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Energy Efficiency and Environmental Sustainability: Investigating the Moderating Role of Trade Openness in Türkiye

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Abstract

This study investigates the role of fossil fuel energy efficiency (FFE) in shaping environmental sustainability in Türkiye, with particular emphasis on the moderating effect of trade openness (TO) over the period 1982–2023. Environmental sustainability is proxied by the Load Capacity Factor (LCF), which integrates ecological footprint and biocapacity within the Load Capacity Curve (LCC) framework. Long-run relationships are examined using the Fourier ARDL bounds testing approach to account for structural breaks, while coefficient robustness is ensured through Fully Modified Ordinary Least Squares (FMOLS) and Canonical Cointegrating Regression (CCR) estimators. The empirical findings indicate that improvements in energy efficiency contribute positively to environmental sustainability, and this effect is significantly strengthened when energy efficiency interacts with trade openness ($FFE \times TO$). This suggests that trade openness enhances the environmental gains of energy efficiency through technological spillovers. In addition, the results reveal an inverted-N-shaped nonlinear relationship between economic growth and environmental sustainability, indicating varying environmental pressures across different income levels. Overall, the findings highlight the importance of integrating trade policies with energy efficiency-oriented green technology strategies to achieve sustainable environmental outcomes in Türkiye.

Keywords: energy efficiency; environmental sustainability; trade openness; load capacity curve; Türkiye



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1. Introduction

Today, increasing energy demand, accelerating urbanization, and industry-based growth strategies are raising environmental pressures in developing countries [1,2]. For this reason, environmental sustainability is central to the global development agenda due to climate change, ecological degradation, and the rapid depletion of natural resources [3,4]. These issues make the balance between economic growth targets and environmental sustainability more apparent. Achieving this balance is a significant challenge for policymakers, especially in emerging market economies such as Türkiye. The current implications of this challenge are outlined in various policy reports. For example, UNDP [5] states that Türkiye has made progress in environmental indicators, but ongoing structural problems in the energy and transportation sectors increase environmental risks. Similarly, OECD (2019) [6] emphasizes that rapid urbanization and industrialization have intensified environmental

pressures. The World Bank (2022) [7] also reports that the fossil fuel-based energy structure in Türkiye increases risks to sustainability. These findings necessitate a more comprehensive examination of Türkiye's sustainability performance using indicators based on natural resource capacity.

Instead of relying on single-dimensional emission indicators of environmental sustainability, examining it through the Load Capacity Curve (LCC) which is based on the balance between biocapacity and ecological footprint—is an approach gaining importance in the literature [8,9]. However, in developing economies such as Türkiye, there is still no theoretical or empirical consensus on the functional structure (U, N, or inverted-N shape) of the relationship between growth and environmental balance [10,11]. Much of the existing research generalizes energy efficiency based on total energy consumption, overlooking the distinct effect of fossil fuel efficiency (FFE) and its dynamic relationship with foreign trade [12]. In particular, how openness transforms environmental sustainability through the energy efficiency channel remains under-researched. This highlights a significant theoretical and empirical gap that needs to be addressed, both regarding the validity of the inverted-N pattern and the efficiency–trade interaction.

Failure to address these theoretical and empirical gaps may weaken the effectiveness of environmental policies. Interpreting sustainability solely through the lens of carbon emissions may cause policymakers to overlook the degradation of water resources and forest cover, resulting in misdiagnoses [13]. Türkiye's net imports, which covered approximately 71.7% of its total energy consumption as of 2023 [14], make increasing energy efficiency (FFE) not only an environmental preference but also a strategic necessity to reduce economic vulnerability. Similarly, trade policies that are not aligned with energy efficiency targets may result in missed opportunities for green transformation. If the technology transfer channels enabled by openness to the global market are not used effectively, Türkiye may lose its international competitive strength and become vulnerable to global mechanisms such as border carbon adjustments [15]. Therefore, the multidimensional measurement and interactive analysis framework emphasized in this study is critical for illuminating these blind spots in policy design.

In line with these requirements, this study primarily examines the impact of fossil fuel energy efficiency on environmental sustainability in Turkey, within the framework of the Load Capacity Factor (LCF) and with a particular emphasis on the moderating role of openness to the outside world. In addition, the study assesses whether the relationship between economic growth and environmental sustainability is inverted-N-shaped. In this context, the study seeks to answer two main research questions: (i) Does the impact of fossil fuel energy efficiency on environmental sustainability vary depending on the level of openness? (ii) What is the nature of the relationship between economic growth and environmental sustainability in Turkey, and does this relationship exhibit an inverted-N shape? To answer these questions, the Fourier ARDL approach, which takes structural breaks into account, and related robustness tests were applied using annual data from 1982 to 2023. The analysis aims to empirically explain the dynamics of the growth–LCF relationship, as well as reveal the direction of the interaction between energy efficiency and openness.

The study contributes to the literature in four fundamental ways, consistent with its stated objectives. This study empirically contributes to the literature by modeling the interaction between fossil fuel energy efficiency and external openness and examining the transformative role of trade specifically in the context of Turkey. Second, it re-evaluates the LCC hypothesis for Turkey by examining the nonlinear relationship between economic growth and environmental sustainability using the LCF indicator, and contributes to theoretical discussions by testing the validity of the inverse-N pattern, which has been

largely neglected in the literature. Third, the use of the Fourier ARDL method, which takes structural breaks into account, and the validation of the results with FMOLS and CCR analyses increase the methodological reliability of the findings. Finally, it draws attention to the need for a holistic perspective on energy efficiency and openness to the outside world, presenting a policy roadmap that coordinates environmental and economic goals.

The first part of the four-part study provides a comprehensive literature review on the subject. This is followed by an explanation of the theoretical background and data analysis set. Finally, the findings are discussed and recommendations are presented.

2. Literature Review

This section reviews the literature on the effects of economic growth, energy efficiency, and trade openness on environmental sustainability and summarizes current findings in the context of Türkiye.

2.1. Economic Growth and Environmental Pollution

The relationship between economic growth and environmental degradation has long been examined in environmental economics literature within the framework of the Environmental Kuznets Curve (EKC). Adapting Kuznets' [16] approach to the environmental field, Grossman and Krueger [17] predicted an inverted U-shaped relationship between per capita income and pollution. In this model, during the early stages of industrialization, economic growth increases environmental degradation, showing a positive relationship. However, after a certain income threshold, growth begins to reduce pollution through compositional and technological effects, resulting in a negative relationship. This structure is supported by examples such as the G20 [18], India [19], and Türkiye [20,21]. However, the literature indicates that the relationship is more complex than quadratic in most countries; N-shaped, inverted-N, and S-shaped patterns show that pollution may increase again at high income levels [22–25]. Some studies state that pollution continuously increases with income growth, suggesting that the EKC hypothesis is entirely invalid [23,26]. Furthermore, the EKC approach focuses only on demand-side indicators such as CO₂ emissions and Ecological Footprint (EF), failing to consider nature's regenerative capacity and addressing sustainability within a narrow framework [1,27].

