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How do crop and livestock production affect carbon emissions? Empirical evidence from Türkiye

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Abstract

Purpose: The main purpose of this study is to reveal the role of agricultural activities on environmental quality by analysing the effects of renewable energy use, trade openness, gross domestic product and crop and livestock production on CO_2 emissions in Türkiye for the period 1980-2022.

Design/Methodology/Approach: In the study, the ARDL bounds test approach, known for providing reliable results even in small samples, is employed to examine the factors affecting CO_2 emissions and to reveal the model's short and long-run relationships. During the analysis process, the stationarity of the variables is first evaluated with ADF and PP tests, and then long-term relationships is determined. The reliability of the model is verified with various diagnostic tests, and the effects of the variables on CO_2 emissions is revealed.

Findings: The ARDL test results indicate that there is a long-run cointegration relationship between the variables. According to the calculated long-run coefficient results, renewable energy consumption, crop production and livestock production have a decreasing effect on CO_2 emissions. On the other hand, gross domestic product and urbanisation are determined as factors that increase CO_2 emissions.

Originality/Value: It is noteworthy that studies on the impact of crop and livestock production on CO_2 emissions in Türkiye are limited. It is estimated that the inclusion of factors such as renewable energy, GDP per capita and urbanisation in the model will provide a projection for both the literature and policy recommendations for improving environmental quality in Türkiye.

Keywords: Agriculture activities, ARDL bounds test, environmental quality, renewable energy.

Bitkisel ve hayvansal üretim karbon emisyonlarını nasıl etkiler? Türkiye'den ampirik kanıtlar

Özet

Amaç: Bu çalışmanın temel amacı, Türkiye'de 1980-2022 dönemine ait veriler doğrultusunda yenilenebilir enerji kullanımı, ticari açıklık, gayri safi yurt içi hâsıla ile bitkisel ve hayvansal üretimin CO_2 emisyonları üzerindeki etkilerini analiz ederek, tarımsal faaliyetlerin çevresel kalite üzerindeki rolünü ortaya koymaktır.

Tasarım/Metodoloji/Yaklaşım: Çalışmada CO_2 emisyonlarını etkileyen faktörleri incelemek ve modelin kısa ve uzun dönem ilişkilerini ortaya koymak için küçük örneklemlerde dahi güvenilir sonuçlar vermesiyle bilinen ARDL sınır testi yaklaşımı kullanılmıştır. Analiz sürecinde öncelikle değişkenlerin durağanlığı ADF ve PP testleri ile değerlendirilmiş, ardından uzun dönemli ilişkiler tespit edilmiştir. Modelin güvenilirliği çeşitli tanısal testler ile doğrulanmakta ve değişkenlerin CO_2 emisyonu üzerindeki etkileri ortaya konulmaktadır.

Bulgular: ARDL testi sonuçları, değişkenler arasında uzun dönemli bir eşbütünleşme ilişkisi olduğunu göstermektedir. Hesaplanan uzun dönem katsayı sonuçlarına göre, yenilenebilir enerji tüketimi, bitkisel üretim ve hayvansal üretim CO_2 emisyonlarını azaltıcı etkide bulunmaktadır. Buna karşılık, gayri safi yurt içi hasıla ve kentleşme CO_2 emisyonlarını artıran faktörler olarak belirlenmiştir. Ticari açıklık değişkeni istatistiksel olarak anlamlı bulunmamıştır.

Özgünlük/Değer: Türkiye'de bitkisel ve hayvansal üretimin CO_2 emisyonları üzerindeki etkisini ele alan çalışmaların sınırlı olduğu dikkat çekmektedir. Yenilenebilir enerji, kişi başına düşen GSYİH ve kentleşme gibi faktörlerin modele dahil edilmesi yapılacak analizler ile Türkiye'de çevre kalitesinin artırılmasına dönük gerek literatüre gerekse de politika önerileri için bir projeksiyon oluşacağı tahmin edilmektedir.

Anahtar kelimeler: Tarımsal aktiviteler, ARDL sınır testi, çevresel kalite, yenilenebilir enerji.

INTRODUCTION

Carbon emissions released into the atmosphere as a result of human activities such as industrialization, transportation, and energy production cause global climate change, leading to serious environmental problems worldwide (Çıtak et al., 2021; Ozturk et al., 2022; Dağ and Aktaş, 2024; Sagynay and Karataş, 2024). In this context, many countries aim to ensure environmental sustainability while maintaining economic growth and develop policies to improve environmental quality (Zhou et al., 2024). Developing effective policies and strategies to reduce the adverse effects of greenhouse gases on climate change requires firstly the accurate and comprehensive identification of the activities and sectors from which these gases originate. Thus, the measures to be taken to reduce greenhouse gas emissions can become more targeted and sustainable (Inekwe et al., 2020).

