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The Relationship between CO_2 Emissions, Energy Consumption, Economic Growth, Exports, and Imports in Turkey

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Abstract*:* This study investigates the relationship between CO_2 emissions, energy consumption, economic growth, exports, and imports in Turkey (Türkiye) between 1970 and 2023. The vector error correction model (VECM) and the Granger causality tests are employed to observe the interactions between these variables. The findings imply that CO_2 emissions and energy consumption, CO_2 emissions and exports, energy consumption and exports, and economic growth and exports have bidirectional causal relationships. Furthermore, unidirectional causal relationships from imports to exports and from economic growth to imports are also observed. Energy consumption positively affects CO_2 emissions in the short and long-run. Regarding the short-run, economic growth, exports and imports stimulate CO_2 emissions. In the long-run, economic growth and exports negatively impact CO_2 emissions. Finally, the current study recommends vital policies that focus on energy-saving production in Turkey.

Keywords: Turkish Economy, CO_2 Emissions, Vector Error Correction Model, Granger Causality, Energy Consumption

Introduction

Carbon dioxide (CO_2) emissions have attained unprecedented levels not observed for millions of years; however, their implications remain undetermined (Hansen et al., 2025). Nevertheless, recent studies, such as the study of Li et al. (2022), indicate that carbon neutrality in a nation could diminish global warming. Global warming, defined as the gradual increase in Earth's atmospheric, temperature, adversely affects human health through ecosystem and soil degradation, diminishing. agricultural output and biodiversity, and a reduction in freshwater resources (Rossati, 2016). Hence, the determinants of CO_2 emissions that cause global warming have become crucial to observe. In response to the importance of addressing global warming, Turkey signed the Paris Agreement, which aims to combat global climate change, in 2016, and started to provide financial and technical assistance for it. In this aspect, Turkey aims for net-zero emissions in 2053 (Republic of Türkiye Ministry of Environment, Urbanization and Climate Change, 2025). Nevertheless, regarding the importance of CO_2 emissions on global warming, Turkey's air pollution measured by CO_2 emissions has been increasing tenfold, while the energy demand and international trade volume of Turkey have been enhanced almost fivefold over the last half-century (WDI-WB, 2025). Hence, for developing countries such as Turkey, where economic growth and international trade are essential, it is crucial to understand the factors that cause CO_2 emissions in order to design greener and sustainable policies.

Given the importance of air pollution, as measured by CO_2 emissions, in Turkey, it is essential to investigate how energy consumption, economic growth, exports, and imports affect air pollution. To answer this question, this study contributes to existing literature through the investigation of the relationship between CO_2 emissions, energy consumption, economic growth, exports, and imports in Turkey (Türkiye) between 1970 and 2023. The vector error correction model (VECM), Granger causality tests, and variance decomposition are applied to observe the relationship among employed variables. The empirical results show that bilateral causality relationships between CO_2 emissions and energy consumption, between CO_2 emissions and exports, between energy consumption and exports, and between economic growth and exports are observed by employing the Granger causality tests based on VECM. Moreover, unidirectional causalities from economic growth to imports and from imports to exports are also found. In the short term, energy consumption, economic growth, exports, and imports exacerbate CO2 emissions. In the long-run, energy consumption positively influences CO_2 emissions, while economic growth and exports demonstrate a negative effect on CO_2 emissions.

The organization of this study is as follows: the second part includes a succinct empirical assessment of the existing literature. The third part identifies applied econometric strategies, which include the empirical model and dataset. The fourth part indicates the findings and their discussions. The last part provides a summary of this study, policy recommendations based on the study's findings, the limitations of the study, and recommendations for future research directions.

Literature Review

The environmental degradation related to air pollution literature is extensive. Therefore, to focus on more specific areas, the literature review of this study focuses on studies that are about the relationship between energy consumption and CO_2 emissions, between economic growth and CO_2 emissions, between exports and CO_2 emissions, and between imports and CO_2 emissions. The reason for selecting these relationships is to create parallelism with the employed variables in this study. Moreover, the selected studies in the literature review focus on the most recent studies, particularly those from the last five years, to ensure relevance in the environmental degradation literature.

Existing literature consists of studies that focus on the relationship between energy consumption and CO_2 emissions in different countries and country groups, yielding varying results. Some of these studies conclude with the positive impact of energy use on CO_2 emissions, such as the study by Raihan et al. (2022), which is based on Malaysia from 1990 to 2019, employing the autoregressive distributed lag (ARDL) model approach and the dynamic ordinary least squares (DOLS) method. Liu et al. (2023) studied China between 1995 and 2020 by using the pooled mean group (PMG-ARDL) approach and found the positive impact of energy use on CO_2 emissions. Gurbuz (2024) also focused on China over the period 1979 to 2013 by applying the vector error correction model (VECM) and the Granger causality tests, which observed that energy consumption increases air pollution measured by CO_2 emissions. On the other hand, regarding the European Union between 1995 and 2019, Li et al. (2023) found that, in their study focusing on the top five carbon-emitting countries, employing data from 1975 to 2015, there is a positive correlation between energy consumption and CO_2 emissions. On the other hand, in terms of the relationship between energy consumption and CO_2 emissions, Gurbuz (2022) focuses on China by employing the Granger causality test over the period 1971–2014. It is found that there is a bidirectional relationship between energy consumption and CO_2 emission.