The LCC hypothesis, developed to address this methodological limitation, defines sustainability using the LCF ratio of biocapacity to ecological footprint [8]. Because LCF directly reflects environmental conditions, LCC predicts a U-shaped relationship between growth and environmental quality, in contrast to the EKC. This finding has been empirically supported in G7 countries [28] and OECD samples [29]. In Türkiye, Güneysu [10], Camkaya [30], and Aslan [12] have also shown that LCF tends to improve after a certain income level.

However, recent studies indicate that even the LCC hypothesis does not have a uniform structure. Altıntaş et al. [31] report that LCC is not valid for Türkiye in the MENAT panel, while Savaş [11] confirms the N-shaped LCC form in Türkiye and shows that economic growth has a multi-stage, fluctuating effect on LCF. These findings demonstrate that the growth–environment relationship in the Turkish literature has mostly been analyzed using quadratic models (U or inverted U); however, cubic specifications capable of capturing the complex structure of the relationship, especially N- or inverted N-shaped LCC models, are extremely limited. This study aims to address this methodological gap.

2.2. Fossil Fuel Energy Efficiency and Environmental Pollution

Various definitions and measurement approaches are prominent in the energy efficiency literature. Özbuğday and Erbas [32] calculated efficiency using sectoral energy

intensity and Gross Domestic Product (GDP) share by separating energy consumption and economic activities by sector. Shokoohi et al. [33] defined energy intensity as the ratio of energy consumption to GDP and found that this indicator increases both CO₂ and EF in Türkiye. Similarly, Zhou et al. [34], Akbar et al. [35], Khurshid et al. [36], and Alam et al. [37] measured energy efficiency as the ratio of economic output to energy consumption. Adebayo and Ullah [38] defined coal- and gas-based energy efficiency separately for Sweden, while Aslan [12] used non-renewable energy efficiency in Türkiye as the ratio of GDP to fossil energy consumption. In this study, FFE is defined as the ratio of per capita GDP to per capita fossil fuel consumption, consistent with the output/energy approach widely accepted in the literature [34,35,37].

There are also various methodological approaches in the literature. Tajudeen et al. [39] developed an energy efficiency index using sectoral decomposition analysis (IDA) in OECD countries. Kazemzadeh et al. [40] examined the effect of energy efficiency on the ecological footprint in 16 emerging economies using panel data methods. Zhou et al. [34] applied the FMOLS and MMQR approaches to China. Chen et al. [41] analyzed carbon emissions in countries with high energy efficiency using the GMM and FGLS methods. Akram et al. [42] used quantile regression to show that energy efficiency reduced emissions across all income groups in 66 developing countries. Xu and Xu [43] conducted sectoral analysis to reveal how environmental regulations affected energy efficiency in China's logistics sector across 30 provinces.

The findings generally show that energy efficiency reduces environmental pressures. However, Bataille and Melton [44] found that energy consumption increased in some sectors in Canada due to the "rebound effect." Awan et al. [45] found that emissions decreased in their study of 107 countries; Alam et al. [37] found that carbon efficiency increased; and Khurshid et al. [36] found that the ecological footprint increased in Pakistan. Aslan [12] defined non-renewable energy efficiency in Türkiye as the ratio of GDP to fossil energy consumption and used the Fourier ARDL method to show that this indicator reduces CO₂ and EF but increases LCF.

In summary, differences in definitions and methodological diversity in the energy efficiency literature lead to heterogeneous findings. While most studies emphasize that energy efficiency reduces environmental pressures, rebound effects and regional differences can produce varying results. In the case of Türkiye, the literature is quite limited, and testing the impact of FFE on environmental sustainability using a fossil energy-based measurement fills an important gap in the literature.

2.3. Trade Openness and Environmental Pollution

The literature on the effects of trade openness on environmental quality indicates that foreign trade can increase emissions by shifting production toward polluting sectors, as described by the "pollution haven" and "composition effect" hypotheses. This theoretical perspective is supported by empirical studies showing that trade negatively affects environmental performance through scale effects in countries with weak environmental regulations [46]. For example, Khan et al. [47] in Pakistan and Durgun Kaygısız [48] in Türkiye have shown that trade and growth increase emissions. Studies examining income disparities also highlight trends toward specialization in polluting activities [49] and an increase in the share of polluting industries [50] in developing countries. A similar negative effect has been observed through the investment channel; Wen et al. [51] found that foreign investments in BRICS countries increase environmental degradation, while Yurtkuran [52] found that direct investments and financial development in Türkiye increase CO₂ emissions.

However, a substantial body of literature argues that trade can reduce pollution through its “technical effect” and by increasing energy efficiency via technology transfer. Liobikienė and Butkus [53] found that trade increases energy efficiency, while Chen et al. (2021) [54] showed that it limits pollution through technological development. Evidence that sectoral transformation reduces pollution in OECD countries [55] and that trade reduces emissions in Gulf countries over the long term [56] supports this perspective. Specifically for Türkiye, Çütcü et al. [57] found that technology imports improve standards, while Bayraktutan and İnmez [58] found that environmental policies support the shift toward clean technology. However, Yurtkuran [52] noted that the use of renewable energy has not yet led to a significant reduction in emissions, indicating that the technical effect may not always prevail.

Recent literature indicates that the impact of trade is not one-sided but instead displays a non-linear and interactive structure. Qayoom and Altaf [59] found that trade openness in India produced an inverted-N relationship by moderating the EKC. Sharif et al. (2022) [60] reported that the trade-growth interaction reduced emissions in high-income countries but increased emissions in lower-middle-income groups. Similarly, Shahbaz et al. [61] highlighted an inverse-U relationship in high-income countries. For China, Fayaz et al. [62] found that trade improved environmental quality; however, studies such as Zafar et al. [63], Kitila [64], and Xia et al. [65] emphasize that the direction of the effect depends on countries’ energy profiles and financing conditions.

Although the moderating effect of trade on growth has been examined in the existing literature, no study has addressed the regulatory role of trade openness in the context of the Load Capacity Factor (LCF) for Türkiye, particularly its interaction with energy efficiency (FFE). Whether trade enhances the effectiveness of energy efficiency policies is a critical question for energy-dependent countries such as Türkiye. This study aims to fill this gap in the literature by modeling trade openness as a moderator shaping the LCF-growth relationship and by testing its interaction effect with energy efficiency.

3. Theoretical Background, Data Set, and Empirical Method

3.1. Data Set and Theoretical Background

This study uses an annual data set covering the period from 1982 to 2023. The starting year, 1982, was chosen because data on per capita fossil fuel consumption in kilowatt-hours (kWh) is only available from that year onward. The analysis ends in 2023, as this is the most recent year for which data published by the World Bank is available. Table 1 below summarizes the definitions of the variables obtained from the data set, the types of transformations applied, and the data sources.

Table 1. Data set and sources.

Symbol	Description	Source
LCF	Carrying Capacity Factor (Biocapacity/Ecological Footprint)	Global Footprint
lnGDP	Gross domestic product per capita (constant 2015 US\$)	WDI
FFE	Fossil Fuel Efficiency	Our World in Data, WDI
TO	Trade openness % of aggregate exports and imports to GDP	WDI

To reduce differences in measurement units between series, minimize potential issues with varying variance (heteroscedasticity), and facilitate the interpretation of flexibility coefficients, the GDP variable has been converted to logarithmic form and prefixed with the symbol “ln”. Since the other variables are ratio variables, they were not log-transformed. The study used non-renewable energy efficiency as a variable, which indicates how much

non-renewable energy is required to generate 1 US dollar of income. Non-renewable energy efficiency was calculated using the formula [66]: $\frac{\text{Real per capita GDP}}{\text{Fossil Fuel Consumption Per Capita (kWh)}}$.