Understanding the environmental threats posed by carbon emissions on a global scale has necessitated countries to reshape their climate policies. In this regard, it is important to determine the main factors that cause carbon emissions in order to ensure environmental sustainability. The diversity of economic activities and the level of development of countries directly affect the level of greenhouse gas emissions. In this framework, the environmental impacts of factors such as economic growth, trade openness, energy use, urbanization and agricultural production have increasingly become the subject of research. Theoretical approaches and empirical findings on the relationship between these variables and carbon dioxide emissions are discussed in detail below.

Sustainable development is a multidimensional process that encompasses not only economic growth but also the preservation of environmental quality (Todaro and Smith, 2020). In this framework, it is of great importance to establish the relationship between economic growth and environmental quality and to develop appropriate policy instruments for this relationship. Grossman and Krueger (1991) examined the relationship between per capita income and environmental pollution, inspired by Simon Kuznets' (1955) model analysing the relationship between economic growth and income distribution. They defined this relationship as an 'inverted U'. According to this definition, in the initial stages of economic growth, the use of natural resources intensifies due to the increase in industrialisation, urbanisation and energy consumption, and thus environmental pollution levels increase. However, after the per capita income exceeds a certain threshold, the sensitivity of the society to environmental issues increases, environmental protection measures become widespread, and cleaner production technologies are adopted due to the influence of public pressure and environmentalist policies. As a result of this process, environmental degradation slows down and it is observed that pollution levels tend to decrease (Panayotou, 1993; Dinda, 2004). With this approach, the relationship between environmental quality and economic growth has started to be examined more intensively in the literatüre, and carbon dioxide (CO_2) emissions have been widely used as one of the main indicators of environmental pollution (Raihan, 2023; Akıncı et al., 2024; Çetin and Can., 2024; Xuan, 2025).

In addition to economic growth, trade openness also has significant effects on environmental quality. Two different approaches to the impact of trade openness on the environment stand out in the literature. According to the first approach, trade openness increases the level of income, raises environmental awareness and thus positively affects environmental quality (Hossain, 2011; Shabani and Shahnazi, 2019; Zhang, 2021; Çetin et al., 2023). The other approach argues that trade openness causes environmental destruction through increased production and industrialization activities (Ren et al., 2014; Rahman et al., 2020; Chen et al., 2021; Çetin et al., 2022; Bibi and Jamil, 2025).

The use of renewable energy is one of the main factors affecting environmental quality. Compared to fossil fuels, renewable energy sources emit much lower levels of carbon and make a significant contribution to environmental sustainability in economic growth processes (Paramati et al., 2017; Bak et al., 2021). Many empirical studies have found that the use of renewable energy reduces carbon emissions (Dogan and Şeker, 2016; Liu et al., 2017; Adams and Acheampong, 2019; Okumuş, 2020; Fatima et al., 2021; Bashir et al, 2023, Çetin and Can, 2024).

With the modernization of societies, urbanisation has become one of the important determinants of environmental degradation. The increase in urbanisation, housing, transportation and entertainment areas has led to an increase in carbon dioxide emissions (Ali et al., 2017; Ma and Ogata, 2024). The rapid and irregular urbanization process has brought environmental problems such as increased use of natural resources, decreased biodiversity, and increased air pollution (Xu et al., 2024). However, it is possible to reduce these effects through sustainable urban planning practices.