Numerous substantial studies exist regarding the linkages between economic growth and CO_2 emissions. In this aspect, Kongkuah et al. (2022) focused on China by using VECM and observed the positive impact of GDP on CO2 emissions. Likewise, for Egypt, Raihan et al. (2023) employ DOLS with the data between 1990 and 2019 and found that economic growth stimulates CO2 emissions. For Malaysia, Raihan et al. (2022) applied DOLS through the data from 1990 to 2019 and observed that economic growth boosts CO_2 emissions. In the same parallel, Raihan (2023) also found an enhancing effect of economic growth on CO_2 emissions for Vietnam by utilizing ARDL and VECM employing data from 1984 to 2020. Similarly, Onofrei et al. (2022) observed the positive impact of economic growth on CO_2 emissions in 27 EU member states through the implementation of DOLS for the period 2000–2017. On the contrary, Mujtaba and Jena (2021) studied India by employing nonlinear ARDL over the period 1986 to 2014. They observed that economic growth decreases CO_2 emissions. Acheampong et al. (2022) observed that economic growth decreases CO_2 emissions, as found by the dynamic system-generalised method of moments. Namahoro et al. (2021) also found a negative impact of economic growth on CO_2 emissions in 50 African countries from 1980 to 2018. On the other hand, in terms of the relationship between economic growth and CO2 emissions, Adebayo and Akinsola (2021) found the bidirectional causality from GDP to CO_2 emissions in Thailand by employing Granger and the Toda-Yamamoto causality tests for the period 1971-2018.

Scholars have conducted empirical studies that observe the relationship between exports and CO_2 emissions, and between imports and CO_2 emissions. In this aspect, Mahmood et al. (2023) focused on twelve MENA economies by employing a spatial autoregressive model between 1995 and 2020 and observed that exports reduce consumption-based CO_2 emissions. Mahmood et al. (2020) also found the negative impact of exports on CO_2 emissions in five North African countries between 1990 and 2014. On the other hand, regarding Malaysia, Majekodunmi et al. (2023) found a positive effect of exports on CO_2 emissions from 1989 to 2019 by employing ARDL. In terms of causality between exports and CO_2 emissions, for Thailand, Anatasia (2015) investigated unidirectional Granger causality from exports to CO2 emissions over the period 1978 to 2008. Moreover, Aghasafari et al. (2021) studied the MENA region between 2002 and 2014 by implementing a spatial panel simultaneous equations model. It is found that there is a bilateral causality between exports and CO_2 emissions. Besides the linkages between exports and CO_2 emissions, Akerman, Forslid, and Prane (2024) investigated the Swedish manufacturing sector from 2004 to 2016 and found an adverse effect of imports on carbon intensity. Gao et al. (2025) employed an input–output model across 15 economies for 2014 and observed that there is a positive impact of imports on CO_2 intensity in the construction industry. Moreover, Bouznit and Pablo-Romero (2016) observed a positive effect of imports on CO_2 emissions in Algeria between 1970 and 2019 by employing ARDL. Mikayilov et al. (2020) also found a positive impact of imports on consumption-based CO_2 emissions in Azerbaijan over the period of 1995–2013. On the other hand, Mpeqa, Sun, and Beraud (2023) investigated the negative effect of imports on CO_2 emissions in 29 selected countries in the Belt and Road Initiative from 2008 to 2019 by applying STIRPAT modeling and cross-sectional analysis.

Methodology and Data

This empirical study is extracted annual data of Turkey between 1970 and 2023. Carbon dioxide emissions (CO_2) are used as the dependent variable to observe the level of environmental degradation. To measure the impact of energy consumption on other selected variables, energy use (EU) data is used. Export of goods and services (EXPORT) is also considered to observe its impact among the variables. Gross domestic product (GDP) is employed to analyze the effect on economic growth on considered variables. Regarding measuring the impact of imports (IMPORT) on variables, data on imports of goods and services is covered. All employed variables are extracted from the World Bank- World Development Indicators (WB-WDI). Notations, definitions, and their source are shown in Table 1.

Table 1: Notations and Sources of Variables

Notation	Definition	Source
CO2*	Carbon dioxide (CO_2) emissions (total)	WDI-WB
EU*	Energy use (kg of oil equivalent per capita)	WDI-WB
EXPORT*	Exports of goods and services (current US$)	WDI-WB
GDP*	GDP (constant 2015 US$)	WDI-WB
IMPORT*	Imports of goods and services (current US$)	WDI-WB

Note: *Denotes the logarithm form. WDI-WB indicates World Development Indicator-World Bank.

