104826
Observations	34	34	34	34

Unit root tests reveal a mixed form of stationarity among the series. Except for the LAGDP variable, the other variables remain stationary after the first differencing in both ADF and PP tests, while the LAGDP variable is stationary at the level. These results support the applicability of the ARDL approach as shown in Table 4.

Table 4. The unit root tests.

At Level				
	LCO ₂	LGDP	LEC	LAGDP
ADF test	3.727460	2.217239	3.418342	−2.735396 ***
PP test	3.814509	2.217239	9.141964	−3.448491 ***
At first difference				
ADF test	−4.215248 ***	−5.115862 ***	−5.204047 ***	−5.017169 ***
PP test	−4.280865 ***	−5.210701 ***	−5.296733 ***	−5.017169 ***

*, **, and *** indicate 10%, 5%, and 1% significance levels, respectively.

Table 5 presents the results of the ARDL bounds test that explains the cointegration relationship between the variables. According to the model results, the computed F-statistic value (23.63303) exceeds both the lower and upper critical values. This indicates evidence of a long-run relationship between the variables.

Table 5. The ARDL bounds test.

Statistic	Value	K (Represents the Number of Independent Variables)
F-statistic	23.63303	3
Crucial limit values		
Significance (%)	Low bound I(0)	Upper bound I(1)
10	2.72	3.77
5	3.23	4.35
2.5	3.69	4.89
1	4.29	5.61

Note: The minimum Akaike Information Criterion (AIC) was taken into account in the model.

After verifying the cointegration relationship between the variables, the long-run coefficients of all variables were calculated with the ARDL model. The estimated coefficients and *p*-value outputs are given in Table 6.

Table 6. ARDL long-run coefficients.

Variables	Coefficient	Standard Error	t-Statistics	<i>p</i> -Value
LGDP	0.081109 ***	0.019981	4.059351	0.0007
LEU	0.808857 ***	0.037691	21.46016	0.0000
LAGDP	−0.008163 ***	0.002552	−3.199044	0.0050
C (constant term)	−1.687890	0.371103	−4.548305	0.0002
EC = $LCO_2 - (-0.0082LAGDP + 0.8089LEU + 0.0811LGDP - 1.6879)$				

*, **, and *** indicate 10%, 5%, and 1% *p*-value significance levels, respectively.

The estimated long-run coefficient for LGDP is positive and significant at the 1% level, indicating that a 1% increase in economic growth is associated with a 0.081% rise in CO₂ emissions, suggesting a minor contribution to environmental degradation. Similarly, the long-run coefficient for LEU is also positive and significant, meaning a 1% increase in energy consumption correlates with an 81% increase in CO₂ emissions in Türkiye, indicating significant negative effects on environmental quality. In contrast, the coefficient for agricultural value added is negative and significant, showing that a 1% increase leads to a 0.0082% reduction in CO₂ emissions, highlighting its positive role in improving environmental quality through CO₂ absorption. The model also includes short-run dynamic parameters estimated through an ECM, which clarifies long-run dynamics and explains how variables adjust when deviating from equilibrium. The results of these short-run coefficients are shown in Table 7.

Table 7. ARDL error correction model.

Variables	Coefficient	Standard Error	t-Statistics	<i>p</i> -Value
ΔLGDP	−0.107195 ***	0.028186	−3.803178	0.0013
ΔLEC	0.869286 ***	0.118511	7.335062	0.0000
ΔLAVA	−0.095068 *	0.049077	−1.937096	0.0686
ΔC	−1.928153	0.186098	−10.36097	0.0000
ECM(−1)	−1.007345 ***	0.108776	−10.50178	0.0000

ECM = $LCO_2 - (0.0951LAVA + 0.8693LEC - 0.1072LGDP - 1.9281)$. *, **, and *** indicate 10%, 5%, and 1% *p*-value significance levels, respectively.

