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THE RELATIONSHIP BETWEEN EXTERNAL DEBT AND ENVIRONMENTAL QUALITY IN TÜRKIYE: A FRACTIONAL FREQUENCY FOURIER ARDL BOUNDS TEST APPROACH

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Abstract

As efforts to achieve global sustainability goals intensify, it is increasingly important to understand the environmental consequences of countries' economic policies, particularly the impact of macroeconomic variables such as external debt. This study analyses the impact of Türkiye's external debt on environmental sustainability for 1970–2023 using the Fractional Frequency Fourier Autoregressive Distributed Lag (FFF-ARDL) method. Moreover, the variables of economic growth, renewable energy consumption (REN), and non-renewable energy (NREN) consumption were included in the model, and the Environmental Kuznets Curve (EKC) hypothesis was tested. Carbon dioxide (CO2) emissions were used as a proxy for environmental sustainability. The long-run coefficient findings indicate that increases in external debt reduce CO2 emissions, while economic growth initially increases emissions but then declines after a certain income threshold, confirming the EKC hypothesis. Moreover, REN energy consumption decreases CO2 emissions, whereas NREN energy consumption increases them. The Fourier Toda-Yamamoto test results indicate unidirectional causality running from CO2 emissions, REN, and external debt to NREN consumption. There is also unidirectional causality running from economic growth, REN, and NREN consumption to external debt. These findings suggest that Türkiye's external debt management and the transition toward REN sources are crucial for reducing CO2 emissions.

Keywords: *Environmental sustainability, economic growth, renewable energy consumption, external debt, fractional frequency fourier ARDL, Türkiye*

JEL codes: *Q53, Q56, F34, C22*

1. Introduction

As the devastating effects of climate change and environmental degradation become increasingly evident globally, sustainability has become a top priority on the international agenda. Considering the interaction between countries' economic growth models, financial structures, and environmental protection policies is vital. Developing and emerging market economies face the dilemma of preserving their natural assets and leaving an environmentally sound legacy for future generations while feeling compelled to achieve economic progress that enhances their populations' welfare (Baret and Menuet 2024).

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External borrowing has commonly financed these countries' economic development. However, recent scholarly studies (Akam et al. 2022; Bachegour and Qafas 2023; Carrera and de la Vega 2024; Saleem, Ahmed, and Samour 2024; Warsame, Dirie, and Nor 2024) have begun to question the potential negative environmental consequences of these financial strategies for environmental sustainability. These studies raise concerns that increasing external debt levels may lead to economic activities that intensify environmental pressure.

The link between the growing burden of external debt and environmental degradation is multifaceted and complex, requiring in-depth analysis. It can manifest through various transmission routes. One approach suggests that governments burdened by heavy external debt service obligations may be tempted to reduce public spending on environmental protection to redirect their limited fiscal space toward debt repayments or relax environmental standards to attract foreign investment and boost economic growth (Dong et al. 2018; Carrera and de la Vega 2024). Moreover, to generate the foreign currency inflows needed for external debt repayments, countries may resort to unsustainable and excessive exploitation of natural resources, including forests, minerals, and other natural assets, which can lead to serious ecological consequences, such as deforestation, soil erosion, water pollution, and irreversible biodiversity loss (Akam et al. 2022; Saleem, Ahmed, and Samour 2024). These mechanisms illustrate how economic pressures can lead to sacrificing long-term environmental health in search of short-term solutions. This perspective aligns with the debt overhang hypothesis, which posits that excessive debt burdens constrain fiscal capacity and distort investment priorities, often at the expense of environmental protection (Krugman 1988; Xu et al. 2022; Hu et al. 2024; Carrera and de la Vega 2024; Saleem, Ahmed, and Samour 2024).

Conversely, there is a different view that external financing flows can inherently support environmental sustainability; this perspective argues that environmental quality can be enhanced through the strategic use of external debt, particularly to accelerate the transition to renewable energy (REN) or to finance pollution-reducing infrastructure projects. However, whether this positive potential will be realised depends on the specific projects toward which debt resources are directed and how rigorously the environmental impacts of these investments are assessed. The fact that empirical studies generally depict that economic growth, at least in its initial stages, intensifies environmental pressures (Akam et al. 2022) further complicates the question of how external debt shapes environmental outcomes while simultaneously promoting economic growth. The Environmental Kuznets Curve (EKC) hypothesis provides a theoretical lens here, suggesting that environmental degradation follows an inverted U-shaped trajectory with respect to income levels: pollution rises during early growth phases but declines after a certain income threshold (Grossman and Krueger 1991, 1995). External debt can influence this trajectory by accelerating growth while potentially delaying the EKC turning point if debt-financed projects are environmentally harmful rather than green (Bachegour and Qafas 2023).

Furthermore, the Pollution Haven Hypothesis offers another important explanatory channel, arguing that countries with weaker environmental regulations may attract foreign direct investment (FDI) in polluting industries, a dynamic that can be indirectly reinforced by debt-driven liberalisation policies (Cole, Elliott, and Fredriksson 2006; Millimet and Roy 2016; Garsous and Kozluk 2017; Gill, Viswanathan, and Abdul Karim 2018; Dagar et al. 2022; Chiappini and Gerard 2025). Therefore, external borrowing may not only affect domestic fiscal choices but also shape the regulatory environment and investment patterns, thereby amplifying environmental risks in emerging economies.

Considering this global context and general trends, the case of Türkiye, which is both a dynamic emerging economy and is increasingly exposed to environmental pressures, deserves academic scrutiny. Türkiye has employed external borrowing as a strategic and widely used instrument to finance the rapid economic growth triggered by free-market-oriented reforms adopted in the 1980s. Factors such as global financial shocks, regional instability, and the country's domestic economic requirements have significantly increased Türkiye's external debt stock (EXTD) over time (Beşe and Friday 2022). This financing has generally facilitated investments in mega infrastructure projects, urbanisation, and the expansion of industrial capacity. However, this accelerated economic and physical transformation process also incurs environmental costs that cannot be overlooked. Türkiye faces serious environmental challenges, such as rapidly rising energy demand and a consequent increase in greenhouse gas emissions (Saleem Jabari, Aga, and Samour 2022), which may partly reflect the debt-financed growth model.