The empirical model of this study is based on the related literature, with some critical modifications in terms of the importance of selected variables. As the dependent variable, CO2 is chosen as a measure of environmental degradation in Turkey. The EU is considered a factor endowment structure of production in Turkey. Picking EXPORT and IMPORT is based on observing the impact of major international trade indicators of Turkey. EXPORT also shows the part of the total production and the comparative advantages of Turkey. GDP measures the level of development of Turkey, indicating its productivity. Hence, EU, EXPORT, GDP, and IMPORT are considered as independent variables in the empirical econometric model as below;

$$CO2 = f(EU, EXPORT, GDP, IMPORT) \quad (1)$$

The generalized and extended econometric model is;

$$CO2 = \alpha_0 + \alpha_1 EU + \alpha_2 EXPORT + \alpha_3 GDP + \alpha_4 IMPORT \quad (2)$$

Regarding the second (2) equation, α_0 presents the intercept of the model, while α_1, α_2, α_3, and α_4 indicate respectively the elasticity coefficients of EU, EXPORT, GDP, and IMPORT.

To test the stationarity of each variable, this study employs Phillips-Perron unit root test (Phillips and Perron, 1988), and Augmented Dickey–Fuller unit root test (Dickey and Fuller, 1981). The stationarity of the variables could provide robust cointegration. After Phillip-Perron (PP) and Augmented Dickey–Fuller (ADF) unit root tests, lag order is selected by the criterion of sequential modified LR test statistic (LR), final prediction error (FPE), Akaike information criterion (AIC), Schwarz information criterion (SC), and Hannan–Quinn information criterion (HQ). The Johansen cointegration test is then applied to determine the number of long-run equilibrium relationships among the variables. The critical values of trace and maximum eigen statistics of the Johansen cointegration test determine whether the null hypothesis accepts no cointegration connection between variables. If cointegration exists, the vector error correction model (VECM) model is developed as follows;

$$dCO2_t = c_1 + \sum_{i=1}^{n} \alpha_{1i} dCO2_{t-i} + \sum_{i=1}^{n} \beta_{1j} dEU_{t-j} + \sum_{i=1}^{n} e_{1l} dEXPORT_{t-l} + \sum_{i=1}^{n} \gamma_{1k} dGDP_{t-k} + \sum_{i=1}^{n} x_{1m} dIMPORT_{t-m} + \emptyset_1 ETC_{t-1} + \varepsilon_{1t} \quad (3)$$

$$dEU_t = c_2 + \sum_{i=1}^{n} \alpha_{2i} dEU_{t-i} + \sum_{i=1}^{n} \beta_{2j} dCO2_{t-j} + \sum_{i=1}^{n} e_{2l} dEXPORT_{t-l} + \sum_{i=1}^{n} \gamma_{2k} dGDP_{t-k} + \sum_{i=1}^{n} x_{2m} dIMPORT_{t-m} + \emptyset_2 ETC_{t-1} + \varepsilon_{2t} \quad (4)$$

$$dEXPORT_t = c_3 + \sum_{i=1}^{n} \alpha_{3i} dEXPORT_{t-i} + \sum_{i=1}^{n} \beta_{3j} dCO2_{t-j} + \sum_{i=1}^{n} e_{3l} dEU_{t-l} + \sum_{i=1}^{n} \gamma_{3k} dGDP_{t-k} + \sum_{i=1}^{n} x_{3m} dIMPORT_{t-m} + \emptyset_3 ETC_{t-1} + \varepsilon_{3t} \quad (5)$$

$$dGDP_t = c_4 + \sum_{i=1}^{n} \alpha_{4i} dGDP_{t-i} + \sum_{i=1}^{n} \beta_{4j} dCO2_{t-j} + \sum_{i=1}^{n} e_{4l} dEU_{t-l} + \sum_{i=1}^{n} \gamma_{4k} dEXPORT_{t-k} + \sum_{i=1}^{n} x_{4m} dIMPORT_{t-m} + \emptyset_4 ETC_{t-1} + \varepsilon_{4t} \quad (6)$$

$$dIMPORT_t = c_5 + \sum_{i=1}^{n} \alpha_{5i} dIMPORT_{t-i} + \sum_{i=1}^{n} \beta_{5j} dCO2_{t-j} + \sum_{i=1}^{n} e_{5l} dEU_{t-l} + \sum_{i=1}^{n} \gamma_{5k} dEXPORT_{t-k} + \sum_{i=1}^{n} x_{5m} dGDP_{t-m} + \emptyset_5 ETC_{t-1} + \varepsilon_{5t} \quad (7)$$

where c, α, β, e, γ, and x indicate the coefficients of the polynomials, and d presents the first differentiation. ETC_{t-1} denotes lagged error correction terms. n shows the optimal lag. ε_{1t}, ε_{2t}, ε_{3t}, ε_{4t}, and ε_{5t} illustrate disturbance terms. Each VECM equation (equations 3 to 7) describes the causality relationship from right to left of equality. If the null hypothesis (an example for equation 3, $H_0 = \beta_{1j} = e_{1l} = \gamma_{1k} = x_{1m}$) of an equation 3 to 7 is rejected, the short-run Granger causality relationship from right to left of equality is observed. Furthermore, $\emptyset_1$ indicates the error correction term that determines the change speed toward the CO_2 equilibrium. The variance decomposition method is also applied to compare the contributions of different variables to each other.