The short-run coefficient for LGDP is negative and significant at the 1% level, contradicting the long-run analysis. Specifically, a 1% increase in economic growth is linked to a 0.11% decrease in CO₂ emissions, suggesting that environmental protection measures in Türkiye have had minimal short-run impact. This finding can be theoretically explained through the Environmental Kuznets Curve (EKC) framework [40,41]. In the early phases of economic growth, structural shifts toward less carbon-intensive sectors such as services, along with temporary efficiency improvements and environmental regulations, may contribute to lower emissions. However, as economic expansion continues over time, energy demand rises and industrial activities intensify, particularly in energy- and resource-intensive sectors, leading to higher CO₂ emissions. This suggests that Türkiye has not yet reached the income threshold at which economic growth consistently translates into environmental improvements. The LEC coefficient is positive and significant, indicating that a 1% increase in energy consumption results in a 0.87% rise in CO₂ emissions. In contrast, the LAGDP coefficient is negative and significant, revealing that a 1% increase in agricultural GDP is associated with a 0.09% reduction in CO₂ emissions. The ECM coefficient of −1.0073, significant at the 1% level, shows that short-run disequilibrium is corrected annually at a rate of 1.01%. This rapid adjustment suggests almost complete

rectification of equilibrium deviation in the short run. Dynamic coefficients imply that while economic growth and agricultural value added positively affect environmental quality, increased energy consumption negatively impacts it. Diagnostic tests for the ARDL model show R^2 values of 0.9966 and adjusted R^2 of 0.9945, indicating a strong fit, with independent variables explaining 99% of the variation in the dependent variable (Table 8).

Table 8. The results of ARDL model diagnostic tests.

Diagnostic Tests	Coefficient	<i>p</i> -Value	Decision
R^2	0.996615		The model is a good fit.
Adj. R^2	0.994546		The model is a good fit.
Functional error	1.341265	0.0052	There is no functional error.
Jarque–Bera	0.192663	0.9082	Residuals are distributed normally.
Breusch–Pagan–Godfrey	0.485688	0.8885	There is no evidence of heteroscedasticity.
Heteroskedasticity	1.190091	0.2850	There is no evidence of heteroscedasticity.
F-statistic	481.7559	0.0000	The model is statistically significant.
Ramsey Reset	0.420417	0.5254	The model is not biased.

The ARDL model used in this study underwent diagnostic tests to ensure its robustness and validity. The results showed no issues with serial correlation, functional specification errors, or heteroscedasticity, confirming a good fit to the data. The F-statistics supported the ARDL regression, with a p -value of 0.0000, indicating a statistically significant relationship between the dependent and independent variables. The Ramsey Reset test confirmed the correct model specification, as the coefficients were insignificant. To assess stability, CUSUM (cumulative sum) and CUSUMQ (cumulative sum of squares) tests were performed; the plots in Figure 3 show that residual values remain within the confidence intervals, demonstrating the model's stability. CUSUM is based on the cumulative sum of recursive residuals. If the cumulative sum stays within the critical bounds, the model is considered stable. If it crosses the bounds, it suggests a structural change in the model. CUSUMQ is based on the cumulative sum of squared recursive residuals. If the test statistics remain within the confidence bounds, the model is considered variance-stable. If it crosses the bounds, it indicates heteroskedasticity or structural change in the error variance [42]. Overall, these findings reinforce the reliability and accuracy of the ARDL model in this analysis.