LCF, used as the dependent variable in the model, is an important indicator of environmental sustainability. A decrease in LCF indicates increased environmental pressure due to the ecological footprint exceeding biocapacity. Conversely, an increase in LCF indicates that natural resource use has become more aligned with the capacity provided by the ecosystem and that environmental conditions have improved. LCF reflects the ratio of biocapacity to ecological footprint. This ratio is a direct measure of the environmental supply-demand balance. A decrease in LCF indicates that demand exceeds supply, while an increase indicates that ecological demand is approaching current capacity.

The main objective of this study is to examine the effects of economic growth (GDP), fossil fuel energy efficiency (FFE), and openness to trade (TO) variables on LCF in Türkiye. Furthermore, the transformative role of openness is tested through the energy efficiency channel. The FFE $\times$ TO interaction term in Model 2 tests under which conditions openness strengthens or weakens the effect of energy efficiency on LCF. The functional structures of the models used in the study are presented in Equations (1) and (2).

$$\text{Model 1: } LCF_t = f(\ln GDP_t, (\ln GDP_t)^2, (\ln GDP_t)^3, FFE_t, TO_t) \quad (1)$$

$$\text{Model 2: } LCF_t = f(\ln GDP_t, (\ln GDP_t)^2, (\ln GDP_t)^3, FFE_t, TO_t, FFE_t * TO_t) \quad (2)$$

After the natural logarithmic transformation, Equations (1) and (2) are re-expressed in the following regression form.

$$\text{Model 1: } LCF_t = \beta_0 + \beta_1 \ln GDP_t + \beta_2 (\ln GDP_t)^2 + \beta_3 (\ln GDP_t)^3 + \beta_4 FFE_t + \beta_5 TO_t + u_t \quad (3)$$

$$\text{Model 2: } LCF_t = \mu_0 + \mu_1 \ln GDP_t + \mu_2 (\ln GDP_t)^2 + \mu_3 (\ln GDP_t)^3 + \mu_4 FFE_t + \mu_5 TO_t + \mu_6 (FFE_t \times TO_t) + v_t \quad (4)$$

These models aim to test the effects of economic growth, energy efficiency, and openness on environmental sustainability both directly (Model 1) and interactively (Model 2). The theoretical expectations of these variables are discussed below in light of the literature and mechanisms.

Economic growth affects environmental outcomes through three main mechanisms [17]. The combination of these mechanisms can create a nonlinear, three-stage dynamic on LCF, leading to an inverted-N relationship. In the first stage, the scale effect dominates. Increases in production and energy use increase the ecological footprint faster than biocapacity, reducing LCF ($\beta_1 < 0$). As income rises, compositional and technical effects driven by structural transformation, the adoption of cleaner technologies, and efficiency gains become apparent and improve LCF ($\beta_2 > 0$). At high income levels, however, increased mobility, residential energy demand, and overall consumption intensification re-accelerate the ecological footprint, making the scale effect dominant again and causing LCF to decline once more ($\beta_3 < 0$). This three-stage progression forms the theoretical basis for the inverse-N relationship between economic growth and environmental sustainability; within this framework, the marginal effect of growth in Model 1 is obtained by taking the derivative of the regression equation with respect to GDP, as shown in Equation (5).

$$\frac{\partial \ln LCF_t}{\partial \ln GDP_t} = \beta_1 + 2\beta_2 \ln GDP_t + 3\beta_3 (\ln GDP_t)^2 \quad (5)$$

If $\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 = 0$ ise ters – U; $\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 < 0$, an inverse-N relationship is present.

This three-stage scale–composition–rescale cycle demonstrates that the impact of economic activities on environmental sustainability can change direction depending on the

income level. Therefore, the coefficients β_1 , β_2 , and β_3 are key indicators that determine which effect is dominant in the economic growth process and provide a critical theoretical reference for interpreting the analysis findings.

Energy efficiency is a critical component of sustainable growth. Fossil fuel energy efficiency (FFE), as used in this study, is the ratio of GDP per capita to fossil energy consumption per capita. When efficiency increases, it is possible to produce the same output with less energy, thereby reducing the ecological footprint and increasing LCF. The marginal dimension of this effect is shown in Model 1 by taking the derivative of LCF with respect to FFE and is expressed in the following equation:

$$\frac{\partial \ln LCF_t}{\partial FFE_t} = \beta_4 > 0 \quad (6)$$

Here β_4 shows the elasticity of energy efficiency on LCF. When energy efficiency increases, the same production can be achieved with less fossil fuel. In this case, the ecological footprint decreases and LCF increases. However, the rebound effect, which is often discussed in the literature, can limit these gains. This effect arises from the stimulating impact of lower energy costs on demand. Lower energy costs can directly cause a rebound effect by increasing total energy demand. Furthermore, an indirect rebound may occur if the savings are diverted to other energy-intensive activities [67].

Openness to trade also affects environmental sustainability through different mechanisms. When the scale effect is dominant, increased trade volume leads to intensified production and transportation activities, which increases environmental pressures and leads to a decrease in LCF, a situation defined as the pollution haven effect. Conversely, when composition and technical effects are dominant, cleaner technologies and environmental standards can spread through trade, increasing LCF and pointing to the pollution halo effect. In this context, the marginal effect of openness is derived from Model 1.

$$\frac{\partial \ln LCF_t}{\partial TO_t} = \beta_5 \quad (7)$$

$\beta_5 < 0$ the scale effect is dominant and environmental quality deteriorates; when $\beta_5 > 0$, the composition/technical effects become dominant and environmental quality improves.

In Model 2, since the growth channel does not interact with TO, the effect of growth on LCF depends entirely on income level. The coefficients $\ln GDP$, $\ln GDP^2$ and $\ln GDP^3$ indicate that this relationship is not linear. At low income levels, the scale effect may be dominant and growth may reduce LCF. At medium income levels, technical and composition effects may create a temporary improvement. At high incomes, however, increased energy and resource use may again have a negative impact on LCF. This pattern is clearly evident in the marginal effect function defined by the derivative of Model 2 with respect to $\ln GDP$.

$$\frac{\partial \ln LCF_t}{\partial \ln GDP_t} = \mu_1 + 2\mu_2 \ln GDP_t + 3\mu_3 (\ln GDP_t)^2 \quad (8)$$