Results and Discussions

Descriptive statistics of the selected variables that are carbon dioxide emissions (CO2), energy use (EU), exports of goods and services (EXPORT), economic growth (GDP), and imports of goods and services (IMPORT) are shown in Table 2. The Kurtosis value of each variable is less than three. Since all the variables follow a normal distribution, we can assume that the concentration is lower than usual. The variables' distribution can be judged to be approximately symmetrical. Moreover, the visual representation of variables is shown in Figure 1.

Table 2: Descriptive Statistics

	CO2	EU	EXPORT	GDP	IMPORT
Mean	213.5425	1114.932	9.07E+10	4.63E+11	1.00E+11
Median	199.4795	1066.849	4.29E+10	3.75E+11	4.71E+10
Maximum	460.6554	1894.627	3.57E+11	1.26E+12	3.86E+11
Minimum	45.44920	497.0836	7.91E+08	1.16E+11	1.14E+09
Std. Dev.	126.4367	411.9004	1.02E+11	3.15E+11	1.12E+11
Skewness	0.469035	0.430588	0.979632	0.947493	0.946841
Kurtosis	1.951341	1.953493	2.750803	2.800310	2.621986
Jarque-Bera	4.454232	4.132799	8.776833	8.169404	8.390083
Probability	0.107839	0.126641	0.012420	0.016828	0.015070
Sum	11531.30	60206.32	4.90E+12	2.50E+13	5.42E+12
Sum Sq. Dev.	847270.1	8992081	5.56E+23	5.25E+24	6.62E+23
Observations	54	54	54	54	54

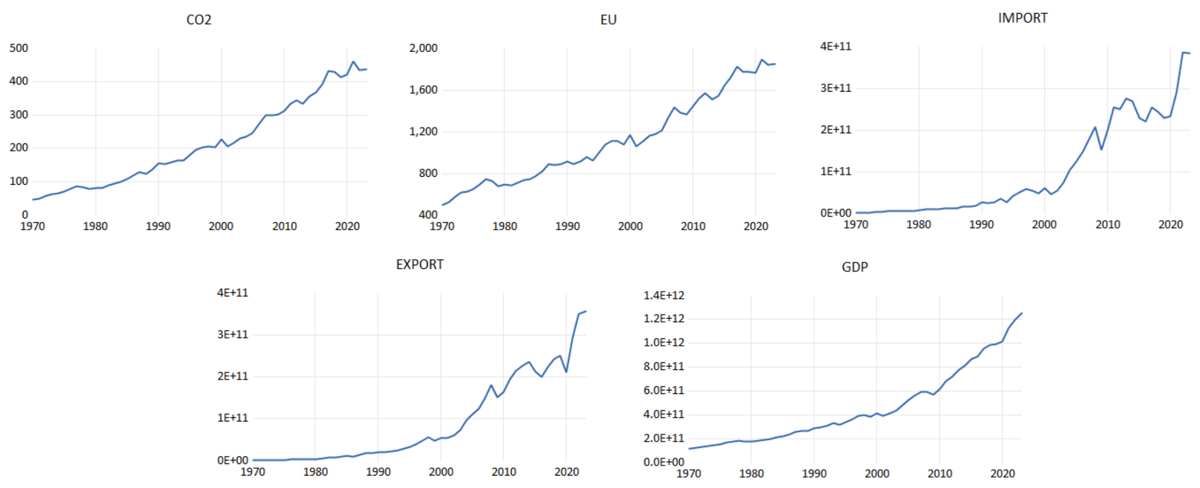

Figure 1: Line Graphs of the Variables

Before the Johansen cointegration test, the stationarity of the variables is tested by PP and ADF unit root tests, as in Table 3, to avoid spurious regressions. In terms of PP and ADF under all three specifications (with constant, with constant and trend, and without constant and trend) together, CO2, EU, EXPORT, GDP, and IMPORT are stationary at the first difference. Hence, all variables are stationary at I(1). Since all variables are stationary at I(1), all five variables are suitable for the Johansen cointegration test and VECM implementations. However, firstly, the optimal lag has to be selected.