Agriculture is a comprehensive field of activity that includes obtaining crop and animal products, increasing the productivity and quality of these products, storing them under appropriate conditions, processing them and offering them to the market. In this context, the crop and livestock sectors are two main areas that directly affect environmental quality. The livestock sector, in particular, plays a role in accelerating climate change by releasing greenhouse gases such as nitrous oxide, methane and carbon dioxide into the atmosphere (McMichael et al., 2007; Çelik, 2024). Similarly, the agricultural sector also causes an increase in CO_2 and other greenhouse gas emissions due to intensive resource use (Raihan, 2023). With the increasing need for food production, the intensification of fertilizer, water, energy and fuel use increases emissions (Raihan et al., 2022; Zhou et al., 2022). In addition, the implementation of environmentally eco-agricultural and livestock policies can contribute to emission reductions in the long term (Rehman et al., 2021). While large-scale crop production (intensive farming) increases oxygen emissions, reducing fertiliser use and reducing energy-intensive feed consumption through organic farming practices can reduce greenhouse gas emissions (Lee and Choe, 2019). It is useful to explain the mechanism of how crop and livestock production reduces CO_2 emissions. Photosynthesizing plants store carbon in their bodies. This helps to reduce the level of CO_2 in the atmosphere. Similarly, since the increase in animal husbandry will increase the production of plants, which are the basic nutrients of animals, this situation affects CO_2 emissions in a reducing direction. Moreover, using animal manure instead of chemical fertilizers can also reduce CO_2 emissions (Özbay, 2024). There are different views in the literature on the impact of crop and livestock sectors on CO_2 emissions. While some studies argue that these sectors increase emissions (Ayyildiz and Erdal, 2021; Balogh, 2022), others have suggested that they can reduce emissions (Liu et al., 2017; Çetin et al., 2020; Zhou et al., 2022; Chowdhury et al., 2022; Raihan, 2023; Zhang et al., 2022).

Türkiye is among the countries with a weak performance in terms of climate change performance (Özbek and Özbek, 2024). Due to insufficient climate policies, low utilization of renewable energy, and a heavy reliance on imported fossil fuels to meet its energy needs, Türkiye ranks 53rd out of 63 countries in terms of greenhouse gas emissions performance, according to the Climate Change Performance Index (CCPI, 2025). While CO_2 emissions per capita were 2.70 tons in 1990, this value increased to 4.95 tons in 2023 (Our World in Data, 2025). This situation shows that Türkiye needs to develop more effective policies both in combating climate change and in reducing CO_2 emissions. Therefore, it is important to analyze the determinants that cause CO_2 emissions in Türkiye.

The main purpose of this study is to analyze the effects of renewable energy use, trade openness, urbanization, gross domestic product, crop production, and livestock production on CO_2 emissions in Türkiye using data from the period 1980-2022. The limited number of studies in the literature in which these variables are analysed together and especially the inclusion of crop and livestock production variables in the model constitute the original contribution of this study. Thus, it is thought that the study will contribute to the existing literature in this respect. In this context, the long-run relationship between variables has been analysed by using the ARDL bounds test, one of the time series analysis methods.

In the rest of the study, the relevant literature review, research methodology, data set and model, analysis method, findings and conclusion sections are given respectively.

LITERATURE RESEARCH

In recent years, the increase in CO_2 emissions and their negative effects on the environment have accelerated the studies on the factors that cause the formation of these emissions. When the studies on carbon dioxide emissions in the literature are examined, it is seen that the relationship between CO_2 emissions and variables such as trade openness, renewable energy, non-renewable energy and urbanisation are mostly focused. In this study, in addition to these variables, the effect of crop and livestock production, which is included in the model, on CO_2 emissions is tried to be explained. In this context, academic studies on the effect of these variables, which are the focus of the study, on CO_2 emissions are given in Table 1.

When the literature is examined in general, it is noteworthy that there are limited studies addressing the impact of crop and livestock production on CO2 emissions in Türkiye. In this context, the current study aims to fill this gap in the literature by analyzing the impact of crop and livestock production on CO2 emissions in Türkiye.