Empirical research in the Turkish context confirms the expected multifaceted and complex relationship between external debt accumulation and environmental sustainability. For instance, Beşe and Friday (2022) revealed that external debt can significantly impact environmental emissions and ecological footprints by influencing economic growth dynamics. Similarly, Saleem Jabari, Aga, and Samour (2022) examined the relationship between Türkiye's external debt levels and the country's adoption and consumption of REN sources. These and similar studies strongly suggest that external debt is not only a general macroeconomic variable but also a critical factor influencing a country's production structure and energy dependencies, and thus its overall environmental performance through both indirect and direct channels. Türkiye's continued heavy reliance on fossil fuels, despite its substantial REN potential (Saleem Jabari, Aga, and Samour 2022), underscores the need for a detailed and critical analysis of the role of external debt in the country's transition to a cleaner energy system.

The central research question of this study can be articulated as follows: "Whether Türkiye's accumulated EXTD has had a statistically significant impact on the country's environmental sustainability performance (CO_2) over the broad period between 1970 and 2023, and if so, what is the nature (positive or negative) and severity of this impact" In addition to this main enquiry, the study also addresses the direct or indirect effects of variables that may mediate the environmental consequences of debt accumulation, such as the pace of economic growth (GDP per capita and GDP per capita squared), and the use of REN and non-renewable energy sources (NREN) sources. Furthermore, the methodological framework of this study includes the identification and assessment of potential structural changes or breaks in the Turkish economy or environmental policies that may have occurred from 1970 to 2023, which could affect the analysis.

Focusing on the Turkish economy, this study utilises annual time series data covering the period from 1970 to 2023, a choice made considering the limitations arising from the availability of datasets. The analytical framework is based on a model with carbon dioxide (CO_2) emissions as the environmental indicator and economic growth (GDP and GDP^2), REN, NREN consumption, and EXTD accumulation as the main explanatory variables. To effectively capture potential long-run stable relationships and short-run dynamics among the variables, the methodological approach employed is the Fractional Frequency Fourier ARDL (FFF-ARDL), which is more robust to potential structural breaks in the series.

The following sections of the paper are organised as: In the next section, we provide a comprehensive review of the existing empirical literature on the relationship between external debt and the environment both internationally and in Türkiye. Next, the characteristics of the dataset used in the study are detailed, and the econometric methodology applied is explained according to scientific principles. In the fourth section, the findings of the econometric analyses are rigorously presented and interpreted. The final section summarises the main conclusions of the study, providing concrete implications and recommendations for policymakers and guiding suggestions for potential areas of future research.

2. Literature Review

The complex and multi-faceted relationship between economic growth, development processes, and efforts to protect the environmental health of the planet has recently become one of the most hotly debated topics in both economic literature and environmental science. Within this broader framework, external borrowing, which developing nations have extensively used to finance their development efforts, has attracted increasing academic attention for its effects on macroeconomic performance and its environmental consequences. This emerging literature focuses on gaining a deeper understanding of the mechanisms through which the accumulation of external debt can affect environmental quality directly or indirectly. The following section provides a closer look at the literature by summarising the main findings of key seminal and influential studies in this area.

Katircioglu and Celebi (2018) analysed the relationship between CO_2 emissions and EXTD using the ARDL method, drawing on data from Türkiye from 1960 to 2013. Their empirical results indicate a positive correlation between EXTD and CO_2 emissions, which is attributed to the idea that increasing debt stimulates investments and raises energy demand, thereby worsening environmental pollution.

In a study on China, Beşe, Friday, and Özden (2021a) investigated the link between CO_2 emissions and EXTD for 1984–2018 using an ARDL model. Their analysis demonstrated that, in addition to EXTD, energy consumption and economic growth also significantly and positively affect CO_2 levels. In another study, Beşe, Friday, and Özden (2021b) examined the effects of EXTD on CO_2, methane, and emissions from various fossil fuel consumptions in India for 1971-2012, again applying the ARDL technique. This study confirms the positive and significant effect of EXTD on CO_2 and finds an inverted U-shaped relationship between economic development and methane and gas fuel emissions.

Akam, Owolabi, and Nathaniel (2021) analysed the growth-energy-emissions relationship of 33 heavily indebted poor countries (HIPCs) from 1990 to 2015 using DCCE-MG, AMG, and CCE-MG estimators. Their empirical results revealed that economic growth negatively affects the environment by increasing CO_2 emissions, whereas REN promotes environmental sustainability by reducing CO_2 emissions. The study also found that EXTD contributes to higherCO_2 emissions. Akam et al. (2022) investigated the environmental impacts (CO_2 and ecological footprint [EF]) of EXTD in South Africa, Algeria, Nigeria, and Egypt (SANE) from 1970 to 2018 using the AMG method. Their findings demonstrate that economic growth and energy consumption increase environmental pressure, whereas EXTD increases the EF, particularly in South Africa and Algeria. This study also provides policy recommendations for reducing dependence on NREN.

Using the Bootstrap ARDL method for Türkiye, Xu et al. (2022) examined the dynamic effects of EXTD, energy use, and real income on the EF from 1985 to 2017. Their empirical analysis found that EXTD positively impacts environmental quality in both the short and long run, whereas energy consumption and real income have negative effects. This study recommends that Türkiye focus on debt consolidation programs to achieve long-term environmental sustainability goals. Beşe and Friday (2022) examined the relationships between CO_2, EF, GDP, and EXTD in Türkiye from 1970 to 2016 using the ARDL method. Their empirical findings show an inverted U-shaped relationship between CO_2 and EXTD, but not between EF and EXTD. They also concluded that GDP has a significant, long-run impact on the EF.

Samour and Adebayo (2022), evaluating the environmental quality of BRICS countries through the Load Capacity Factor (LCF), investigated the impact of EXTD and REN utilisation for 1990–2018 using MMQR, CCEMG, and AMG methods. Their analysis demonstrated that REN positively impacts LCF in the BRICS countries, whereas NREN, EXTD and GDP negatively affect LCF. Carrera and de la Vega (2024) examined the causal effect of EXTD on greenhouse gas emissions in 78 emerging and developing market economies from 1990 to 2015 using panel data analysis and found that EXTD increased emissions.

Sadiq et al. (2022) investigated the relationship between CO_2 emissions and EXTD for BRICS countries from 1990 to 2019 using CS-ARDL, CCEMG, and AMG methods and intriguingly found that EXTD supports environmental sustainability. This study suggests that the EXTD can positively promote ecological sustainability by financing green energy investments.