Table 3: Results of the Augmented Dickey–Fuller and Phillips–Perron Unit Root Tests

Variable	Augmented Dickey–Fuller					
	Level			1st difference		
	Constant	Constant + Trend	None	Constant	Constant + Trend	None
CO2	-2.6032 (0.0987)*	-2.6649 (0.2549)	5.2109 (1.0000)	-6.7515 (0.0000)***	-7.2196 (0.0000)***	-4.7022 (0.0000)***
EU	-1.5302 (0.5107)	-4.0463 (0.0129)**	4.7199 (1.0000)	-7.3696 (0.0000)***	-7.5305 (0.0000)***	-5.5890 (0.0000)***
EXPORT	-2.8642 (0.0564)*	-1.6727 (0.7495)	5.5028 (1.0000)	-6.6223 (0.0000)***	-7.2468 (0.0000)***	-4.5001 (0.0000)***
GDP	0.2899 (0.9756)	-2.5305 (0.3129)	9.5693 (1.0000)	-7.0995 (0.0000)***	-7.0606 (0.0000)***	-3.7709 (0.0003)***
IMPORT	-2.2477 (0.1925)	-2.8542 (0.1854)	4.1612 (1.0000)	-7.0867 (0.0000)***	-7.3900 (0.0000)***	-5.6125 (0.0000)***
	Phillips–Perron					
	Level			1st difference		
	Constant	Constant + Trend	None	Constant	Constant + Trend	None
CO2	-2.3773 (0.1529)	-2.6649 (0.2549)	5.3821 (1.0000)	-6.7620 (0.0000)***	-6.2985 (0.0000)***	-2.5352 (0.0122)***
EU	-1.3899 (0.5804)	-3.9981 (0.0146)**	4.1239 (1.0000)	-7.1545 (0.0000)***	-7.1799 (0.0000)***	-5.6282 (0.0000)***
EXPORT	-2.4632 (0.1301)	-1.6727 (0.7495)	5.7343 (1.0000)	-6.6177 (0.0000)***	-7.2210 (0.0000)***	-4.4092 (0.0000)***
GDP	0.1979 (0.9700)	-2.5305 (0.3129)	8.2949 (1.0000)	-7.0506 (0.0000)***	-7.0085 (0.0000)***	-2.4034 (0.0171)***
IMPORT	-2.1280 (0.2348)	-2.8542 (0.1854)	4.1364 (1.0000)	-7.0870 (0.0000)***	-7.3758 (0.0000)***	-5.5089 (0.0000)***

Note: The significance values are represented as ∗∗∗(1%), ∗∗(5%), and ∗(10%). The parentheses represent the likelihood values.

Following the democratic multiplicity of the criteria to select optimal lag, the criteria are shown in Table 4. In terms of democratic multiplicity of the criteria, which include sequential modified LR test (LR), final prediction error (FPE), Akaike information criterion (AIC), Schwarz information criterion (SC), and Hannan-Quinn information (HQ), the optimal lag is selected as two.

Table 4: Lag Selection Criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	145.6940	NA	2.47e-09	-5.627760	-5.436557	-5.554949
1	402.5204	452.0144	2.34e-13	-14.90081	**-13.75360***	**-14.46395***
2	428.4223	**40.40699***	**2.33e-13***	**-14.93689***	-12.83367	-14.13597
3	444.0281	21.22389	3.67e-13	-14.56112	-11.50189	-13.39615
4	466.1025	25.60632	4.84e-13	-14.44410	-10.42885	-12.91507

Notes: ∗ indicates lag order selected by the criterion, (LR) sequential modified LR test statistic (each test at 5% level); (FPE) final prediction error; (AIC) Akaike information criterion; (SC) Schwarz information criterion; (HQ) Hannan–Quinn information criterion.

The Johansen cointegration test results, in Table 5, indicate that the null hypothesis is rejected at a 5% significance level in terms of trace and maximum eigenvalue statistics. Trace and maximum eigenvalue statistics confirm the existence of one cointegration relationship among variables. The results of the Johansen cointegration test prove that there is a long-run equilibrium relationship between CO2, EU, EXPORT, GDP, and IMPORT. This cointegration provides the viability of the VECM system.

Table 5: The Results of the Johansen Cointegration Test

	Trace Statistic		Maximum Eigen Value Statistic	
	Statistic	5% Critical Value	Statistic	5% Critical Value
None *	**71.78185***	69.81889	**34.01479***	33.87687
At most 1	37.76706	47.85613	18.05761	27.58434
At most 2	19.70945	29.79707	12.6197	21.13162
At most 3	7.089756	15.49471	7.046187	14.2646
At most 4	0.04357	3.841465	0.04357	3.841465

Note: *(5%) represents the significance values of statistics.

The employed variables are stationary at first difference as investigated by PP and ADF. On the other hand, Johansen cointegration test observed that there is one error correction term. Thus, the VECM could be implemented as in Table 6. Five model estimations of VECM show that they have sufficient explanatory power, with R-squared values of about 57, 49, 33, 26, and 21 percent, respectively. In terms of the long-run equilibrium cointegrating equation, an increase in EU raises CO2, while an increase in GDP and exports decreases CO2.