Table 1. Literature review on factors affecting CO_2 emissions

Author(s) (Year)	Country (Priod)	Variables	Method	Results
Sarkodie and Owusu (2017)	Ghana (1960-2013)	CO_2, CPI and LPI	ARDL bounds test	CPI and LPI increase CO_2 emissions.
Liu et al. (2017)	4 Southeast Asian Countries (1970-2013)	CO_2, GDP, REC, NEC and AVA	FMOLS, DOLS	increasing AVA reduces CO_2 emissions.
Çetin et al. (2018)	Türkiye (1960-2014)	CO_2, GDP, GDP^2, URB and EC	ARDL bounds test	URB increases CO_2 emissions
Çetin et al. (2020)	Türkiye (1968-2016)	CO_2, GDP, REC and AVA	ARDL bounds test	AVA reduces CO_2 emissions
Ayyildiz and Erdal (2021)	184 Countries (1998-2014)	CO_2, CPI and LPI	DCCE Test	CPI increases CO_2 emission only in lower middle–income countries. LPI increases CO_2 emission in all countries except low-income countries.
Öztürk and Saygın (2020)	Türkiye (1974-2016)	CO_2, GDP, FDI and TO	ARDL bounds test	TO increases CO_2 emissions
Zhang et al. (2021)	9 ASEAN Countries (2000-2020)	CO_2, EC, TO, NEC and AVA	FMOLS	AVA reduces CO_2 emissions
Balogh et al. (2022)	152 Non-EU Countries (2000-2018)	CO_2, GDP, GDP^2, AE, AVA and EA	FMOLS, DOLS	AVA reduces CO_2 emissions. Agricultural activities has a negative impact on the environment
Zhou et al. (2022)	China (1971-2019)	CO_2, CPI, LPI, GDP, EC and TO	ARDL bounds test	LPI reduces CO_2emissions. CPI increases CO_2 in the short term.
Chowdhury et al. (2022)	Bangladesh (1985-2017)	CO_2, N_2O, AVA, LPI, AE, RF and CPI	FMOLS, DOLS, CCR	LPI and CPI reduce CO_2
Raihan (2023)	Vietnam (1984-2020)	CO_2, EG, EC and AVA	ARDL bounds test	AVA reduces CO_2 emissions
Bashir et al. (2023)	10 Countries (1995-2019)	CO_2, GDP, URB, FD and REC	CS-ARDL, AMG, CCEMG and FMOLS	Urbanization leads to environmental degradation.
Özbay (2024)	Türkiye (1990-2020)	CO_2, CPI, LPI, FPI and AVA	ARDL bounds test	FPI increases CO_2 emission, CPI, LPI and AVA increase CO_2 emission.
Ngoc Xuan (2025)	India 2000-2023	CO_2, NEC, REC, POP, REC and GDP	FMOLS and DOLS,	REC reduces environmental pollution.

Explanation: AE: Agricultural Equipment, LPI: Livestock Production Index, AVA: Agricultural Value Added, CO_2: Carbon Emissions, CPI: Crop Production Index, EC: Energy Consumption, EG: Economic Growth, FD: Financial Development, FDI: Foreign Direct Investment, FPI: Food Production Index, GDP: Real income per capita, GDP^2: Real income per capita square, PD: Population Density, POP: Population NEC: Non-renewable Energy Consumption, REC: Renewable Energy Consumption, RF: Rice Field, TO: Trade Openness, URB: Urbanization

RESEARCH METHODOLOGY

This study examines the effects of economic growth, trade openness, urbanisation, renewable energy use and crop and livestock production on CO_2 emissions in Türkiye. In the study, firstly, explanations about the data set and the model are given. Then, the theoretical framework for the analyses to be applied is presented and the findings obtained are evaluated in detail. The analysis process includes unit root test, diagnostic and structural break tests, ARDL bounds test and estimation of short and long run coefficients. Finally, a general evaluation of the results of the analyses is presented.

DATA SET AND MODEL

In this study, the impact of crop production, Livestock Production, Urbanisation and trade openness on CO_2 emissions in Türkiye is examined using data for the period 1980-2022. This period represents a timeframe in which Türkiye implemented outward-oriented economic policies, experienced an accelerated process of industrialization and urbanization, and witnessed increasingly pronounced environmental challenges. The preferred period allows for a long-term analysis of the environmental impacts of trade openness, particularly in relation to crop and livestock production. The variables used in the analysis, along with detailed explanations of these variables, are provided in Table 2.

Table 2. Description of the data set

Değişkenler	Açıklaması	Değişken Kısaltması	Kaynak
Environmental pollution	CO_2 per capita (m-tonnes)	lnCO_2	Our Word in Data
Economic Growth	Per capita GDP (2015 Constant)	lnGDP	World Bank Data
Urbanisation	Urban Population	lnUR	World Bank Data
Trade Openness	Trade (% of GDP)	lnTR	World Bank Data
Renewable Energy Consumption	The Share of Primary Energy consumption from Renewable sources	lnRE	Our Word in Data
Crop Production	Crop Production Index	lnCPI	World Bank Data
Livestock Production	Livestock Production Index	lnLPI	World Bank Data

Livestock production index includes meat and milk from all sources, dairy products such as cheese, and eggs, honey, raw silk, wool, and hides and skins. The crop production index shows each year's agricultural production based on the 2014-2016 base period. It includes all crops except forage crops. The trade openness variable is a measure that reflects the degree of an economy's external openness and integration into global trade, and it is calculated as the ratio of total trade volume (exports + imports) to GDP. Finally, the 'urban population' variable, used to represent the level of urbanization, represents the proportion of the total population living in urban areas.