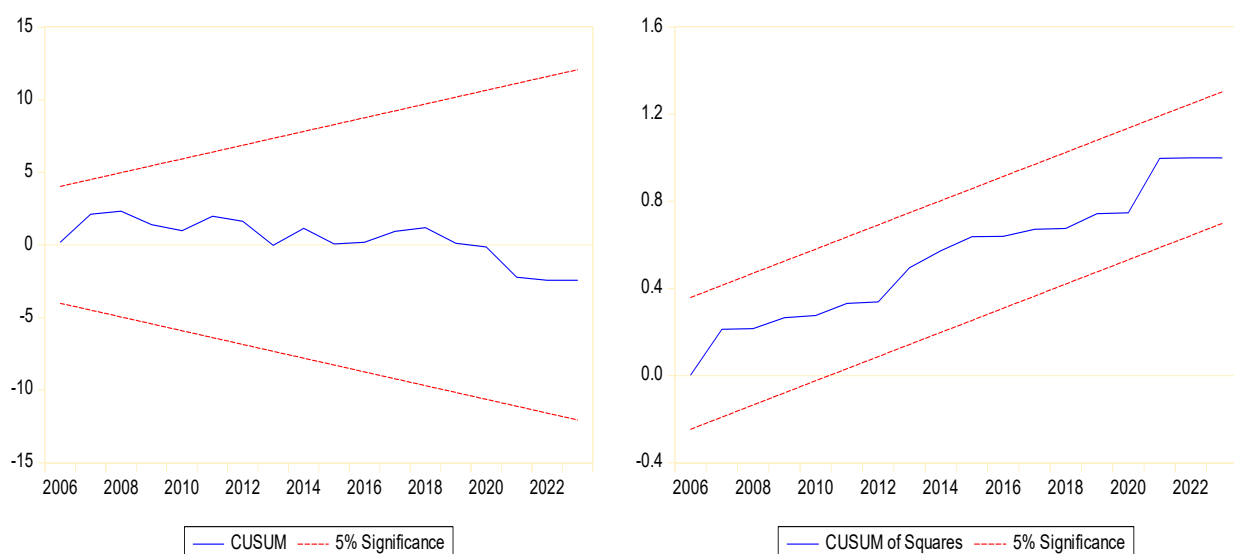


Figure 3. CUSUM test and CUSUM of squares test.

5. Discussion

This study offers crucial empirical insights into the environmental implications of economic and sectoral activity in Türkiye. One of the most significant findings is the positive and statistically significant relationship between economic growth and CO₂ emissions. This result aligns with a substantial body of prior research conducted in the Türkiye context, including studies by [6,19,26,32,43–45].

Comparable findings have also emerged across diverse international settings and country clusters, such as those reported by [8,21–25,27,46]. These studies consistently suggest that while economic growth is necessary for development, it is frequently accompanied by environmental trade-offs, including rising emissions and degradation of ecological systems.

In the case of Türkiye, the adoption of an aggressive economic growth trajectory has coincided with rising greenhouse gas emissions, which reached 564.4 million tons of CO₂ equivalent in 2021, a 7.7% increase from 2020 and a staggering 157.1% rise since 1990. This trend reflects the environmental costs of rapid industrialization and underscores the need for sustainable growth strategies.

Additionally, this study confirms that energy consumption has a statistically significant impact on CO₂ emissions in both the short and long term. This finding reinforces prior empirical evidence from Türkiye [10,44,45,47] and is consistent with global studies demonstrating a strong positive correlation between fossil fuel-based energy use and carbon emissions [8,9,11,36,48,49].

As highlighted by the Intergovernmental Panel on Climate Change (IPCC), the Mediterranean Basin where Türkiye is located is among the regions most acutely affected by climate change. Between 2010 and 2021, Türkiye experienced 8274 meteorological disasters of varying intensity across different regions, including forest fires, floods, heatwaves, and landslides. This trend is expected to worsen unless mitigation strategies are urgently implemented [18].

In light of these challenges, Türkiye has committed to addressing economic, social, and environmental priorities in a balanced and integrated manner. The country is actively engaged in global climate governance and has enacted a series of legal and policy initiatives, including its participation in the United Nations Framework Convention on Climate Change, the Kyoto Protocol, and the Paris Agreement. Notably, Türkiye's ratification of the Paris Agreement in 2021 and its pledge to achieve net-zero emissions by 2053 represent critical milestones in its climate transition strategy.

A particularly novel contribution of this study is the identification of a negative long-run association between agricultural value added and CO₂ emissions. This implies that increases in agricultural GDP may serve as a mitigating factor in Türkiye's emissions profile. The finding is consistent with prior research conducted in Türkiye [10,32] as well as cross-national studies that have demonstrated similar results [9,11,28,29,31,33,36,50,51].

Although Türkiye has made substantial strides toward industrialization, agriculture remains a foundational pillar of its economy. The country ranks 8th globally in agricultural GDP, with the sector accounting for 5.8% of national output and employing 30.7 million people as of 2022 [17,52]. Agriculture not only provides critical food supplies but also supports upstream and downstream industries through raw material provision.