Table 6: Vector Error Correction Estimation Results

Error Correction:	D(CO2)	D(EU)	D(EXPORT)	D(GDP)	D(IMPORT)
ECT1	-0.19214 (0.03882) [-4.94915]**	-0.14921 (0.03486) [-4.28057]**	-0.30209 (0.12957) [-2.33154]	-0.05762 (0.03979) [-1.44811]**	-0.31585 (0.19246) [-1.64111]
D(CO2(-1))	0.134624 (0.23895) [0.56339]	0.035297 (0.21456) [0.16451]	-0.10984 (0.79751) [-0.13773]	0.024419 (0.24491) [0.09971]*	-0.48831 (1.18462) [-0.41221]
D(CO2(-2))	-0.78826 (0.24264) [-3.24867]	-0.5073 (0.21787) [-2.32846]	-1.08544 (0.80982) [-1.34035]	-0.47001 (0.24869) [-1.88993]	-1.39275 (1.2029) [-1.15783]
D(EU(-1))	0.358805 (0.33526) [1.07024]	0.370079 (0.30103) [1.22938]	1.690873 (1.11892) [1.51117]	0.272222 (0.34361) [0.79223]	2.081107 (1.66205) [1.25213]
D(EU(-2))	1.151549 (0.32932) [3.49671]	0.58399 (0.2957) [1.97492]	1.953913 (1.09912) [1.77771]	0.453709 (0.33753) [1.34419]	2.387106 (1.63263) [1.46212]
D(EXPORT(-1))	-0.18791 (0.05235) [-3.58922]*	-0.15087 (0.04701) [-3.20938]**	-0.21936 (0.17473) [-1.25541]	-0.13288 (0.05366) [-2.47637]*	0.052144 (0.25955) [0.20090]
D(EXPORT(-2))	0.048945 (0.05621) [0.87076]*	0.011903 (0.05047) [0.23583]*	-0.40013 (0.1876) [-2.13286]	1.10E-05 (0.05761) [0.00019]*	0.041901 (0.27866) [0.15036]
D(GDP (-1))	0.035229 (0.22046) [0.15980]	0.107107 (0.19795) [0.54107]	-1.86584 (0.73579) [-2.53583]	0.052337 (0.22596) [0.23163]	-1.85159 (1.09294) [-1.69413]
D(GDP (-2))	-0.35158 (0.22267) [-1.57895]	-0.16231 (0.19993) [-0.81182]	-0.80321 (0.74315) [-1.08083]	-0.20733 (0.22822) [-0.90846]	-1.38283 (1.10387) [-1.25270]
D(IMPORT(-1))	-0.04865 (0.04424) [-1.09982]**	-0.06443 (0.03972) [-1.62209]**	0.293206 (0.14763) [1.98602]	-0.01245 (0.04534) [-0.27466]**	-0.06493 (0.2193) [-0.29608]
D(IMPORT(-2))	0.02199 (0.04368) [0.50346]**	0.031426 (0.03922) [0.80131]**	0.139235 (0.14577) [0.95514]	0.076648 (0.04477) [1.71218]**	-0.04227 (0.21653) [-0.19523]
C	0.064341 (0.01393) [4.61722]**	0.042624 (0.01251) [3.40657]**	0.215379 (0.04651) [4.63103]**	0.061459 (0.01428) [4.30317]**	0.220447 (0.06908) [3.19105]*
R-squared	0.573007	0.495478	0.33715	0.268157	0.213507

Note: Standard errors in ( ) & t-statistics in [ ]. The significance values are represented as ***(1%), **(5%), and *(10%).

Diagnostic tests such as autocorrelation, normal distribution, and heteroskedasticity of residuals are employed to test the dependability and consistency of the model. The Lagrange Multipliers (LM) test statistic is 56.71053 at the second lag. The probability value of it is 0.2571. Therefore, it is confirmed that residuals are uncorrelated. The heteroskedasticity test of residuals expresses the validity of the homoscedasticity assumption with a value of $\chi 2$ of 342.4017, with a probability value of 0.3076. Doornik–Hansen normality test shows that the $\chi 2$ and probability values are 5.990661 and 0.8160, respectively. Therefore, any violation of the normality assumption cannot be found.

Based on VECM, the Granger causality test is performed, and the results are shown in Table 7. Moreover, Figure 2 illustrates the Granger causal relationships among employed variables. Bilateral causalities (1) between CO2 and EU, (2) between CO2 and EXPORT, (3) between EU and EXPORT, and (4) between GDP and EXPORT are observed in terms of the short-run Granger causality tests. Moreover, unidirectional causalities (1) from GDP to IMPORT, and (2) from IMPORT to EXPORT are found.