Farooq et al. (2023) examined the relationship between EXTD and ecological degradation (through indicators such as CO_2, NO_2, CH_4, EF, and WEF) in Organisation of Islamic Cooperation (OIC) countries for 1996–2018 using the panel GMM method. They concluded that increasing debt levels leads to greater ecological degradation. Alhassan and Kwakwa (2023) analysed the impact of EXTD on CO_2 emissions in Ghana from 1971 to 2018 using the FMOLS method and found that EXTD had a U-shaped effect on CO_2 emissions. Bachegour and Qafas (2023) analysed the relationship between EXTD and CO_2 emissions in Morocco from 1984 to 2018 using the ARDL model and found that EXTD has a significant negative effect on CO_2 emissions.

Warsame, Dirie, and Nor (2024) investigated the impact of EXTD and government expenditure on CO_2 emissions in Somalia from 1990 to 2019 using the ARDL, FMOLS, and DOLS methods. Their empirical findings report that increased EXTD and government expenditure lead to higher CO_2 emissions. The study suggests that debt and expenditures should be directed toward environmentally sustainable projects. Saleem, Ahmed, and Samour (2024) examined the impact of EXTD and REN on LCF in Brazil from 1970to 2021 using the A-ARDL method. They found that while REN positively affects ecological sustainability and growth by increasing LCF, an increase in EXTD negatively impacts ecological sustainability and growth by decreasing LCF.

Shamwil et al. (2024) examined the effects of EXTD, FDI, financial development, and REN on environmental sustainability in Nigeria from 1990 to 2022 using the ARDL method. Their empirical analysis concluded that EXTD, REN, and FDI improve environmental sustainability in both the short and long run, whereas financial development reduces environmental quality. This study recommends that Nigeria prudently manage EXTD and channel funds into REN investments. Finally, Yakubu and Aladejare (2025) investigated the impact of EXTD on ecological sustainability in 44 African countries from 1990 to 2020 using the CS-ARDL method and found that EXTD negatively affects ecological sustainability in the short and long run.

The varied empirical evidence in the literature suggests that the environmental consequences of external debt burdens can vary significantly depending on the country under study, the period of analysis, the econometric methods applied, and the set of specific variables included in the model. Although the general trend provides evidence that external debt exacerbates environmental degradation, some studies suggest that the strategic allocation of debt resources to "green" projects or under certain institutional and economic conditions can improve environmental quality. Previous research focusing on Türkiye also presents varied and sometimes contradictory results due to different periods and methodological approaches. This study investigates the complex interplay between

Table 1. Summary of Literature

Author(s) (Year)	Country/Region (Period)	Methodology	Result
Katırcıoğlu and Çelebi (2018)	Türkiye (1960–2013)	ARDL	EXTD increases CO2 emissions.
Beşe, Friday, and Özden (2021a)	China (1984–2018)	ARDL	EXTD, energy consumption, and GDP increase CO2 emissions.
Beşe, Friday, and Özden (2021b)	India (1971–2012)	ARDL	EXTD increases CO2 emissions; inverted U-shaped link for methane and gas fuel emissions.
Akam, Owolabi, and Nathaniel (2021)	33 HIPCs (1990–2015)	DCCE-MG, AMG, CCE-MG	GDP & EXTD increase CO2 emissions; REN reduces emissions.
Akam et al. (2022)	SANE (South Africa, Algeria, Nigeria, Egypt) (1970–2018)	AMG	GDP & energy use worsen environment; EXTD increases EF.
Xu et al. (2022)	Türkiye (1985–2017)	Bootstrap ARDL	EXTD improves environment; energy use & GDP worsen it.
Beşe and Friday (2022)	Türkiye (1970–2016)	ARDL	Inverted U-shape between CO2 emissions and EXTD; GDP affects EF.
Samour and Adebayo (2022)	BRICS (1990–2018)	MMQR, CCEMG, AMG	REN improves LCF; EXTD, GDP, NREN reduce LCF.
Sadiq et al. (2022)	BRICS (1990–2019)	CS-ARDL, CCEMG, AMG	EXTD supports environmental sustainability via green financing.
Farooq et al. (2023)	OIC (1996–2018)	Panel GMM	EXTD increases ecological degradation.
Alhassan and Kwakwa (2023)	Ghana (1971–2018)	FMOLS	EXTD has a U-shaped effect on CO2 emissions.
Bachegour and Qafas (2023)	Morocco (1984–2018)	ARDL	EXTD reduces CO2 emissions.
Carrera and de la Vega (2024)	78 Emerging & Developing Economies (1990–2015)	Panel Causality	EXTD increases greenhouse gas emissions.
Warsame, Dirie, and Nor (2024)	Somalia (1990–2019)	ARDL, FMOLS, DOLS	EXTD & government spending increase CO2 emissions.
Saleem, Ahmed, and Samour (2024)	Brazil (1970–2021)	A-ARDL	REN increases LCF; EXTD decreases LCF.
Shamwil et al. (2024)	Nigeria (1990–2022)	ARDL	EXTD, REN, FDI improve sustainability; financial development harms it.
Yakubu and Aladejare (2025)	44 African countries (1990–2020)	CS-ARDL	EXTD negatively affects ecological sustainability.

external debt accumulation, economic growth performance, energy consumption patterns, and environmental sustainability indicators in Türkiye from 1970 to 2023. To perform this analysis, we adopted the FFF-ARDL econometric approach, which offers more robust and reliable results owing to its ability to incorporate potential structural breaks and nonlinear trends into the model. This methodological choice constitutes a contribution to the literature, aiming to clarify the diverging findings in existing studies through a comprehensive analysis over this extended period in Türkiye.

3. Data and Methodology

This study aims to analyse the long-run relationship between external debt and environmental quality and the dynamics of this relationship between 1970 and 2023 in Türkiye. The FFF-ARDL Bound Test approach was used as the analytical method. CO_2 emissions, representing environmental quality, are designated as the dependent variable, while external debt is the main independent variable. Economic growth and REN consumption were included in the model as the control variables. The analyses were carried out using economic software packages (EViews and WinRATS), with logarithmic transformations applied to the variables. Economic growth, REN consumption, and NREN consumption were included in the model as control variables.

$$CO2 = f\ (GDP, GDP^2, REN, NREN, EXTD) \quad (1)$$

The study model is presented in Equation (2) and is inspired by Beşe and Friday (2022) and Akam et al. (2022).

$$lnCO2_t = \beta_0 + \beta_1 lnGDP_t + \beta_2 lnGDP_t^2 + \beta_3 lnREN_t + \beta_4 lnNREN_t + \beta_5 lnEXTD_t + \varepsilon_t \quad (2)$$

Among the variables in the model, CO_2 represents carbon dioxide emissions (metric tons per capita), GDP represents economic growth (GDP per capita, constant 2015 US$), GDP^2 represents the square of economic growth (GDP per capita, constant 2015 US$), REN represents REN consumption (kWh per capita), NREN represents primary energy consumption per capita (kWh per capita), EXTD represents external debt (% of GDP), and ε_t represents the error term. Table 2 provides descriptions and data sources for these variables.