The variables of trade openness, urbanisation, gross domestic product, crop production, livestock production and renewable energy consumption in this study were determined by taking advantage of studies in the literature such as Sarkodie & Owusu (2017), Çetin et al. (2020), Öztürk & Saygın (2020), Zhou et al. (2022) and Bashir et al. (2023), Ngoc Xuan (2025). In this respect, all variables are included in the model by taking their natural logarithms and the functional form of the model is presented below:

$$lnCO2_t = \beta_0 + \beta_1 lnGDP_t + \beta_2 lnUR_t + \beta_3 lnTR_t + \beta_4 lnRE_t + \beta_5 lnCPI_t + \beta_6 lnLPI_t + u_t \tag{1}$$

In Equation 1, ln denotes the natural logarithm, the t represents the time dimension. The parameters β_1, β_2, β_3, β_4, β_5 and β_6 in the model correspond to the estimated coefficients, while μ_t represents the error term. Detailed explanations of GDP, UR, TR, RE, CPI and LPI variables are given in Table 3.

METHODOLOGY

In this study, the relationship between CO_2 variable and gross domestic product, urbanisation, trade openness, per capita renewable energy consumption, crop production and livestock production variables will be examined. It is important to test the stationarity of the series in order to avoid spurious regression in the analysis and to determine the appropriate cointegration method. In this context, firstly, Augmented Dickey-Fuller (ADF-1981) and Phillips-Perron (PP-1988) unit root tests will be applied to examine whether the series of variables are stationary or not. These tests will be applied in the form of two models as constant and constant-trend. The equation representation of these models are as follows.

$$\begin{gathered} \Delta Y_t = c + \delta Y_{t-1} + \sum_{i=1}^{p} \delta_i \Delta Y_{t-i} + u_t \\ \Delta Y_t = c + \beta t + \delta Y_{t-1} + \sum_{i=1}^{p} \delta_i \Delta Y_{t-i} + u_t \end{gathered} \tag{2}$$

In Equation 2, u_t denotes the error term, c denotes the intercept term and β denotes the coefficient.

After the unit root test, cointegration analysis is performed to determine the long-run relationship between the variables. In this context, ARDL test will be applied in this study after the unit root test. Since the ARDL bounds test developed by Pesaran et al. (2001) does not require all variables to be stationary at the same level, the ARDL test can be used as a cointegration test in cases where the variables are stationary at different levels. Within the scope of this test, critical value tests can be performed with the help of F and t statistical tests. The equation for the cointegration relationship is given below.

$$\Delta ln\text{CO2}_t = \alpha_0 + \sum_{i=1}^{m} \alpha_i \Delta lnGDP_{t-i} + \sum_{i=0}^{n} \beta_i \Delta lnUR_{t-i} + \sum_{i=0}^{k} \gamma_i \Delta lnTR_{t-i} + \sum_{i=0}^{l} \omega_i \Delta lnRE_{t-i} + \sum_{i=0}^{l} \omega_i \Delta lnCPI_{t-i} + \sum_{i=0}^{l} \omega_i \Delta lnLPI_{t-i} + u_t. \quad 3$$

Here, $\alpha_i, \beta_i, \gamma_i, \omega_i$ coefficients indicate the short-run relationship between the variables, while $\delta_1, \delta_2, \delta_3, \delta_4$ coefficients indicate the long-run relationship. The m,n, k, l expressions also mean appropriate lag lengths. The null hypothesis stating that there is no cointegration relationship is as follows.

$$H_0 = \delta_1 = \delta_2 = \delta_3 = \delta_4 = 0 \quad 4$$

In the ARDL bound test, two critical values as I(0) and I(1) are calculated. If the F-statistic obtained as a result of the test is less than the lower bound value of I(0), the null hypothesis regarding the existence of cointegration relationship cannot be rejected and it is accepted that there is no long-run relationship between the variables. If the obtained statistic value is greater than the upper limit value of I(1), the null hypothesis is rejected and it is concluded that there is a cointegration relationship between the variables. However, if the test statistic is between both boundary values, the decision is uncertain and a definite judgement cannot be made about the cointegration relationship. In this context, the error correction model that examines short-term dynamics is presented below.

$$\Delta lnCO2_t = \alpha_0 + \sum_{i=1}^{k} \alpha_i \Delta GDP_{t-i} + \sum_{i=0}^{l} \beta_i \Delta lnUR_{t-i} + \sum_{i=0}^{m} \gamma_i \Delta lnTR_{t-i} + \sum_{i=0}^{n} \omega_i\, \Delta lnRE_{t-i} + \sum_{i=1}^{k} \mu_i \Delta CPI_{t-i} + \sum_{i=1}^{k} \lambda_i \Delta LPI_{t-i} + \varphi ECM_{t-1} + u_t \quad 5$$

If the term φ (ECM), expressed as the correction coefficient, is statistically significant and negative, it is said that the deviations that will occur in the short term in the model with a long-term relationship will be balanced after a certain period of time.