Table 7: Results of the Granger Causality Test

Variable	**Short-Run Causality**					
	D(CO2)	**D(EU)**	**D(EXPORT)**	**D(GDP)**	**D(IMPORT)**	**Results**
D(CO2)	----	12.80588 0.0017***	15.99352 0.0003***	2.498721 0.2867	1.469217 0.4797	EU > CO2, EXPORT > CO2
D(EU)	5.42173 0.0665*	----	11.33795 0.0035***	0.840039 0.6570	3.287711 0.1932	CO2 > EU, EXPORT > EU
D(EXPORT)	1.851484 0.3962	5.00376 0.0819*	----	8.600118 0.0136**	4.835798 0.0891*	EU > EXPORT, GDP > EXPORT, IMPORT > EXPORT
D(GDP)	3.573103 0.1675	2.262231 0.3227	6.491287 0.0389**	----	3.012269 0.2218	EXPORT > GDP
D(IMPORT)	1.587046 0.4522	3.405668 0.1822	0.051622 0.9745	5.18237 0.0749*	----	GDP > IMPORT

Note: The significance values are represented as ∗∗∗(1%), ∗∗(5%), and ∗(10%).

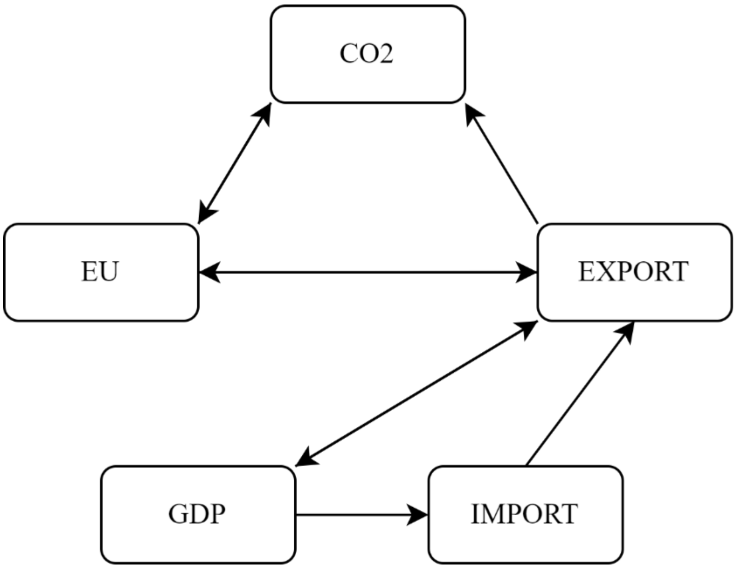

Figure 2: Short-Run Causality Directions

To examine the contributions of variables among each other and to compare their contributions, Table 8 indicates the results of the variance decomposition analysis. The contribution rate of EXPORT, GDP, and IMPORT on CO2 are, respectively, about 31%, 24%, and 11%, at the tenth period. On the other hand, the contribution rates of export and GDP to CO2 are, respectively, about 11% and 33% at the tenth period. The results also show that the explanatory power of the EU on GDP are about 17% at the tenth period. It is also observed that the explanatory power of EXPORT on IMPORT is about 33% at the tenth period.

Table 8: Results of Variance Decomposition Analysis

Period	S.E.	CO2	EU	EXPORT	GDP	IMPORT
Variance Decomposition of CO2						
1	0.037792	100.000000	0.000000	0.000000	0.000000	0.000000
2	0.051840	82.683770	3.341701	7.396901	5.897476	0.680152
3	0.056253	73.651420	3.934085	6.573746	15.159690	0.681055
4	0.063592	58.228710	3.247636	14.503250	22.897040	1.123363
5	0.070795	47.404210	3.149852	17.557560	26.735910	5.152469
6	0.075901	41.291620	3.209781	20.742180	26.664690	8.091724
7	0.080319	36.874160	3.544653	25.041060	25.466710	9.073420
8	0.084537	33.288720	4.255581	27.571180	24.858510	10.026010
9	0.088611	30.298380	4.835109	29.320210	24.695410	10.850890
10	0.092811	27.626390	5.273888	31.282350	24.462390	11.354970
Variance Decomposition of EU						
1	0.033934	65.882080	34.117920	0.000000	0.000000	0.000000
2	0.044938	55.786690	28.933420	7.787109	5.268923	2.223859
3	0.053983	39.554440	35.375450	5.480699	17.645930	1.943482
4	0.062923	29.332730	35.037330	7.694883	26.337360	1.597701
5	0.069078	24.875500	32.947850	8.490300	30.373670	3.312677
6	0.073193	22.388040	33.349030	8.942243	30.823980	4.496701