In time series analyses, structural breaks can undermine the reliability of traditional cointegration tests and even the standard ARDL bounds test (Pesaran, Shin, and Smith 2001). To overcome this potential problem and to examine the relationship between variables on a more robust basis, the FFF-ARDL bounds test method, which models structural breaks through Fourier functions (Becker, Enders, and Lee 2006; Enders and Lee 2012; Omay 2015) and operates within the ARDL framework (Yilanci, Bozoklu, and Gorus 2020), is preferred. This method offers the advantages of flexibly modelling structural breaks and working with series at different levels of stationarity (Enders and Lee 2012; Omay 2015; Yilanci, Bozoklu, and Gorus 2020; Syed, Apergis, and Goh 2023; Apergis, Degirmenci, and Aydin 2023).

The method is based on the ARDL bounds testing approach (Pesaran, Shin, and Smith 2001), which is characterised by its applicability regardless of whether the variables h are integrated of order I(0) or I(1). The main innovation of the FFF-ARDL bounds testing approach is the addition of low-frequency Fourier sine and cosine terms $\left[\gamma_1 sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 cos\left(\frac{2\pi kt}{T}\right)\right]$ to the deterministic components (constant term and/or trend) of the ARDL model (Enders and Lee 2012). These trigonometric terms can capture potential structural breaks in series with abrupt or smooth transitions without prior knowledge of the timing, number or form of the breaks. In this way, the approach aims to prevent forecast biases arising from ignoring structural changes and to increase the statistical power of the test (Yilanci, Bozoklu, and Gorus 2020; Georgescu and Kinnunen 2024).

Another distinguishing feature of the method is that fractional values are considered when determining the frequency parameter (k) used in the Fourier approach. Generally, the value of k (k*) that minimises the Akaike Information Criterion (AIC) (Akaike 1979) or the Sum of Residual Squares within the range k (0.1, 0.2, ..., 5) is chosen as the optimum frequency. A fractional value of k* indicates that the structural change in the series is permanent, whereas a whole number indicates that the change is temporary. This feature is important because it provides additional information about the nature of the structural break (Yilanci, Bozoklu, and Gorus 2020). Equation 3 presents the equation for this test.

Table 2. Variable Descriptions and Data Sources

Variable	Symbols	Description	Data Source
Carbon Emissions	CO_2	Metric tons per capita	World Bank
Economic Growth	GDP	GDP per capita (constant 2015 US$)	World Bank
Economic Growth Squared	GDP^2	Square of GDP per capita (constant 2015 US$)	Calculated by the author.
Renewable Energy	REN	Renewable energy consumption (kWh per capita)	International Energy Agency
Non-Renewable Energy	NREN	Primary energy consumption per capita (kWh per capita)	International Energy Agency
External Debt	EXTD	External Debt to GDP ratio (%)	World Bank

$$\Delta lnCO2_t = \alpha_0 + \gamma_1 sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 cos\left(\frac{2\pi kt}{T}\right) + \Sigma_{i=1}^{k}\beta_i \Delta lnCO2_{t-i} + \Sigma_{i=1}^{l}\gamma_i \Delta lnGDP_{t-i} + \Sigma_{i=1}^{m}\delta_i \Delta lnGDP_{t-i}^2 + \Sigma_{i=1}^{n}\varphi_i \Delta lnREN_{t-i} + \Sigma_{i=1}^{o}\phi_i \Delta lnNREN_{t-i} + \Sigma_{i=1}^{p}¥_i \Delta lnEXTD_{t-i} + \lambda_1 \Delta lnCO2_{t-1} + \lambda_2 \Delta lnGDP_{t-1} + \lambda_3 \Delta lnGDP_{t-1}^2 + \lambda_4 \Delta lnREN_{t-1} + \lambda_5 \Delta lnNREN_{t-1} + \lambda_6 \Delta lnEXTD_{t-1} + \varepsilon_t \quad (3)$$

Considering the terms of Equation (3), α_0 is the coefficient of the constant term. The coefficients λ_1, λ_2, λ_3, λ_4, λ_5, *and* λ_6 capture the effects of the one-period lagged levels of the variables used in the analysis. The coefficients β_i, γ_i, δ_i, φ_i, ϕ_i, and $¥_i$ correspond to the lagged differences of the $lnCO_2$, lnGDP, $lnGDP^2$, lnREN, lnNREN, and lnEXTD variables, respectively. In addition, for the Fourier component, π is a constant approximately equal to 3.14, "k" is the number of selected frequencies, "t" represents the time trend, and "T" is the total number of observations (Yilanci, Bozoklu, and Gorus 2020).

Similar to the standard ARDL test, the existence of a cointegration relationship is assessed through the significance of the coefficients of the lagged level variables in the model. However, because of the presence of Fourier terms in the FFF-ARDL bounds test model, the standard critical values presented by Pesaran, Shin, and Smith (2001) cannot be applied. Instead, special critical values derived from bootstrap simulations are employed to enhance the power and reliability of the test (McNown, Sam, and Goh 2018; Sam, McNown, and Goh 2019). Three main hypotheses were tested using this approach.

[i] H_0: Coefficients of the lagged level variables are jointly zero (F_A statistic),

[ii] H_0: The lagged level coefficient of the dependent variable is zero (t-statistic) and

[iii] H_0: The lagged level coefficients of the independent variables are jointly zero (F_B statistic)

To confirm the existence of a cointegration relationship among the variables, all three calculated F_A, t-statistic, and F_B test statistics should exceed the relevant critical values (considering their absolute values) obtained via the bootstrap method. This implies the rejection of the three main null hypotheses of the study. If this condition is met, the long-run and short-run coefficients of the model can be estimated, and the dynamic relationships between the variables can be interpreted in detail (McNown, Sam, and Goh 2018; Sam, McNown, and Goh 2019).