A well-functioning agricultural sector can foster inclusive growth, generate employment, and contribute to macroeconomic stability through foreign exchange earnings [53]. Furthermore, agriculture-focused policies that promote sustainability such as climate-smart agriculture and resource-efficient technologies may help narrow Türkiye's balance of payment gaps and reduce its carbon footprint.

Nevertheless, economic expansion often brings with it heightened pressure on natural resources and increased energy use. The unchecked exploitation of natural capital and continued reliance on fossil fuels have intensified environmental stress. This has direct consequences for agriculture, as climate change-driven disruptions including droughts, floods, and temperature extremes threaten agricultural yields and food security [54–56].

Türkiye's 12th Development Plan (2024–2028) explicitly acknowledges these risks and underscores the importance of scaling up climate-friendly agricultural practices as part of a broader climate mitigation and environmental protection agenda [18].

In conclusion, aligning Türkiye's economic ambitions with its environmental sustainability goals necessitates an integrated policy approach. The demonstrated inverse relationship between agricultural value added and CO₂ emissions highlights the sector's potential as a lever for climate mitigation. Future research and policymaking should continue to explore and support the agricultural sector's role in advancing Türkiye's green development agenda.

6. Conclusions

The empirical results derived from the ARDL bounds and cointegration tests confirm the existence of a long-term equilibrium relationship among economic growth, energy consumption, agricultural GDP, and CO₂ emissions in Türkiye. The findings demonstrate that while economic expansion and rising energy consumption significantly exacerbate CO₂ emissions, thus contributing to environmental degradation, an increase in agricultural value added plays a mitigating role by reducing CO₂ emissions in both the short and long term. This highlights the pivotal role of sustainable agriculture in shaping Türkiye's environmental performance and contributes novel empirical evidence to the existing literature.

From a policy standpoint, these results underscore the urgency of formulating integrated environmental strategies that balance economic growth imperatives with climate resilience. Türkiye's most viable pathway toward long-term climate stability lies in advancing a low-carbon development trajectory. This study advocates for the establishment of a robust legal and institutional framework to foster innovation, facilitate clean technology adoption, and transition the national economy toward less carbon-intensive modalities.

The inverse relationship observed between agricultural GDP and carbon emissions highlights the transformative potential of climate-smart agriculture and green production practices. Investments in high-efficiency farming technologies, coupled with supportive policy mechanisms, can simultaneously enhance agricultural productivity and environmental quality. In this regard, technologies that reduce the carbon intensity of food systems—such as precision agriculture, renewable-powered irrigation systems, and organic farming infrastructure—should be prioritized.

Türkiye's path to decarbonization also necessitates ambitious reform in the energy sector. Regulatory mechanisms such as carbon pricing, emissions trading schemes, and investments in carbon capture and storage (CCS) are essential to decouple growth from emissions. However, the effectiveness of such instruments hinges on broader structural shifts in institutional coordination, public policy alignment, and technological innovation. Research and development (R&D) incentives must be scaled up to accelerate the diffusion of energy-efficient solutions across industries.

Given Türkiye's heavy dependence on fossil fuels, a strategic reconfiguration of the national energy mix is vital. The country holds substantial untapped potential in renewable sources such as geothermal, solar, wind, and hydro, which can help satisfy growing energy demands while curbing emissions. Encouragingly, the share of renewables in Türkiye's installed electricity capacity has surged dramatically, reaching 24,821 MW by the end of 2022, a nearly 388-fold increase in the past two decades.

The utilization of renewable energy sources is associated with significantly lower CO₂ emissions compared to fossil fuel-based energy production. Turkey can minimize carbon emissions by leveraging its potential and increasing investments in renewable energy. Particularly, carbon pathway policies can be pursued to promote strategies that enhance efficiency in energy production and consumption. As energy efficiency improves, the amount of energy required will decrease, leading to a reduction in emissions. Furthermore, the recycling of renewable energy sources contributes to the management of waste with less environmental impact, thereby aiding in the reduction in emissions. For example, the use of organic waste in the biogas production process not only decreases the volume of waste but also lowers CO₂ emissions.