7	0.076395	20.596430	34.171050	10.008370	30.610010	4.614148
8	0.079359	19.144820	34.190640	10.635400	31.281750	4.747388
9	0.082432	17.802610	33.944170	10.965980	32.334990	4.952250
10	0.085531	16.572670	33.716270	11.510840	33.112020	5.088204
Variance Decomposition of GDP						
1	0.038734	20.017010	14.880870	6.500241	58.601880	0.000000
2	0.057372	20.961530	12.231830	3.245477	63.530120	0.031048
3	0.074456	14.809440	15.147300	2.012140	67.654790	0.376331
4	0.088668	11.379340	16.846870	3.650627	67.466400	0.656758
5	0.099495	10.246200	16.591450	4.108442	67.549500	1.504412
6	0.108072	9.679057	16.883960	4.011578	67.338770	2.086632
7	0.115348	9.185836	17.377740	4.145085	67.161360	2.129986
8	0.122455	8.845018	17.429060	4.187881	67.385700	2.152342
9	0.129520	8.584920	17.391060	4.113996	67.684940	2.225083
10	0.136239	8.334098	17.449340	4.113770	67.839200	2.263586
Variance Decomposition of IMPORT						
1	0.187355	19.520580	8.490383	12.730280	13.386100	45.872660
2	0.246974	14.886280	9.605503	15.237970	9.560188	50.710060
3	0.301077	10.025650	12.239140	19.836970	6.460378	51.437860
4	0.353591	7.594455	11.393060	25.258370	4.755695	50.998420
5	0.397790	6.238248	9.571694	27.725730	3.870732	52.593600
6	0.437452	5.354279	8.277718	29.292200	3.232801	53.843000
7	0.473883	4.755653	7.399778	30.955520	2.756013	54.133030
8	0.507636	4.327794	6.731710	32.101640	2.403815	54.435040
9	0.539588	4.033902	6.208472	32.916480	2.135259	54.705890
10	0.570433	3.824500	5.765133	33.704850	1.920176	54.785340

The results of the Granger causality test and Johansen cointegration test of this study have similarities with studies such as Raihan et al. (2022), Liu et al. (2023), and Gurbuz (2024) in terms of the positive impact of energy consumption on CO2 emissions in the short and long-run. Moreover, the findings have similarities with studies such as Kongkuah et al. (2022), Raihan et al. (2023), Raihan et al. (2022), Raihan (2023), and Onofrei et al. (2022) regarding the positive effect of economic growth on CO2 emission in the short-run.

The findings of this study also have similarities with Mahmood et al. (2020) regarding the negative impact of exports on CO2 emissions in the long run. On the other hand, the findings of the positive effect of exports on CO2 emissions in this study is supported by the study of Majekodunmi et al. (2023). On the other hand, the results of this study also have similarities with Mpeqa, Sun, and Beraud (2023) regarding the positive impact of exports on CO2 emissions in the short-run.

Conclusions and Policy Recommendations

The main aim of this study is to investigate the relationship between CO2 emissions, energy consumption, economic growth, exports, and imports in Turkey (Türkiye) over the period 1970 to 2023. Phillips-Perron and Augmented Dickey–Fuller unit root tests, Johansen cointegration test, VECM, the Granger causality test based on VECM, and the variance decomposition method are employed.

The empirical results prove the existence of one cointegration relationship among variables by implementing the Johansen cointegration test. In the context of the long-run equilibrium cointegrating equation, an increase in energy consumption elevates CO2 emissions, whereas economic growth and an increase in exports diminish CO2 emissions in Turkey. In terms of the Granger causality tests based on VECM, bilateral causality relationships between CO2 emissions and energy consumption, between CO2 emissions and exports, between energy consumption and exports, and between economic growth and exports are observed. Additionally, unidirectional causalities from economic growth to imports and from imports to exports are also found. In the short term, energy consumption, economic growth, exports, and imports exacerbate CO2 emissions. In the long term, energy consumption has a positive impact on CO2 emissions, whereas economic growth and exports exhibit a negative effect on CO2 emissions.

Regarding the crucial findings of this study, some policies that are parallel with the findings are recommended to policy makers in Turkey. Due to the positive effect of energy consumption on CO2 emissions, it is recommended to promote and subsidize energy-saving and/or energy-efficient production structures. Green economic growth strategies that could encourage low-emission production are advocated due to the positive impact of economic growth on CO2 emissions. Moreover, end-of-pipe technologies to reduce or eliminate carbon emissions should be encouraged to be applied. The Turkish government should also organize the regulations and laws to limit CO2 emissions for firms. Furthermore, the Turkish government should offer tax incentives and subsidies for firms, especially for exporters, that adopt low-emission production technologies.

Although this study makes crucial contributions and policy recommendations, it has some limitations. This study has significant contributions to the current literature regarding the results and policy recommendations. However, this study still has some limitations. Regarding the availability of the all selected data, the time period is limited from 1970 to 2023. Hence, the number of observations is limited. Another limitation of this study is that the variables employed in the research model have no city-level data. Future research directions should investigate the impacts of other countries, rather than Turkey, on trade-related indicators and environmental degradation in Turkey.

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