The Fourier Toda-Yamamoto causality test was proposed by Nazlıoğlu, Gormus, and Soytas (2016). This test offers a significant improvement over the traditional approach by incorporating structural changes into the Vector Autoregression (VAR) model (Sims 1980). It also extends the constant term assumption, allowing Fourier terms to be added to explanatory variables. This feature enables the integration of both gradual and smooth structural breaks into the model (Nazlıoğlu, Gormus, and Soytas 2016). The mathematical representation of the Fourier Toda-Yamamoto causality test is presented in Equation (4) below.

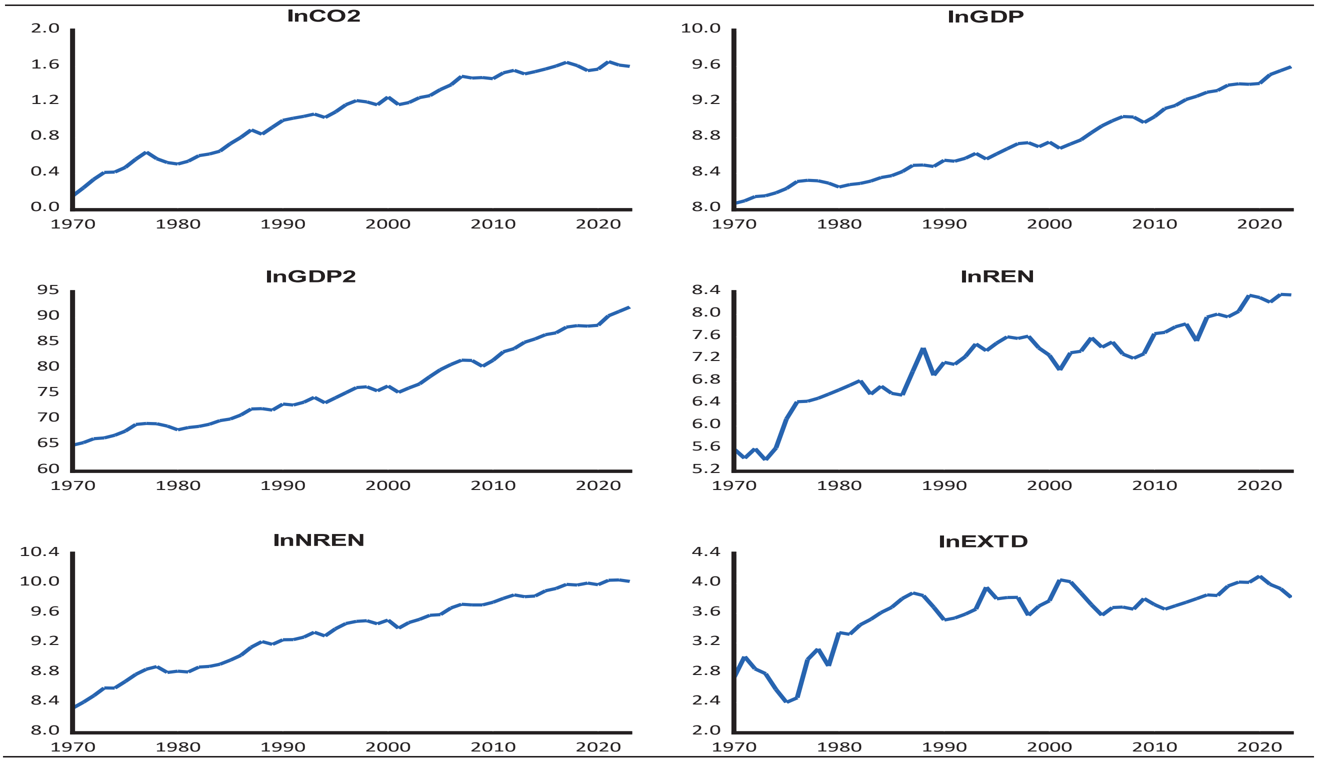
$$y_t = \alpha_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \beta_1 y_{t-1} + \dots + \beta_{p+d}\, y_{t-(p+d)} + \varepsilon_t \quad (4)$$

Table 3. Descriptive Statistics

	$lnCO_2$	lnGDP	$lnGDP^2$	lnREN	lnNREN	lnEXTD
Mean	1.069	8.734	76.47	7.164	9.348	3.570
Median	1.17	8.678	75.315	7.306	9.427	3.690
Maximum	1.653	9.597	92.093	8.36	10.048	4.101
Minimum	0.15	8.063	65.018	5.389	8.325	2.400
Std. Dev.	0.44	0.438	7.715	0.761	0.485	0.425
Skewness	–0.351	0.368	0.429	–0.626	–0.302	–1.281
Kurtosis	1.857	1.96	2.007	2.942	2.014	3.735
JB	4.048	3.651	3.874	3.533	3.006	3.422
Prob.	0.132	0.161	0.144	0.171	0.222	0.180
Observations	54	54	54	54	54	54

Source: Author calculations.

Chart 1. General Course of Variables in the 1970-2023 Period (Logarithmic)



In Equation (4), k represents the selected frequency, t is the deterministic trend, T is the total number of observations, p is the lag length obtained from the VAR model, d is the maximum order of integration of the variables and represents the residuals (Nazlıoğlu, Gormus, and Soytas 2016).

Before presenting the results of the FFF-ARDL bounds test, descriptive statistics summarising the distributional characteristics of the variables such as $lnCO_2$, lnGDP, $lnGDP^2$,lnREN, lnNREN, and lnEXTD were analysed and reported in Table 3. The mean values were 1.069 ($lnCO_2$), 8.734 (lnGDP), 7.164 (lnREN), 9.348 (lnNREN), and 3.570 (lnEXTD), and their proximity to the medians indicates that the distributions were generally symmetrical. $lnCO_2$ exhibits the highest volatility based on its standard deviation, whereas lnGDP and lnEXTD appear to be relatively more stable. The skewness values reveal that $lnCO_2$, lnREN, and lnNREN are left-skewed, lnGDP is slightly right-skewed, and lnEXTD is strongly left-skewed (– 1.281). The kurtosis values indicate that lnEXTD has the sharpest distribution (3.735), suggesting the potential presence of outliers. The Jarque-Bera (JB) test statistics and corresponding probability values confirm that none of the variables fail to reject the null hypothesis of normality at the 5% significance level, implying that the data are approximately normally distributed and suitable for econometric analysis with minimal outlier influence.