Equation (8) shows how the marginal effect of growth on LCF can change direction as income levels increase. For example, when $\mu_1 < 0$, $\mu_2 > 0$, and $\mu_3 < 0$, the environmental impact of growth may initially be negative, then positive, and finally negative again at high income levels, exhibiting an inverted-N relationship. This three-stage pattern forms the theoretical basis for the inverted-N shape observed in Türkiye. In Model 2, since growth does not interact directly with openness to trade, its effect on LCF is shaped entirely by the

varying dominance of scale, composition, and technical effects across income levels. Taking the derivative with respect to FFE yields the conditional marginal effect of energy efficiency:

$$\frac{\partial \ln LCF_t}{\partial FFE_t} = \mu_4 + \mu_6 TO_t \quad (9)$$

Equation (9) shows that the effect of FFE on LCF depends on the level of openness (TO). The term μ_4 reflects the basic (unconditional) effect, while $\mu_6 \ln TO_t$ reflects the extent to which this effect strengthens or weakens as openness increases. If $\mu_4 > 0$ and $\mu_6 > 0$, an increase in FFE raises LCF, and this positive effect strengthens as the TO level rises; conversely, if $\mu_6 < 0$, efficiency gains may weaken at high levels of openness due to rebound and similar mechanisms. The effect of openness on LCF consists of two parts. For the part where TO enters the model as a level, the derivative with respect to TO is shown in Equation (10):

$$\frac{\partial \ln LCF_t}{\partial TO_t} = \mu_5 TO_t \quad (10)$$

According to Equation (10), if $\mu_5 < 0$, the increase in trade volume reduces LCF through the scale effect; if $\mu_5 > 0$, composition and technical effects dominate, and openness increases environmental sustainability. When the derivative is taken with respect to $\ln TO$, the efficiency channel created by the interaction term emerges:

$$\frac{\partial \ln LCF_t}{\partial TO_t} = \mu_6 FFE_t \quad (11)$$

Equation (11) shows that the marginal effect of openness on LCF depends on the level of FFE. When FFE is high (and under the assumption of $\mu_6 > 0$), an increase in openness improves LCF more, while when FFE is low and/or $\mu_6 < 0$, the same increase in openness may limit environmental gains or even undermine them.

Therefore, the theoretically expected inverse-N dynamics describe a fluctuating pattern where environmental pressure first intensifies, then weakens, and finally increases again at high income levels as Türkiye's income level rises. Energy efficiency (FFE), which accompanies this growth cycle, emerges as a strategic element that reshapes environmental balances by interacting with openness (TO), beyond being a direct improver. The current framework provides a critical theoretical basis for interpreting, through a holistic approach, the directional shifts indicated by growth coefficients in econometric analysis and the transformative effect revealed by interaction parameters.

3.2. Methodology

A two-stage methodological approach was followed in this study. First, the stationarity structures of the variables were tested. Then, long-term relationships were analyzed using the Fourier ARDL method. In the first stage of the analysis, the stationarity properties of the time series were examined using both the Augmented Dickey–Fuller (ADF) test and the Fourier Bootstrap ADF (FBADF) test, which considers structural breaks. Within the scope of the ADF test, models with a constant (Equation (12)), with a constant and trend (Equation (13)), and without a constant and trend (Equation (14)) were estimated for the variable *LCF*. Other variables were also evaluated according to the same test structures.

$$\Delta LCF_t = \beta_1 + a LCF_{t-1} + \sum_{i=1}^g \delta_i \Delta LCF_{t-i} + \varepsilon_t \quad (12)$$

$$\Delta LCF_t = \beta_1 + \beta_2 t + a LCF_{t-1} + \sum_{i=1}^g \delta_i \Delta LCF_{t-i} + \varepsilon_t \quad (13)$$

$$\Delta LCF_t = aLCF_{t-1} + \sum_{i=1}^g \delta_i \Delta LCF_{t-i} + \varepsilon_t \quad (14)$$

In these models, the constant term is represented by β_1 , the time trend by β_2 , the lagged level term by the coefficient a , and the error term by ε_t . The lag length is typically determined based on AIC or SC criteria; first-difference lags are added to prevent autocorrelation. The stationarity of the series at the level is tested by comparing the tau-statistic of the coefficient a with the critical values of MacKinnon [68]. However, since classical ADF tests may be inadequate in structural breaks, the Fourier ADF test developed by Enders and Lee [69], which includes sine-cosine terms, is used. The relevant equations are given in Equations (15)–(17).

$$\Delta LCF_t = \beta_1 + aLCF_{t-1} + \theta_1 \sin\left(\frac{2\pi kt}{T}\right) + \theta_2 \cos\left(\frac{2\pi kt}{T}\right) + \sum_{i=1}^g \delta_i \Delta LCF_{t-i} + \varepsilon_t \quad (15)$$

$$\Delta LCF_t = \beta_1 + \beta_2 t + aLCF_{t-1} + \theta_1 \sin\left(\frac{2\pi kt}{T}\right) + \theta_2 \cos\left(\frac{2\pi kt}{T}\right) + \sum_{i=1}^g \delta_i \Delta LCF_{t-i} + \varepsilon_t \quad (16)$$

$$\Delta LCF_t = aLCF_{t-1} + \theta_1 \sin\left(\frac{2\pi kt}{T}\right) + \theta_2 \cos\left(\frac{2\pi kt}{T}\right) + \sum_{i=1}^g \delta_i \Delta LCF_{t-i} + \varepsilon_t \quad (17)$$

In the Fourier ADF test, k represents the frequency, t represents the time trend, and T represents the number of observations. The significance of the added sine and cosine terms in the regression indicates the presence of a structural break in the series and reveals that the classical ADF test may be inadequate. In this case, if the test statistic exceeds the critical value, the series is considered stationary. Fourier components make the test more flexible and reliable by indirectly reflecting structural changes in the model.

In the second stage of the analysis, the long-term relationship between the variables was examined using the Fractional Frequency Fourier ARDL (FARDL) bounds test. This Fourier transform-based method increases the flexibility and statistical power of the test by incorporating the effect of structural breaks into the model through sine and cosine terms. The Fourier approach was developed to address the shortcoming of the traditional ARDL bounds test, which ignores structural changes and can lead to misleading results in long-term relationships. In this context, studies such as Solarin [70], Pata and Aydın [71] consider integer frequencies ($k = 1, 3, 5$), while Yilanci and Pata [72], Christopoulos, and Leon-Ledesma [73] integrated permanent structural breaks into the model based on fractional frequencies ($k = 0.1, 0.3, \dots, 4.8, 5$). In this regard, the model structures used in the study were enriched with Fourier components and estimated within the scope of Equations (18) and (19).