Certainly, government policies and incentives play a crucial role in the widespread adoption of renewable energy sources. The implementation of carbon pathways makes these sources more attractive while facilitating the development of mechanisms that will reduce emissions.

To ensure the sustainability of this transition, cross-border technical partnerships should be fostered to facilitate knowledge transfer and innovation diffusion. Fiscal incentives including targeted subsidies, tax credits, and public procurement schemes should be expanded to make green technologies more accessible. Additionally, public awareness campaigns are crucial to catalyze behavioral shifts toward sustainable consumption and production habits, thereby complementing top-down regulatory efforts.

In parallel, energy efficiency must remain a national priority. Enhancing energy performance across sectors, especially agriculture and manufacturing, requires concerted efforts to integrate advanced technologies and digital solutions into operational workflows. R&D funding in energy-saving innovations, coupled with institutional reforms, will be critical to achieving scalable impact.

As a developing economy, Türkiye must navigate the challenge of ensuring energy affordability while maintaining environmental responsibility. This dual objective can be achieved by synchronizing national energy and agricultural policies with climate mitigation goals. Public policy should particularly focus on promoting resilient food systems by supporting disease-resistant, high-yield crops, upgrading traditional farming techniques, and incentivizing sustainable practices through training and extension services.

This study reaffirms the role of modern agricultural systems in climate mitigation. Sustainable agriculture characterized by reduced emissions, enhanced carbon sequestration, and optimized input use can serve as a cornerstone of Türkiye's green transition. In particular, the integration of renewable energy within agricultural production, such as through solar-powered irrigation and wind-assisted greenhouse systems, holds immense promise in reducing the sector's carbon intensity.

Emerging climate-smart agriculture paradigms, such as no-till farming, vertical and LED-integrated greenhouses, and digital irrigation control, have already demonstrated the capacity to minimize resource use and reduce greenhouse gas emissions. These techniques also strengthen the competitiveness of the Türkiye agricultural sector in international markets by improving environmental performance and lowering production costs. Strengthening global collaborations and multilateral partnerships in agricultural innovation will be key to scaling up these practices and increasing Türkiye's agricultural value added in a carbon-constrained world.

In summary, aligning Türkiye's economic ambitions with environmental sustainability necessitates a cohesive policy framework that simultaneously promotes growth, mitigates emissions, and supports agricultural innovation. The strategic integration of sustainable agricultural development with energy transition policies offers a promising path forward in the global effort to combat climate change.