FINDINGS

Descriptive statistics of the variables used in the study are given in Table 3.

Table 3. Descriptive statistics of variables

	$lnCO_2$	lnGDP	lnUR	lnTR	lnRE	lnCPI	lnLPI
Mean	1.204835	8.835576	17.53325	3.754742	2.472592	4.376174	4.134312
Median	1.216299	8.744617	17.58331	3.843626	2.471377	4.413646	3.961384
Maximum	1.652941	9.550741	17.99685	4.396547	2.911464	4.830631	4.922241
Minimum	0.504609	8.247271	16.80522	2.838483	2.052114	3.937301	3.668422
Std. Dev.	0.341171	0.382185	0.329036	0.311938	0.219160	0.242452	0.379949
Skewness	-0.483686	0.271920	-0.539966	-0.656035	0.006486	-0.155585	0.748992
Kurtosis	2.126991	1.884248	2.367029	3.618217	2.483374	2.072499	2.177194
Jarque-Bera	3.042167	2.760354	2.807373	3.769163	0.478502	1.714777	5.233394
Probability	0.218475	0.251534	0.245690	0.151893	0.787217	0.424269	0.073044
Observations	43	43	43	43	43	43	43

Table 3 presents the descriptive statistics of explanatory variables such as $lnCO_2$, lnGDP, lnUR, lnTR, lnRE, lnCPI, and lnLPI. These statistics describe the characteristics of the series. As can be seen from the table, the variables with the highest mean and median values are lnUR and lnGDP, respectively. lnRE and lnCPI are the indicators with the lowest standard deviation. Furthermore, $lnCO_2$ and lnRE are the variables with the lowest maximum and minimum values. The skewness values close to 0 and kurtosis values close to 2 in the table indicate that the series are normally distributed. The results obtained from the Jarque-Bera test show that the null hypothesis stating that the series are normally distributed cannot be rejected and, therefore, all series follow a normal distribution.

In the literature, unit root tests have been widely used to investigate the effects of shocks on series and to test whether the series are stationary. While the effects of the shock disappear in the short term in stationary series, they can be permanent in non-stationary series. In this context, in studies where time series analysis method is used, the non-stationarity of the series can also cause the applied tests to give incorrect results. This situation is explained as a spurious relationship between the variables. Therefore, in studies where time series analysis method is used, it is important to perform stationarity tests first in order to determine the correct relationship between variables (Tarı, 2019).

In the literature, various unit root tests are applied to determine whether the series are stationary or not. These are Dickey-Fuller, Augmented Dickey-Fuller (1981), Phillips-Perron (1988) and Kwiatkowski, Phillips, Schmidt, Shin's KPSS (1992) tests. In this study, Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests have been used to test the stationarity of the series. The results of the unit root tests are given in Table 4.

Table 4. Unit root test results of the series

	Constant			
	ADF (t-stat)	**PP (t-stat)**	**ΔADF (t-stat)**	**ΔPP (t-stat)**
$lnCO_2$	-2.158765	-4.759021*	6.690688*	-6.732529*
lnGDP	0.511820	1.326484	-6.712800*	-7.092726*
LnCPI	-0.586379	0.102125	-12.47447*	-18.47555*
lnLPI	1.266781	1.519337	-8.127812*	-7.237758*
lnTR	-2.334968	-2.333142	-5.359693*	-5.840432*
lnRE	-2.658781***	-2.583686	7.974011*	-9.198684*
lnUR	-1.789160	-6.366405*	1.349018	-1.449850
				Constant and Trend
	ADF (t-stat)	**PP (t-stat)**	**ΔADF (t-stat)**	**ΔPP (t-stat)**
$lnCO_2$	-1.976622	-1.649662	-7.179629*	-12.51676*
lnGDP	-2.171187	-2.200748	-6.755391*	-7.901723*
lnCPI	-4.892878*	-4.955220*	-12.47447*	-21.05352*
lnLPI	-0.825748	-0.695681	-8.127812*	-8.082621*
lnTR	-4.440362*	-4.159105**	-5.359693*	-5.613095*
lnRE	-2.999048	-2.943983	-7.974011*	-9.363737*
lnUR	-6.848420*	-7.201354*	-1.349018	-1.386151

Lag lengths are determined according to the Schwarz information criterion. The symbol Δ is used to denote the first difference. ***, **, * correspond to the levels of 10%, 5%, and 1%, respectively.