$$\begin{aligned} \Delta LCF_t = & \delta_0 + \delta_1(LCF_{t-1}) + \delta_2(\ln GDP_{t-1}) + \delta_3(\ln GDP_{t-1})^2 + \delta_4(\ln GDP_{t-1})^3 + \delta_5(FFE_{t-1}) + \delta_6(TO_{t-1}) + \\ & \sum_{j=1}^{P_1} \phi_{1j} \Delta(LCF_{t-j}) + \sum_{j=0}^{P_2} \phi_{2j} \Delta(\ln GDP_{t-j}) + \sum_{j=0}^{P_3} \phi_{3j} \Delta(\ln GDP_{t-j}^2) + \sum_{j=0}^{P_4} \phi_{4j} \Delta(\ln GDP_{t-j}^3) + \sum_{j=0}^{P_5} \phi_{5j} \Delta(FFE_{t-j}) + \\ & \sum_{j=0}^{P_6} \phi_{6j} \Delta(TO_{t-j}) + \gamma_1 \cos\left(\frac{2\pi kt}{T}\right) + \gamma_2 \sin\left(\frac{2\pi kt}{T}\right) + \varepsilon_t \end{aligned} \quad (18)$$

$$\begin{aligned} \Delta LCF_t = & \theta_0 + \theta_1(LCF_{t-1}) + \theta_2(\ln GDP_{t-1}) + \theta_3(\ln GDP_{t-1})^2 + \theta_4(\ln GDP_{t-1})^3 + \theta_5(FFE_{t-1}) + \theta_6(TO_{t-1}) + \\ & \theta_7(FFE_{t-1} * TO_{t-1}) + \sum_{j=1}^{r_1} \beta_{1j} \Delta(LCF_{t-j}) + \sum_{j=0}^{r_2} \beta_{2j} \Delta(\ln GDP_{t-j}) + \sum_{j=0}^{r_3} \beta_{3j} \Delta(\ln GDP_{t-j}^2) + \sum_{j=0}^{r_4} \beta_{4j} \Delta(\ln GDP_{t-j}^3) + \\ & + \sum_{j=0}^{r_5} \beta_{5j} \Delta(FFE_{t-j}) + \sum_{j=0}^{r_6} \beta_{6j} \Delta(TO_{t-j}) + \sum_{j=0}^{r_7} \beta_{7j} \Delta(FFE_{t-j} * TO_{t-j}) + \lambda_1 \cos\left(\frac{2\pi kt}{T}\right) + \lambda_2 \sin\left(\frac{2\pi kt}{T}\right) + \varepsilon_t \end{aligned} \quad (19)$$

In Equations (18) and (19), the operator Δ represents the first difference of the variables. The constant term is denoted by δ_0 in Equation (18) and θ_0 in Equation (19). The coefficients from δ_1 to δ_6 in Equation (18) and from θ_1 to θ_7 in Equation (19) represent the long-term relationships of the model. Similarly, the coefficients in Equation (18) from ϕ_{1j} to ϕ_{6j} and in Equation (19) from β_{1j} to β_{7j} reflect the model's short-term dynamics. The terms from p_1 to p_6 and from r_1 to r_7 in both equations represent the lag lengths of the relevant variables, and these values were determined based on the Akaike Information Criterion (AIC). ε_t in Equations (18) and (19) represents the error term. Finally, the hypotheses tested for the models specified in Equations (18) and (19) are presented below.

Equation (18) hypothesis tests	Equation (19) hypothesis tests
$F_{overall} = H_0 : \delta_1 = \delta_2 = \delta_3 = \delta_4 = \delta_5 = \delta_6 = 0$	$F_{overall} = H_0 : \theta_1 = \theta_2 = \theta_3 = \theta_4 = \theta_5 = \theta_6 = \theta_7 = 0$
$t_{dependent} = H_0 : \delta_1 = 0$	$t_{dependent} = H_0 : \theta_1 = 0$
$F_{independent} = H_0 : \delta_2 = \delta_3 = \delta_4 = \delta_5 = \delta_6 = 0$	$F_{independent} = H_0 : \theta_2 = \theta_3 = \theta_4 = \theta_5 = \theta_6 = \theta_7 = 0$

The presented hypotheses are based on three complementary test statistics used to test for the existence of a long-term relationship in the model. The $F_{overall}$ tests the joint significance of all level terms; the $t_{dependent}$ tests only the level term of the dependent variable; and the $F_{independent}$ tests the joint significance of the level terms of the independent variables. The presence of cointegration is accepted when all three tests reject the null hypothesis. The empirical model including the error correction term (ECT) is specified in Equations (20) and (21).

$$\begin{aligned} \Delta LCF_t = & \gamma_0 + \phi_0 LCF_{t-1} + \beta_1 \Delta \ln GDP_t + \phi_1 \Delta \ln GDP_{t-1} + \beta_2 \Delta \ln GDP_t^2 + \phi_2 \Delta \ln GDP_{t-1}^2 + \beta_3 \Delta \ln GDP_t^3 \\ & + \phi_3 \Delta \ln GDP_{t-1}^3 + \beta_4 \Delta FFE_t + \phi_4 \Delta FFE_{t-1} + \beta_5 \Delta TO_t + \phi_5 \Delta TO_{t-1} + \lambda_1 \cos\left(\frac{2\pi kt}{T}\right) + \lambda_2 \sin\left(\frac{2\pi kt}{T}\right) + \\ & \omega_1 ECT_{t-1} + \mu_t \end{aligned} \quad (20)$$

$$\begin{aligned} \Delta LCF_t = & \gamma_0 + \phi_0 LCF_{t-1} + \beta_1 \Delta \ln GDP_t + \phi_1 \Delta \ln GDP_{t-1} + \beta_2 \Delta \ln GDP_t^2 + \phi_2 \Delta \ln GDP_{t-1}^2 + \beta_3 \Delta \ln GDP_t^3 + \\ & \phi_3 \Delta \ln GDP_{t-1}^3 + \beta_4 \Delta FFE_t + \phi_4 \Delta FFE_{t-1} + \beta_5 \Delta TO_t + \phi_5 \Delta TO_{t-1} + \beta_6 (FFE_t * TO_t) + \phi_6 (FFE_{t-1} * \Delta TO_{t-1}) + \\ & \lambda_1 \cos\left(\frac{2\pi kt}{T}\right) + \lambda_2 \sin\left(\frac{2\pi kt}{T}\right) + \omega_2 ECT_{t-1} + \mu_t \end{aligned} \quad (21)$$

Equations (20) and (21) represent the coefficients of the error correction terms, where (ω_1) and (ω_2) , respectively, and this coefficient must be negative and statistically significant.

4. Empirical Results and Discussions

4.1. Descriptive Statistics and Correlation

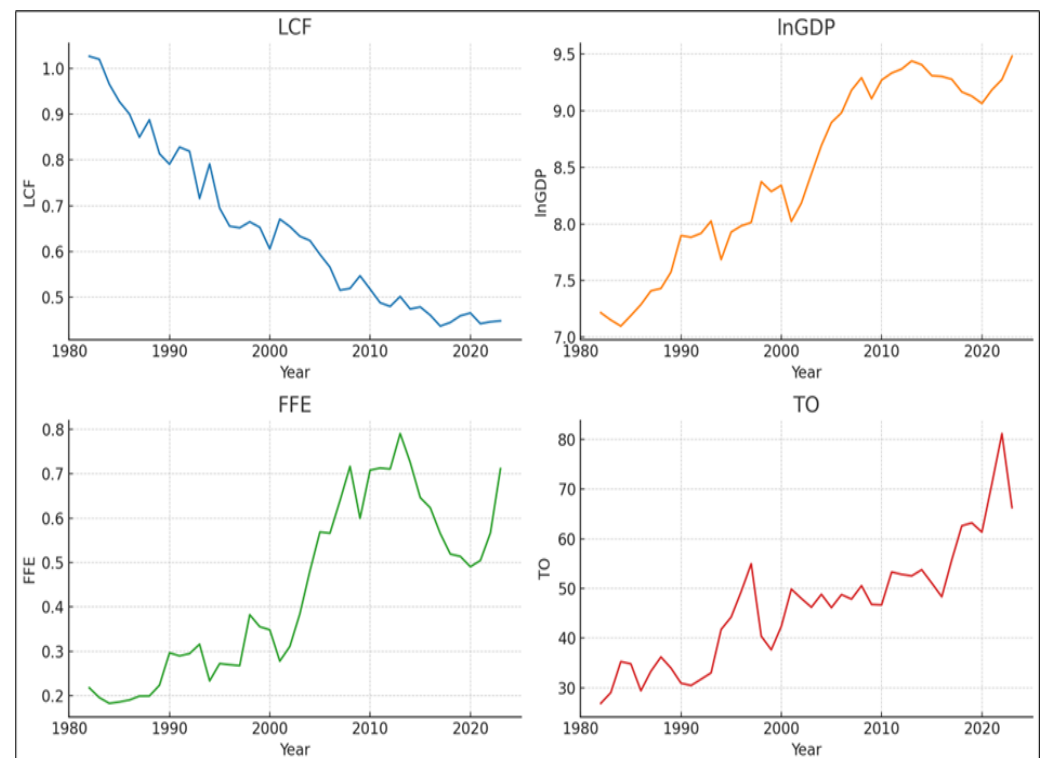
Basic descriptive statistics for the log-transformed variables used in the study are presented in Table 2.