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References

1. United Nations. Climate Action. Available online: <https://www.un.org/en/climatechange/raising-ambition/renewable-energy> (accessed on 18 May 2023).
2. IEA, International Energy Agency. Data and Statistics. 2025. Available online: <https://www.iea.org/data-and-statistics> (accessed on 10 May 2025).
3. British Petroleum. BP Statistical Review of World Energy 2022, 71st ed. Available online: <https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html> (accessed on 15 March 2023).
4. IEA. Global CO₂ Emissions Rebounded to Their Highest Level in History in 2021. Available online: <https://www.iea.org/news/global-CO2-emissions-rebounded-to-their-highest-level-in-history-in-2021> (accessed on 26 March 2025).
5. IPCC. *Climate Change 2022: Mitigation of Climate Change*; Intergovernmental Panel on Climate Change, Ed.; Cambridge University Press: Cambridge, UK, 2022.
6. Erdal, G.; Erdal, H.; Esengün, K. The Causality Between Energy Consumption and Economic Growth in Turkey. *Energy Policy* **2008**, *36*, 3838–3842. [CrossRef]
7. Sadorsky, P. Renewable Energy Consumption and Income in Emerging Economies. *Energy Policy* **2009**, *37*, 4021–4028. [CrossRef]
8. Odugbesan, J.A.; Rjoub, H. Relationship Among Economic Growth, Energy Consumption, CO₂ Emission, and Urbanization: Evidence from MINT Countries. *Sage Open* **2020**, *10*. [CrossRef]
9. Wang, L.; Vo, X.V.; Shahbaz, M.; Ak, A. Globalization and Carbon Emissions: Is There Any Role of Agriculture Value-Added, Financial Development, and Natural Resource Rent in the Aftermath of COP21? *J. Environ. Manag.* **2020**, *268*, 110712. [CrossRef]
10. Raihan, A.; Tuspekova, A. Dynamic Impacts of Economic Growth, Renewable Energy Use, Urbanization, Industrialization, Tourism, Agriculture, and Forests on Carbon Emissions in Turkey. *Carbon Res.* **2022**, *1*, 20. [CrossRef]
11. Liu, X.; Zhang, S.; Bae, J. The Impact of Renewable Energy and Agriculture on Carbon Dioxide Emissions: Investigating the Environmental Kuznets Curve in Four Selected ASEAN Countries. *J. Clean. Prod.* **2017**, *164*, 1239–1247. [CrossRef]
12. Kabir, M.; Ekici, S. Energy-Agriculture Nexus: Exploring the Future of Artificial Intelligence Applications. *Energy Nexus* **2024**, *13*, 100263. [CrossRef]
13. Popp, J.; Lakner, Z.; Harangi-Rákos, M.; Fári, M. The Effect of Bioenergy Expansion: Food, Energy, and Environment. *Renew. Sustain. Energy Rev.* **2014**, *32*, 559–578. [CrossRef]
14. Burney, J.A.; Davis, S.J.; Lobell, D.B. Greenhouse Gas Mitigation by Agricultural Intensification. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 12052–12057. [CrossRef]
15. FAO. *The Future of Food and Agriculture, Trends and Challenges*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2017.
16. World Bank. World Development Indicators. Available online: <https://databank.worldbank.org/source/world-development-indicators> (accessed on 15 March 2024).
17. TURKSTAT. The Results of Address Based Population Registration System. 2022. Available online: <https://data.tuik.gov.tr/Bulten/Index?p=The-Results-of-Address-Based-Population-Registration-System-2022-49685&dil=2> (accessed on 30 October 2024).
18. Republic of Türkiye Ministry of Environment, Urbanization and Climate Change. Climate Change Mitigation Strategy and Action Plan (2024–2030). Available online: [https://www.iklim.gov.tr/db/turkce/haberler/files/climate%20change%20mitigation%20strategy%20and%20action%20plan%20_en\(1\).pdf](https://www.iklim.gov.tr/db/turkce/haberler/files/climate%20change%20mitigation%20strategy%20and%20action%20plan%20_en(1).pdf) (accessed on 12 December 2024).
19. Ozturk, I.; Acaravci, A. CO₂ Emissions, Energy Consumption and Economic Growth in Turkey. *Renew. Sustain. Energy Rev.* **2010**, *14*, 3220–3225. [CrossRef]
20. Menyah, K.; Wolde-Rufael, Y. CO₂ Emissions, Nuclear Energy, Renewable Energy and Economic Growth in the US. *Energy Policy* **2010**, *38*, 2911–2915. [CrossRef]
21. Saidi, K.; Hammami, S. The Impact of CO₂ Emissions and Economic Growth on Energy Consumption in 58 Countries. *Energy Rep.* **2015**, *1*, 62–70. [CrossRef]
22. Esso, L.J.; Keho, Y. Energy Consumption, Economic Growth and Carbon Emissions: Cointegration and Causality Evidence from Selected African Countries. *Energy* **2016**, *114*, 492–497. [CrossRef]