When Table 4 is analysed, according to the ADF and PP test results in the model with constant, CPI, GDP, TR and LPI variables are non-stationary at level, but stationary in their first differences at 1% significance level. According to the ADF test, CO_2 variable is stationary at first difference, while it is stationary at level according to PP test. According to the ADF and PP tests, the RE variable is stationary at the 10% significance level. The UR variable is stationary only at the 1% significance level according to the PP unit root test. It is not stationary in the first difference.

According to the ADF and PP test results in the model with constant and trend, while the CO_2, GDP, RE, LPI variables are non-stationary at level, they become stationary according to 1% significance level at first differences. While CPI, TR and UR variables are stationary at level according to ADF and PP tests.

The fact that some of the variables are stationary at the level and some at first difference level requires the ARDL bounds test to determine the cointegration relationship. However, before applying this test, the appropriateness of the model and the results obtained from the diagnostic and stability tests to be performed for the model are important. The diognastic test results of the model are given in Table 5.

Table 5. The result of diognastic test

Test	**Statistic**	**Prob.**
Breusch-Godfrey Autocorrelation	1.837776	0.1793
Breusch-Pagan-Godfrey Heteroscedasticity	0.480230	0.9095
Ramsey RESET	0.493533	0.6256
Jargue-Bera Normality Test	2.531887	0.2819

As seen in Table 5, there is no autocorrelation, heteroscedasticity and specification problems in the model.

In addition, the probability value of the Jargue-Bera normality test being greater than 0.05 shows that the error terms are also normally distributed. In addition, the stability of the model has been tested with the help of Cusum and CusumQ tests. The results of the stability tests are given in Figure 1.

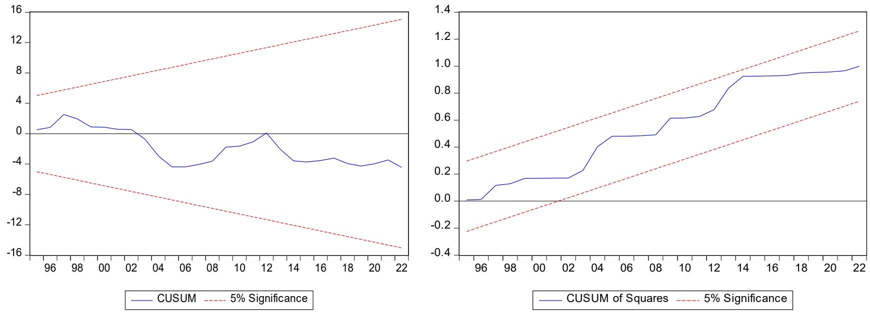

Figure 1. Stability test results

In Figure 1, the fact that the sum of consecutive errors and their sum of squares remain within a certain confidence interval indicates that there is no structural break in the model. ARDL bounds test has been applied to determine whether there is a long-run relationship between the series and the test results are given in Table 6.

Table 6. The result of the ARDL bounds test (ARDL, 2, 1, 2, 0, 0, 0, 1 Model)

K	F-Statistic	%1 Critical Value	
		I(0)	I(1)
6	6.755296	2.88	3.99

According to the ARDL bounds test results given in Table 6, the F statistic value calculated for the model has been found to be 6.76. Since this value is greater than the calculated I(0) and I(1) critical values at 1% significance level, the null hypothesis stating that there is no cointegration is rejected. After determining the cointegration relationship between the variables, the short and long run coefficients of the variables have been estimated. The short-run coefficients of the variables are given in Table 7.

Table 7. The result of the short run coefficients

Variables	Coefficient	Std. Error	t-Statistic	Prob.
D(CO_2(-1))	-0.152211	0.079326	-1.918810	0.0653
D(GDP)	0.871650	0.086232	10.10818	0.0000
D(CPI)	-0.031577	0.097360	-0.324337	0.7481
D(CPI(-1))	0.375020	0.102428	3.661294	0.0010
D(UR)	-2.266443	0.385038	-5.886280	0.0000
ECM(-1)	-0.549441	0.066850	-8.219061	0.0000

When Table 7 is analysed, the error term (ECM) is statistically significant at 1% significance level. The coefficient of the error term is negative as expected. This indicates that short-term deviations in the model with a long-run relationship will be offset after a certain period of time. The coefficient of ECM(-1) (-0.55) is statistically significant and indicates that the deviation in the model will be corrected by 55% in each period.