According to the descriptive statistics presented in Table 2, the fact that the average value of LCF is below 1 (0.65) indicates that Türkiye's biocapacity was insufficient to meet its ecological footprint during the period under review and that an ecological deficit occurred. The high standard deviation in the trade deficit (TO) series indicates that the volume of foreign trade fluctuated significantly throughout the period, while the low average of FFE indicates that the intensity of fossil fuel use continued. When examining the distribution characteristics of the data set, the Jarque–Bera test results confirm that all variables meet the normal distribution assumption ($p > 0.05$) and that the series have a structure suitable for parametric econometric analysis.

While descriptive statistics reveal the general distribution characteristics of the variables, it is important to visually examine the trends followed by these variables over time. Accordingly, the time path graphs of the key variables used in the study are presented in Figure 1.

Table 2. Descriptive statistics.

	LCF	lnGDP	FFE	TO
Mean	0.645798	8.464086	0.434601	46.40136
Median	0.628420	8.407617	0.383496	47.31894
Maximum	1.026461	9.480799	0.790207	81.17013
Minimum	0.436791	7.097591	0.182939	26.88092
Std.Dev.	0.176765	0.791873	0.193498	12.20024
Skewness	0.602751	−0.266113	0.246413	0.545819
Kurtosis	2.218187	1.622763	1.618318	3.195443
Jarque–Bera	3.612815	3.815081	3.765863	2.152272
Probability	0.164243	0.148445	0.152143	0.340910
Observations	42	42	42	42

**Figure 1.** Time path graphs of series.

Graphical analysis shows that the LCF variable follows a clear negative trend and that environmental sustainability has weakened over time. In contrast, positive trends are evident in the lnGDP, FFE, and TO variables. However, changes in the means and variances of the series over time suggest that they are non-stationary, particularly for LCF, lnGDP, and TO. This situation necessitates testing the series for unit root and performing cointegration analyses in the modeling. Furthermore, trend structures and possible structural breaks methodologically support the preference for break-sensitive methods such as Fourier ARDL.

4.2. Unit Root Test Results

In the first stage of the empirical analysis process, the stationarity structures of the variables were evaluated using the Fourier component-extended Bootstrap ADF (FBADF) test. The relevant test statistics and their corresponding bootstrap-based critical values are reported in Table 3.

Table 3. FBADF test results.

Intercept Model						
Variable	k	Wald F	Critical Value (5%)	p	FBADF Test Statistics	Critical Value (5%)
LCF	1	169.30343 *	6.929690	0	−0.15043	−4.090391
lnGDP	2	166.63199 *	12.225635	1	−0.79581	−3.130215
lnGDP2	1	167.39769 *	12.303212	1	−0.17156	−3.226382
lnGDP3	1	167.31126 *	12.521650	1	−0.24490	−3.038150
FFE	5	162.78239 *	10.037324	0	−0.54947	−2.710093
TO	5	159.20063 *	9.089334	1	−1.51990	−3.043328
FFE × TO	4	164.54903 *	9.132590	1	−1.35361	−2.270218
Trent and Intercept Model						
LCF	1	169.79332 *	6.271722	0	−5.24538	−8.678321
lnGDP	4	162.84809 *	12.530951	1	−1.37481	−3.405653
lnGDP2	4	161.84132 *	12.571428	1	−4.18361	−5.598124
lnGDP3	5	162.90808 *	12.589676	1	−4.39051	−6.007798
FFE	4	161.86563 *	10.370101	0	−3.76691	−6.810558
TO	3	158.47208 *	9.285815	1	−6.69333	−8.497212
FFE × TO	5	161.99158 *	8.444575	1	−5.52652	−7.534896

Note: * indicates a 5% significance level. k and p indicate the frequency number of Fourier terms and the optimum delay length, respectively. Critical values were determined at 10,000 renewals.

When examining the unit root test results presented in Table 3, it is seen that the Wald F statistics calculated for both the constant and trend models exceed the bootstrap critical values at the 5% significance level for all series. This finding statistically confirms the necessity of including Fourier functions (trigonometric terms) in the model by proving that the series do not follow a linear structure and contain structural breaks. On the other hand, the FBADF test results reveal that the null hypothesis cannot be rejected at the level values of the variables, thus indicating that they exhibit a non-stationary structure containing a unit root. In this context, the traditional ADF (Augmented Dickey–Fuller) unit root test was applied to determine the integration degrees of the series, and the results obtained are reported in Table 4.

Table 4. ADF unit root test results.

Variables	ADF Test Statistics (Level)		ADF Test Statistics (First Difference)	
	Intercept	Trent and Intercept	Intercept	Trent and Intercept
LCF	−3.195698 **	−2.713187	−8.994766 *	−7.593293 *
lnGDP	−0.964201	−1.781902	−6.405359 *	−6.398076 *
lnGDP2	−0.837597	−1.813185	−6.241243 *	−6.199377 *
lnGDP3	−0.714453	−1.835191	−6.057061 *	−5.991692 *
FFE	−0.751986	−1.870630	−5.552684 *	−5.463325 *
TO	−1.420384	−3.529761 **	−6.964834 *	−6.935931 *
FFE × TO	0.014607	−2.270844	−5.799746 *	−5.803940 *
		Critical Values		
1	−3.610453	−4.198503	−3.611000	−4.192000
5	−2.938987	−3.523623	−2.939000	−3.524000

Note: * and ** indicate 1%, 5% significance levels, respectively.

The Traditional ADF unit root test results presented in Table 4 show that the integration degrees of the variables exhibit a mixed structure. According to the analysis findings, the LCF and TO variables were found to be stationary at level (I(0)) in the constant, constant, and trend models, respectively; while the first differences of the other series were found to be stationary (I(1)). The fact that the variables have a mixed structure of I(0) and I(1) and that none of the series are second-order stationary (I(2)) provides the necessary methodological

prerequisite for the applicability of the ARDL bounds test approach in examining the long-term relationships between the variables. Since the series meet the condition of stationarity, the next step, the cointegration stage, was taken.