23. Salahuddin, M.; Alam, K.; Ozturk, I.; Sohag, K. The Effects of Electricity Consumption, Economic Growth, Financial Development and Foreign Direct Investment on CO₂ Emissions in Kuwait. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2002–2010. [\[CrossRef\]](#)
24. Gorus, M.S.; Aydin, M. The Relationship Between Energy Consumption, Economic Growth, and CO₂ Emission in MENA Countries: Causality Analysis in the Frequency Domain. *Energy* **2019**, *168*, 815–822. [\[CrossRef\]](#)
25. Gozgor, G.; Lau, C.K.M.; Lu, Z. Energy Consumption and Economic Growth: New Evidence from the OECD Countries. *Energy* **2018**, *153*, 27–34. [\[CrossRef\]](#)
26. Beşer, M.K.; Beşer, B.H. The Relationship Between Energy Consumption, CO₂ Emissions and GDP per Capita: A Revisit of the Evidence from Turkey. *Alphanumeric J.* **2017**, *5*, 353–368. [\[CrossRef\]](#)
27. Dogan, E.; Seker, F.; Bulbul, S. Investigating the Impacts of Energy Consumption, Real GDP, Tourism and Trade on CO₂ Emissions by Accounting for Cross-Sectional Dependence: A Panel Study of OECD Countries. *Curr. Issue Tour.* **2017**, *20*, 1701–1719. [\[CrossRef\]](#)
28. Jebli, M.B.; Youssef, S.B. The Role of Renewable Energy and Agriculture in Reducing CO₂ Emissions: Evidence for North Africa Countries. *Ecol. Indic.* **2017**, *74*, 295–301. [\[CrossRef\]](#)
29. Zhang, L.; Pang, J.; Chen, X.; Lu, Z. Carbon Emissions, Energy Consumption and Economic Growth: Evidence from the Agricultural Sector of China's Main Grain-Producing Areas. *Sci. Total Environ.* **2019**, *665*, 1017–1025. [\[CrossRef\]](#)
30. Topcu, E.; Altinoz, B.; Aslan, A. Global Evidence from the Link Between Economic Growth, Natural Resources, Energy Consumption, and Gross Capital Formation. *Resour. Policy* **2020**, *66*, 101622. [\[CrossRef\]](#)
31. Raihan, A. An Econometric Evaluation of the Effects of Economic Growth, Energy Use, and Agricultural Value Added on Carbon Dioxide Emissions in Vietnam. *Asia-Pac. J. Reg. Sci.* **2023**, *7*, 665–696. [\[CrossRef\]](#)
32. Özbay, Ü. Industrialization, CO₂ Emission, Economic Growth and Agricultural Nexus in Turkey: An Empirical Investigation. *Turk. J. Agric. Econ.* **2023**, *29*, 79–91. [\[CrossRef\]](#)
33. Raihan, A.; Tuspekova, A. Dynamic Impacts of Economic Growth, Energy Use, Urbanization, Tourism, Agricultural Value-Added, and Forested Area on Carbon Dioxide Emissions in Brazil. *J. Environ. Stud. Sci.* **2022**, *12*, 794–814. [\[CrossRef\]](#)
34. EMRA. Energy Markets Regulatory Authority: Electricity Market 2021 Market Development Report. Available online: <https://www.epdk.gov.tr/Detay/Icerik/3-0-24/elektrikyllik-sektor-raporu> (accessed on 19 May 2023).
35. Friedman, M. Marshallian. Demand Curve. *J. Polit. Econ.* **1949**, *57*, 463–495. [\[CrossRef\]](#)
36. Raihan, A.; Tuspekova, A. Nexus Between Economic Growth, Energy Use, Agricultural Productivity, and Carbon Dioxide Emissions: New Evidence from Nepal. *Energy Nexus* **2022**, *7*, 100113. [\[CrossRef\]](#)
37. Dickey, D.A.; Fuller, W.A. Likelihood Ratio Statistics for Autoregressive Time Series with a Unit Root. *Econometrica* **1981**, *49*, 1057–1072. [\[CrossRef\]](#)
38. Engle, R.; Granger, C.W.J. Co-Integration and Error Correction: Representation, Estimation and Testing. *Econometrica* **1987**, *55*, 251–276. [\[CrossRef\]](#)
39. Pesaran, M.H.; Shin, Y.; Smith, R.J. Bounds Testing Approaches to the Analysis of Level Relationships. *J. Appl. Econom.* **2001**, *16*, 289–326. [\[CrossRef\]](#)
40. Acheampong, A.O.; Opoku, E.E.O. Environmental Degradation and Economic Growth: Investigating Linkages and Potential Pathways. *Energy Econ.* **2023**, *123*, 106734. [\[CrossRef\]](#)
41. Grossman, G.M.; Krueger, A.B. Economic Growth and the Environment. *Q. J. Econ.* **1995**, *110*, 353–377. [\[CrossRef\]](#)
42. Brown, R.L.; Durbin, J.; Evans, J.M. Techniques for Testing the Constancy of Regression Relationships Over Time. *J. R. Stat. Soc. Ser. B* **1975**, *37*, 149–192. [\[CrossRef\]](#)
43. Katircioğlu, S.T.; Taşpinar, N. Testing the Moderating Role of Financial Development in an Environmental Kuznets Curve: Empirical Evidence from Türkiye. *Renew. Sustain. Energy Rev.* **2017**, *68*, 572–586. [\[CrossRef\]](#)
44. Pata, U.K. The Influence of Coal and Non-Carbohydrate Energy Consumption on CO₂ Emissions: Revisiting the Environmental Kuznets Curve Hypothesis for Türkiye. *Energy* **2018**, *160*, 1115–1123. [\[CrossRef\]](#)
45. Karaaslan, A.; Çamkaya, S. The Relationship Between CO₂ Emissions, Economic Growth, Health Expenditure, and Renewable and Non-Renewable Energy Consumption: Empirical Evidence from Türkiye. *Renew. Energy* **2022**, *190*, 457–466. [\[CrossRef\]](#)
46. Al-Mulali, U.; Saboori, B.; Ozturk, I. Investigating the Environmental Kuznets Curve Hypothesis in Vietnam. *Energy Policy* **2015**, *76*, 123–131. [\[CrossRef\]](#)
47. Durgun, B.; Durgun, F. The Causality Relationship Between Renewable Energy Consumption And Economic Growth: Evidence From Turkey. *Int. Rev. Econ. Manag.* **2018**, *6*, 1–27. [\[CrossRef\]](#)
48. Nondo, C.; Kahsai, M.S. The Impact of Energy Intensity, Urbanisation, Industrialisation, and Income on CO₂ Emissions in South Africa: An ARDL Bounds Testing Approach. *Afr. J. Econ. Sustain. Dev.* **2020**, *7*, 307–330. [\[CrossRef\]](#)
49. Zmami, M.; Ben-Salha, O. An Empirical Analysis of the Determinants of CO₂ Emissions in GCC Countries. *Int. J. Sustain. Dev. World Ecol.* **2020**, *27*, 469–480. [\[CrossRef\]](#)
50. Rafiq, S.; Salim, R.; Apergis, N. Agriculture, Trade Openness and Emissions: An Empirical Analysis and Policy Options. *Aust. J. Agric. Resour. Econ.* **2016**, *60*, 348–365. [\[CrossRef\]](#)