Table 8. The result of the long run coefficients

Variables	Coefficient	Std. Error	t-Statistic	Prob.
lnGDP	1.012532	0.242575	4.174090	0.0003
lnCPI	-1.070673	0.491959	-2.176346	0.0381
lnLPI	-0.260486	0.139046	-1.873380	0.0715
lnTR	-0.045826	0.073732	-0.621520	0.5393
lnRE	-0.189438	0.061730	-3.068809	0.0047
LnUR	0.771704	0.303717	2.540863	0.0169

When the results of the long-run coefficients in Table 8 are analysed, it is seen that the coefficients of GDP and RE are statistically significant at 1% significance level and the coefficient of CPI, UR are statistically significant at 5% significance level. LPI is statistically significant at 10%. Accordingly, a 1% increase in agricultural production reduces CO_2 emissions by 1.07%, while a 1% increase in livestock production reduces CO_2 emissions by 0.26%. These results indicate that increasing crop and livestock production increases environmental quality. The finding that agricultural production increases environmental quality is similar to the results of Liu (2017), Çetin et al. (2020), Balogh et al. (2022), Zhang et al. (2022) and the finding that livestock production increases environmental quality is similar to the results obtained from Zhou et al. (2022), Chowdhry et al. (2022) and Raihan et al. (2023). A 1% increase in renewable energy use reduces CO_2 emissions by 0.19%. Encouraging the use of renewable energy reduces CO_2 emissions. On the other hand, a 1% increase in GDP increases CO_2 emissions by 1.01%. Accordingly, increasing economic growth has a negative effect on environmental quality. In addition, the coefficient of the TR variable included in the model is negative and statistically insignificant.

In general, when the results of the analysis are evaluated, it is seen that there are no autocorrelation, changing variance and specification problems in the model, the series are normally distributed and there is no structural break in the model. In addition, according to the ARDL bounds test results, it is determined that there is a cointegration relationship between the variables in the model.

CONCLUSION

This study aimed to examine the effects of trade openness, gross domestic product, urbanization, renewable energy use, crop and livestock production on CO_2 emissions in Türkiye. There are previous studies on the current issue conducted in different countries, and it is seen that different views are defended regarding the effects of trade openness, crop production and livestock production on CO_2 emissions. However, it can be said that the number of studies in the literature to examine the effect of crop and livestock production on CO_2 emissions is limited. In this framework, the current study contributes to the literature; in addition, the fact that the variables used in the study have not been considered together in the same model in previous studies reveals the originality of the study.

The study, which used data from 1980 to 2022, conducted an ARDL bounds test, revealing a long-term cointegration relationship between the variables in the model. Analysis of the long-term coefficients showed that both crop and livestock production reduce CO_2 emissions. It was concluded that crop production improves environmental quality, and similarly, livestock production also contributes positively to environmental quality. Furthermore, the estimation methods used in the study revealed that the coefficient of the crop production variable is quite high (1.07) and that encouraging this type of production could significantly contribute to reducing CO_2 emissions.

The research findings reveal the importance of adopting eco-friendly policies in Türkiye in order to achieve the goal of sustainable development. Implementation of sustainable and climate-friendly agricultural practices such as increasing the amount of oxygen in the atmosphere by large-scale cultivation, activating irrigation systems in agriculture and increasing soil fertility by reducing the use of chemicals will contribute to the reduction of CO_2 emissions in Türkiye. In addition, preventing the negative effects that deteriorate environmental quality, such as the destruction of green areas and the intensive use of non-renewable and high energy as a result of rapid and unregulated urbanization, will help create a cleaner and more livable environment.

This study reveals the main factors causing CO_2 emissions and provides an important framework on how environmental quality can be increased as well as economic growth in the sustainable development process. Future studies on this subject, addressing different factors that have a negative impact on the environment, will make significant contributions to the existing knowledge in this field. In the sustainable development process, it is important to determine the factors that deteriorate environmental quality and to implement stronger policies that will increase environmental quality in this direction. Additionally, the transition to organic agricultural practices and the reduction in pesticide and fertiliser use are expected to have a positive impact on environmental quality as part of the sustainable development process. In this context, the study reveals the importance of supporting low-carbon technologies in order to reduce emissions, implementing policies such as carbon taxes to reduce CO_2 emissions from fossil fuel use, and encouraging the use of renewable energy in production processes. Furthermore, future studies that conduct more detailed model analyses by separating the crop and livestock production indices into their components will contribute to a deeper understanding of this relationship.

Contribution Rate of Researchers Declaration Summary

The authors declare that they have contributed equally to the article and have not plagiarized.

Conflict of Interest Declaration

The authors of the article declare that there is no conflict of interest between them.

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