4.3. Fourier ARDL Cointegration Test Results

After determining the stationarity of the series, the Fractional Fourier ARDL Bound Test was used to determine whether there was a cointegration relationship between the variables in the long term. The optimal lag lengths for Model 1 and Model 2, the appropriate frequency values, and the statistical values and critical values of the three tests ($F_{overall}$, $t_{dependent}$, $F_{independent}$) are reported in Table 5.

Table 5. Cointegration test results with Fourier terms.

Models	Lag Length	K *	Test Statistics	Upper Critical Values I(1)		
				%	%5	10
Model 1	1, 1, 1, 1, 0, 0	0.6	$F_{overall}$	10.197 **	5.598	4.268
			$t_{dependent}$	−7047 **	−4790	−4190
			$F_{independent}$	7445 **	5020	3900
Model 2	1, 1, 1, 1, 0, 0, 0	0.7	$F_{overall}$	9.963 **	4.430	3.610
			$t_{dependent}$	−7503 **	−4990	−4380
			$F_{independent}$	8172 **	5740	4150

Note: *, The appropriate frequency value determined according to the Model 1 AIC information criterion, Model 2 AIC information criterion, **, indicates significance at the 1% level. The upper critical values were obtained from Narayan [74] for the $F_{overall}$, Pesaran et al. [75] for the $t_{dependent}$, and Sam et al. [76] for the $F_{independent}$.

The results in Table 5 show that the fractional frequencies calculated for Model 1 and Model 2 indicate that the structural breaks are permanent in nature. For a long-term cointegration relationship to be established within the FARDL framework, the test statistics for the $F_{overall}$, $t_{dependent}$, and $F_{independent}$ must exceed the upper critical values. This condition is met in all three models; all test statistics are statistically significant at the 1% level. Thus, the existence of a long-term relationship in the models is strongly confirmed.

4.4. Diagnostic Test Results of FARDL

The FARDL model reports a series of diagnostic test results in Table 6 to ensure the accuracy and reliability of the results.

Table 6. Diagnostic tests.

Tests	Model 1		Model 2		Decision
	Values	Probability	Values	Probability	
Ramsey RESET	2.098	0.159	1.3276	0.259	✓
Serial Correlation LM	0.347	0.841	0.682	0.711	✓
Heteroscedasticity (White)	1.135	0.287	17.999	0.116	✓
Heteroscedasticity (Harvey)	14.703	0.197	15.695	0.206	✓
Jargue–Bera	1.0463	0.592	1.242	0.538	✓
Qusum and CusumSQ	Stable (Figure 2)		Stable (Figure 2)		✓
R-squared and Adjusted R-squared	0.99	0.986399	0.991	0.988	✓

The findings in Table 6 show that the estimated model successfully passed the basic diagnostic tests. The stability of the coefficients over time in FARDL models is evaluated using the CUSUM and CUSUM-SQ tests developed by Brown et al. [77]. Figure 2 presents the results of these tests, showing that the model maintains its structural stability.

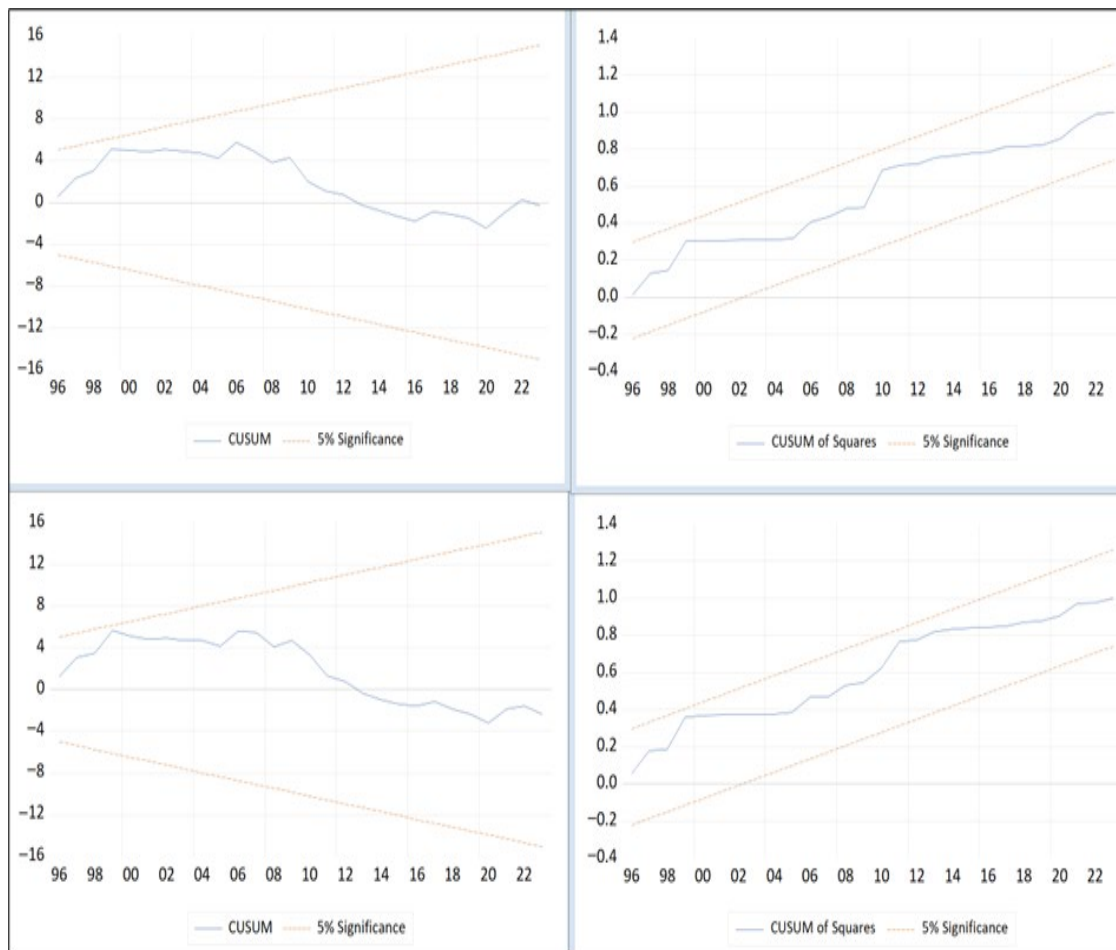


Figure 2. CUSUM and CUSUM-SQ.

4.5. Long-Term ARDL Estimates

Since the boundary test results in the fractional Fourier function ARDL model indicate that there is a cointegration relationship between the series, the results of the short- and long-term forecasts of the selected ARDL model are presented in Table 7.

In this section, to enable the analytical interpretation of the results, the coefficients corresponding to the terms $\ln GDP_t$, $(\ln GDP_t)^2$, and $(\ln GDP_t)^3$ in Model 1 (Equation 3) are shown as β_1 , β_2 , and β_3 , respectively. The coefficients corresponding to the FFE and TO variables are shown as β_4 and β_5 , respectively. In Model 2 (Equation 4), the corresponding growth coefficients are μ_1 , μ_2 , and μ_3 ; the basic effects are μ_4 (FFE) and μ_5 (TO); and the coefficient for the interaction term is defined as μ_6 .