4. Empirical Results

The first step prior to presenting the FFF-ARDL bounds test findings is to determine the stationarity properties of the time series data used in the study. Structural breaks inherent in economic data may affect the results of the stationarity tests. Therefore, this analysis used methods that account for both structural breaks and standard unit root tests. The Augmented Dickey-Fuller (ADF) test, developed by Dickey and Fuller (1979, 1981), was applied for a traditional stationarity assessment. The Zivot-Andrews (ZA) unit root test proposed by Zivot and Andrews (1992) was used to test for the presence of single endogenously determined structural breaks. Moreover, the Fourier ADF test proposed by Christopoulos and León-Ledesma (2010) was included to capture potentially more complex or smoother structural changes. The unit root test results obtained from these different approaches provide comprehensive preliminary information on the degree of integration in the series. The results of the ADF test are presented in Table 4, while the results of the Fourier ADF and ZA tests, which account for structural breaks, are presented in detail in Tables 5 and 6. Each test provides a different perspective that enhances the reliability of the conclusions regarding the stationarity of the series.

Table 4. ADF Unit Root Test Results

	Level		1. Difference	
Variables	Constant	Constant & Trend	Constant	Constant & Trend
$lnCO_2$	–2.327 (0.167)	–2.162 (0.499)	–6.564 (0.000)***	–6.068 (0.000)***
lnGDP	0.884 (0.995)	–1.545 (0.801)	–6.908 (0.000)***	–7.035 (0.000)***
lnGDP2	1.179 (0.997)	–1.263 (0.886)	–6.807 (0.000)***	–7.027 (0.000)***
lnREN	–1.500 (0.526)	–2.870 (0.180)	–8.504 (0.000)***	–8.504 (0.000)***
lnNREN	–2.239 (0.195)	–3.210 (0.093)*	–7.461 (0.000)***	–7.784 (0.000)***
lnEXTD	–2.052 (0.264)	–2.123 (0.521)	–7.178 (0.000)***	–7.145 (0.000)***

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% significance levels, respectively.

Source: Author's calculations.

Table 5. Fourier ADF Unit Root Test Results

	Constant				Constant&Trend			
Variables	MinSSR	Frequency (k)	Test Statistics	F Test Statistics	MinSSR	Frequency (k)	Test Statistics	F Test Statistics
$lnCO_2$	3.679	1	–1.437	45.587***	0.192	1	–3.733	24.150***
lnGDP	4.197	1	–0.602	36.146***	0.098	1	–3.610	50.864***
$lnGDP^2$	1311.362	1	–0.542	35.841***	30.495	1	–3.992	67.078***
lnREN	19.755	1	–1.441	14.078***	1.931	1	–4.142	33.700***
lnNREN	5.31	1	–1.288	34.266***	0.17	1	–3.592	17.529***
lnEXTD	5.986	1	–1.621	15.316***	1.665	1	–4.314	31.550***

Note: ***, **, and * denote statistical significance at 1%, 5%, and 10% significance levels, respectively. The critical values for the FADF test were –4.43, –3.85, and –3.52 (constant) and –5.11, –4.46, and –4.15 (constant & trend) at the 1%, 5%, and 10% levels, respectively. For the F-test, the corresponding critical values were 6.730, 4.929, and 4.133 (constant) and 6.873, 4.972, and 6.873 (constant and trend).

Source: Author's calculations.

Table 6. ZA Unit Root Test Results

	Level		1. Difference	
	Model A	Model C	Model A	Model C
Variables	(Constant Breaking)	(Constant & Trend Breaking)	(Constant Breaking)	(Constant & Trend Breaking)
$lnCO_2$	–3.600 (B: 1985)	–3.750 (B: 2007)	–6.332*** (B: 1984)	–6.984*** (B: 1981)
lnGDP	–3.116 (B: 2011)	–4.074 (B: 1999)	–5.638*** (B: 2004)	–7.374*** (B: 1981)
$lnGDP^2$	–2.906 (B: 2011)	–4.108 (B: 1999)	–7.310*** (B: 2003)	–7.313*** (B: 1981)
lnREN	–4.388 (B: 1999)	–4.441 (B: 1999)	–8.917*** (B: 2009)	–8.817*** (B: 2009)
lnNREN	–4.409 (B: 1986)	–4.215 (B: 1987)	–8.651*** (B: 1982)	–8.248*** (B: 1979)
lnEXTD	–4.524 (B: 1980)	–4.467 (B: 1980)	–7.299*** (B: 1988)	–5.612*** (B: 1988)
Critical Values	Model A:		Model C:	
	1% [–5.34], **5%** [–4.93], **10%** [–4.58]		**1%** [–5.57], **5%** [–5.08], **10%** [–4.82]	

Note: ***, **, and * denote statistical significance at 1%, 5%, and 10% significance levels, respectively.

Source: Author's calculations.

Table 7. Lag Selection Criteria Result

Lag	LogL	LR	FPE	AIC	SC	HQ
0	238.6534	NA	3.66E-12	−9.30614	−9.07669	−9.21876
1	**522.0548**	**487.4505***	**1.86e-16***	**−19.20219***	**−17.59609***	**−18.59058***
2	540.7601	27.68382	3.96E-16	−18.5104	−15.5277	−17.3746
3	574.2892	41.57604	5.17E-16	−18.4116	−14.0522	−16.7515
4	611.7608	37.47162	6.93E-16	−18.4704	−12.7344	−16.2861

Source: Author's calculations.

The findings from the unit root tests applied in this analysis provide important information regarding the stationarity levels of the lnCO_2, lnGDP, lnGDP^2, lnREN, lnNREN, and EXTD time series for Türkiye. When the results of the standard ADF test (Table 4), the Fourier ADF test considering structural breaks and nonlinear components (Table 5), and the ZA test identifying single structural breakpoints (Table 6) are evaluated together, all series are non-stationary at levels. Therefore, the findings from these three different unit root tests reveal a common view that the variables are stationary at the first-difference level. Defining the variables as I(1) satisfies the fundamental assumptions of the FFF-ARDL bounds test model used in this study and enables the analysis of long-run cointegration relationships.

According to the lag selection criteria presented in Table 7, the optimal lag length for the model was determined to be one, based on all the criteria (LR, FPE, AIC, SC, and HQ).