51. Balsalobre-Lorente, D.; Driha, O.M.; Bekun, F.V.; Osundina, O.A. Do Agricultural Activities Induce Carbon Emissions? The BRICS Experience. *Environ. Sci. Pollut. Res.* **2019**, *26*, 25218–25234. [CrossRef] [PubMed]
52. OECD. OECD Economic Surveys: Türkiye 2025. Available online: https://www.oecd.org/en/publications/oecd-economic-surveys-turkiye-2025_d01c660f-en.html (accessed on 10 May 2025).
53. Ijeh, S.O. Promoting Sustainable Development in Nigeria through the Non-Oil Sector Export. *Res. J. Humanit. Soc. Sci.* **2014**, *4*, 89–96.
54. Amponsah, L.; Kofi Hoggar, G.; Yeboah Asuamah, S. Climate Change and Agriculture: Modelling the Impact of Carbon Dioxide Emission on Cereal Yield in Ghana. 2015. Available online: <https://mpira.ub.uni-muenchen.de/68051/> (accessed on 25 May 2025).
55. Binsuwadan, J.; Alotaibi, L.; Almugren, H. The Role of Agriculture in Shaping CO₂ in Saudi Arabia: A Comprehensive Analysis of Economic and Environmental Factors. *Sustainability* **2025**, *17*, 4346. [CrossRef]
56. Bathaei, A.; Štreimikienė, D. Renewable Energy and Sustainable Agriculture: Review of Indicators. *Sustainability* **2023**, *15*, 14307. [CrossRef]

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