There are various reasons why the FFF-ARDL bounds test approach is preferred to examine the long-run relationships among series. One of the main advantages of this method is that, unlike classical cointegration tests, it allows the variables used in the analysis to have different orders of integration, that is, both I(0) and I(1). Moreover, the "FFF-ARDL" component of the method enables the incorporation of smooth and/or multiple structural breaks into the analysis. It is critical not to ignore such breaks, which are common in economic and environmental time series and can be caused by significant policy changes, global shocks, or other structural transformations over time, to obtain more reliable and robust coefficient estimates that accurately reflect the true long-run dynamics between variables (Aliyev et al. 2024; Aliyev and Eylasov 2025). The FFF-ARDL approach provides a more robust analysis of the long-run link between external debt and environmental quality by considering the complex relationships and effects of possible structural changes over the study period.

The FFF-ARDL bounds test results presented in Table 8 strongly confirm the existence of a long-run cointegration relationship among the variables used in the model. The findings indicate a long-run equilibrium relationship between the variables at a high statistical significance level of 1%. This finding is supported by the calculated test statistics: F_A statistic (26.094), t- (−10.714), and F_B (29.839) statistics. Each value significantly exceeds the critical values obtained via the bootstrap method (including being more negative in absolute value for the t-statistic) at all conventional significance levels. For instance, the F_A statistic of 26.094 is far above the 1% critical upper bound (5.977), and the t-statistic of −10.714 is much lower than the 1% critical value (−5.13), confirming strong evidence against the null hypothesis of no cointegration. Similarly, the F_B statistic of 29.839 exceeds the 1% upper bound (5.67) by a large margin. This provides the conditions for rejecting the null hypothesis (no cointegration relationships). Thanks to the inclusion of the Fourier component in the model, which successfully controls for possible structural breaks and nonlinearities, this study identifies a statistically strong and significant long-run relationship between these variables. Hence, the FFF-ARDL bounds test findings confirm the existence of a persistent cointegration structure among the series.

The results of the various Diagnostic Tests conducted to assess the statistical power and reliability of the model are presented in Table 8 (Diagnostic Tests section). These findings support the validity and robustness of the estimated FFF-ARDL model. Specifically, the JB test confirms that the residual terms satisfy the assumption of a normal distribution (JB statistic = 0.645 and p = 0.724). The Breusch-Godfrey Lagrange Multiplier (BG-LM) test indicates that there is no serial correlation problem in the model (BG-LM statistic = 0.669, and p = 0.517). The Harvey test, which assesses heteroskedasticity, revealed a constant variance in the model's residuals (Harvey statistic = 1.392 and p = 0.213), indicating no issues with changing variance. Moreover, the Ramsey RESET (RR) test results confirm that the model has the correct functional form (RR

Table 8. FFF-ARDL Bounds Cointegration Test Results

Lag Length	Frequency (k)	F_A		t-Statistic		F_B	
1, 0, 1, 0, 0, 1	1.8	26.094***		−10.714***		29.839***	
	Critical Values	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
	1%	4.608	5.977	−3.96	−5.13	3.42	5.67
	5%	3.442	4.69	−3.41	−4.52	2.4	4.19
	10%	2.927	4.068	−3.13	−4.21	1.98	3.51
Diagnostic Tests							
Tests		t-Statistic			Prob.		
JB		0.645			0.724		
BG-LM		0.669			0.517		
Harvey		1.392			0.213		
RR		0.71			0.482		
Cusum: Stability				**CusumSq:** Stability			

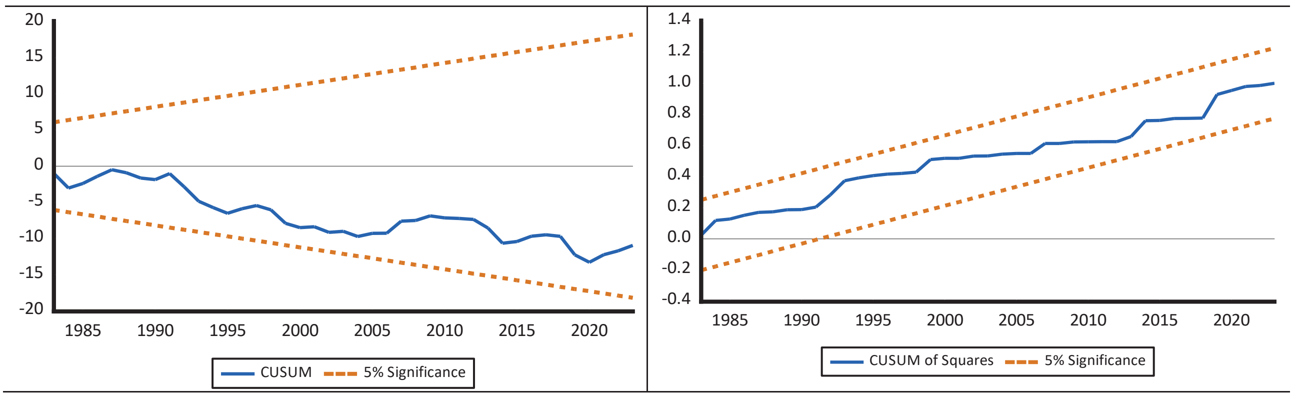
Note: ***, **, and * denote statistical significance at 1%, 5%, and 10% significance levels, respectively.

Source: Author's calculations.

statistic = 0.710, p = 0.482). The graphs of the CUSUM and CUSUM of Squares (CusumSq) tests, which evaluate the stability of the coefficients over time and the presence of structural breaks, remain within the critical limits, indicating that the model coefficients are stable and that there are no significant structural breaks during the analysis period. The positive results of these comprehensive diagnostic tests demonstrate that the estimated model is statistically appropriate and suitable for making reliable inferences.

The long-run coefficient results of the FFF-ARDL bounds test in Table 9 confirm the validity of the EKC hypothesis in Türkiye. The positive and significant coefficient of lnGDP (5.976) and the negative and significant coefficient of $lnGDP^2$ (−0.336) at the 1% level indicate that CO_2 emissions initially increase with economic growth but decline after the income threshold is reached. Renewable energy use (lnREN) has a negative and highly significant effect (−0.134), reducing emissions, whereas non-renewable energy consumption (lnNREN) has a positive and significant impact (0.791), increasing environmental degradation. External debt (lnEXTD) also exhibits a negative and significant coefficient (−0.082), suggesting that higher debt may indirectly limit emissions. The error correction term (CointEq(−1)) is strongly significant (−0.994), implying that approximately 99.4% of short-run deviations are corrected in the next period, ensuring rapid convergence to the long-run equilibrium. Overall, these findings indicate that Türkiye's economic growth

Figure 1. Cusum and Cusumsq Graphs



Source: Author's calculations.

Table 9. FFF-ARDL Coefficient Results

Model: $lnCO_2 = f(lnGDP, lnGDP^2, lnREN, lnNREN, lnEXTD)$				
Long-Run Coefficient				
Variables	Coefficient	Std. Error	t-Statistic	Prob.
lnGDP	5.976	1.22	4.898	0.000***
$lnGDP^2$	–0.336	0.062	–5.350	0.000***
lnREN	–0.134	0.016	–8.194	0.000***
lnNREN	0.791	0.116	6.821	0.000***
lnEXTD	–0.082	0.022	–3.726	0.000***
Short-Run Coefficient				
Variables	Coefficient	Std. Error	t-Statistic	Prob.
$D(lnGDP^2)$	–0.319	0.024	–13.203	0.000***
D(lnEXTD)	–0.007	0.017	–0.411	0.682
COS	0.001	0.003	0.111	0.911
SIN	–0.032	0.004	–7.734	0.000***
CointEq(-1)	–0.994	0.065	–15.195	0.000***

Note: ***, **, and * denote statistical significance at the 1, 5, and 10% significance levels, respectively.

Source: Author's calculations.

initially worsens environmental quality but eventually improves it as income rises, while promoting REN and managing external debt play crucial roles in reducing emissions. Conversely, dependence on NREN remains a major driver of environmental degradation, highlighting the need to transition to cleaner energy sources to achieve sustainable development.

According to the Fourier Toda-Yamamoto causality test results presented in Table 10, a unidirectional causality relationship was observed between CO_2 emissions and NREN consumption. Furthermore, significant causality relationships were identified between REN consumption and external debt to NREN consumption. Furthermore, a unidirectional causality relationship was found between economic growth, REN and NREN consumption, and external debt. These findings reveal a complex interaction between the energy consumption structure and financial dynamics (especially external debt) in the Turkish economy, which directly or indirectly affects environmental quality.

Table 10. Fourier Toda-Yamamoto Causality Test Results

H_0 Hypothesis	W-Statistics	Bootstrap Prob.	Frequency (k)
$lnGDP => lnCO_2$	1.215	0.278	0.6
$lnREN => lnCO_2$	0.356	0.554	0.6
$lnNREN => lnCO_2$	0.406	0.522	0.6
$lnEXTD => lnCO_2$	0.022	0.884	0.6
$lnCO_2 => lnGDP$	1.452	0.236	0.6
lnREN => lnGDP	1.491	0.228	0.6
lnNREN => lnGDP	0.612	0.437	0.6
lnEXTD => lnGDP	2.468	0.127	0.6
$lnCO_2 => lnREN$	1.298	0.263	0.6
lnGDP => lnREN	0.135	0.717	0.6
lnNREN => lnREN	0.022	0.891	0.6
lnEXTD => lnREN	1.985	0.157	0.6
$lnCO_2 => lnNREN$	7.817	0.006***	0.6
lnGDP => lnNREN	0.94	0.339	0.6
lnREN=> lnNREN	4.008	0.049**	0.6
lnEXTD=> lnNREN	4.295	0.044**	0.6
$lnCO_2 => lnEXTD$	1.397	0.246	0.6
lnGDP => lnEXTD	5.195	0.029**	0.6
lnREN=> lnEXTD	5.909	0.020**	0.6
lnNREN => lnEXTD	8.358	0.005***	0.6

Note: ***, **, and * denote statistical significance at 1%, 5%, and 10% significance levels, respectively. The lag length was determined to be 1 according to the AIC information criterion.

Source: Author's calculations.

5. Conclusion and Recommandations

While the relationship between environmental sustainability and external debt is an important area of research in academic and policy circles globally, analysing the dynamics specific to emerging economies such as Türkiye is critical to better understanding this interaction. An increasing EXTD, which is integral to Türkiye's economic growth strategy, can significantly affect the country's environmental performance. The influence of debt structure, the sectors to which it is directed, and repayment terms on environmental protection efforts are essential questions that need to be addressed. Empirical evidence from Türkiye enhances our understanding of this complex relationship by examining the environmental consequences of external debt from various perspectives. It is vital to design external debt management strategies in an integrated manner with environmental policies, enabling Türkiye to achieve both sustainable economic development goals and protect its environmental assets.

This study analyses the long-run impact of Türkiye's external debt burden on environmental sustainability between 1970 and 2023. CO_2 emissions are employed as the dependent variable to represent environmental quality, and economic growth, REN consumption, and NREN consumption variables are also included in the model while the EKC hypothesis is tested. The FFF-ARDL bounds test method is used to explore the long-run relationship, following unit root tests such as ADF, Fourier ADF, and ZA, to account for structural breaks. The results indicate that all series are non-stationary at the level but become stationary at the first differences. Long-run findings reveal that increases in external debt decrease CO_2 emissions, economic growth initially raises emissions but declines after a certain income threshold, confirming the EKC hypothesis, REN consumption reduces emissions, and NREN consumption increases emissions. The Fourier Toda-Yamamoto test results indicate unidirectional causality from CO_2 emissions, REN, and external debt to NREN consumption. There is also unidirectional causality from economic growth, REN, and NREN consumption to external debt. These findings align with those of similar studies in the literature and emphasise that managing external debt and promoting REN are crucial for reducing CO_2 emissions. These findings align with similar studies in the literature by researchers such as Beşe, Friday, and Özden (2021b), Xu et al. (2022), Beşe and Friday (2022), Sadiq et al. (2022), Bachegour and Qafas (2023), and Shamwil et al. (2024).

These results indicate that Türkiye's external debt management strategies are critical to environmental sustainability. Effective and efficient external debt management can significantly contribute to achieving environmental sustainability. Proper management of external debt, increased investments in REN sources, and incentivising these investments can effectively reduce carbon emissions. Policymakers should consider environmental factors in external borrowing processes and support economic growth with sustainable energy policies. Moreover, promoting REN consumption will substantially contribute to ensuring long-term sustainability. Utilising REN sources decreases dependence on fossil fuels, reduces carbon emissions, and minimises environmental pollution. Therefore, increasing investments in REN projects and supporting technological advancements in this sector are crucial for achieving environmental sustainability. This study serves as an important reference for understanding the environmental impacts of external debt and achieving sustainable development goals. By integrating external debt management and REN policies, policymakers can sustain economic growth while ensuring the environmental sustainability. A comprehensive and holistic approach should be adopted to minimise the environmental impacts of external debt. Future research following this study can explore various variables and methods across different countries and country groups to contribute significantly to the literature.

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