The long-term results presented in Table 7 reveal a three-stage inverse-N-shaped relationship between economic growth and LCF within the scope of the LCC hypothesis. In Model 1, the negative and significant coefficient of $\ln GDP_t$ (-5.3785), indicates that the scale effect is dominant at low income levels and that growth reduces LCF. The positive and significant coefficient of $(\ln GDP_t)^2$ (0.6839), indicates that composition and technical effects come into play at middle income levels, temporarily improving environmental sustainability. The coefficient of $\ln GDP^3$ is negative again (-0.0306), confirming that scale effects are reinforced again and environmental pressure increases in the high-income stage due to the effects of consumption growth, energy demand, and mobility. This triple coefficient structure ($\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 < 0$) shows that all stages of the inverted-N form empirically occur in the Turkish context.

Table 7. Results of short and long-term forecasts.

Model 1: LCF = f(lnGDP, lnGDP², lnGDP³, FFE, TO)					
	Variables	Coefficient	Std. Error	t-Statistic	Prob.
Long-Term	lnGDP	−5.3 78 5	2.4986	−2.1526	0.0398
	lnGDP2	0.6839	0.2999	2.2807	0.0301
	lnGDP3	−0.0306	0.0120	−2.5449	0.0165
	FFE	0.9142	0.1581	5.7823	0.0000
	TO	−0.0016	0.0006	−2.7023	0.0114
Error Correction	COS	0.0562	0.0077	7.3247	0.0000
	SIN	−0.0813	0.0095	−8.5927	0.0000
	ECM(−1)	−1.0318	0.1171	−8.8140	0.0000
Model 2: LCF = f(lnGDP, lnGDP2, lnGDP3, FFE, TO, FFE*TO)					
	Variables	Coefficient	Std. Error	t-Statistic	Prob.
Long-Term	lnGDP	−6.4574	2.4370	−2.6497	0.0131
	lnGDP2	0.8087	0.2892	2.7962	0.0092
	lnGDP3	−0.0353	0.0114	−3.0973	0.0044
	FFE	0.4069	0.2644	1.5391	0.1350
	TO	−0.0056	0.0017	−3.2678	0.0029
	FFExTO	0.0090	0.0033	2.6937	0.0118
Error Correction	COS	0.0053	6.2900	0.0000	0.0053
	SIN	0.0051	−6.8489	0.0000	0.0051
	ECM(−1)	−1.0587	0.1099	−9.6380	0.0000

In Model 1, the FFE coefficient is positive and significant (0.9142); this result indicates that energy efficiency reduces the ecological pressure per unit of production and strengthens sustainability. In contrast, the negative and significant TO coefficient (−0.0016) indicates that openness reduces LCF by expanding the scale of production and that scale effects dominate in the trade channel.

Model 2 results show that the reverse-N structure is preserved regardless of the level of openness to the outside. The unchanged triple coefficient structure ($\mu_1 < 0$, $\mu_2 > 0$, $\mu_3 < 0$) clearly confirms this finding. The insignificance of the FFE coefficient in Model 2 suggests that energy efficiency alone does not have a strong long-term effect. In contrast, the positive and significant value of the FFE $\times$ TO interaction term (0.0090) indicates that the environmental impact of energy efficiency varies depending on the level of openness to the outside world. This result shows that openness to the outside world statistically strengthens the relationship between energy efficiency and LCF. Furthermore, the fact that the TO coefficient remains negative and significant (−0.0056) in Model 2 confirms that the independent effect of openness weakens environmental sustainability.

The negative and statistically significant ECM(−1) coefficient in both models indicates that short-term deviations quickly adjust to long-term equilibrium. The absolute value of the coefficient being above 1 indicates that the system approaches equilibrium through an overshooting mechanism [74].

4.6. Robustness Analysis of the F

FMOLS and CCR methods were also applied to test the reliability of the long-term results obtained with the FARDL model. The results are reported in Table 8.

Table 8 FMOLS and CCR results indicate that the estimated coefficients are largely consistent with the FARDL findings. The similarity in coefficient signs and significance levels confirms that the results are not sensitive to the choice of estimation method and supports the robustness of the empirical framework.

Table 8. FMOLS and CCR.

		FMOLS			CCR		
		Coefficient	t-Statistic	p	Coefficient	t-Statistic	p
Model 1	lnGDP	−7.228459	−3.408313	0.0017	−7.212341	−3.059931	0.0044
	lnGDP2	0.925120	3.612405	0.0010	0.925435	3.249796	0.0027
	lnGDP3	−0.041230	−4.014577	0.0003	−0.041340	−3.619626	0.0010
	FFE	1.075655	7.460566	0.0000	1.088241	6.671623	0.0000
	TO	−0.001724	−3.730926	0.0007	−0.001746	−3.091549	0.0040
Model 2	lnGDP	−7.827468	−3.547746	0.0012	−7.801803	−3.267354	0.0026
	lnGDP2	0.995245	3.765438	0.0007	0.979164	3.397035	0.0018
	LNGDP3	−0.043880	−4.177926	0.0002	−0.042478	−3.676148	0.0009
	FFE	0.298416	1.442446	0.1589	0.558074	1.545739	0.1320
	TO	−0.005171	−3.021938	0.0049	−0.005377	−3.251451	0.0027
	FFE × TO	0.007947	2.190599	0.0359	0.008839	2.528428	0.0166

5. Discussion

This discussion section focuses on the role of FFE in shaping environmental sustainability in Turkey within the LCC framework and how this effect is conditioned by TO. The empirical findings obtained show that openness alone can increase environmental pressure. Furthermore, openness significantly strengthens the positive contribution of energy efficiency to environmental sustainability through technological spillover effects. Accordingly, it is understood that environmental sustainability in Turkey is determined not only by growth dynamics but also by structurally important factors from a policy perspective, such as the interaction between energy efficiency and openness to the outside world. In this context, the non-linear growth–environment relationship is considered a complementary analytical mechanism that helps explain how environmental pressures evolve at different income levels.

The inverse-N-shaped relationship between economic growth and environmental sustainability indicates that Türkiye’s environmental pressure dynamics operate in a three-stage cycle. Considering that LCF is the ratio of biocapacity to ecological footprint, a decline in LCF indicates increased environmental pressure, while an increase indicates strengthened ecological capacity. This finding, in contrast to studies such as Güneysu [10], Camkaya [30], and Aslan [12], which argue that the LCC hypothesis is valid in Türkiye but suggest that the relationship is uniform (U-shaped), aligns with Savaş’s findings that the relationship between growth and the environment exhibits a more complex and fluctuating structure [11].

In the first stage, the scale effect is dominant, and increases in production, energy demand, and resource use lead to a decrease in LCF. In the middle stage, composition and technical effects come into play; industrial transformation, efficiency gains, and the spread of clean technologies temporarily alleviate environmental pressures. In the third stage, consumption, transportation, and residential energy demand accelerate again with high income, and the scale effect becomes dominant again, causing LCF to decrease. The coefficient structure obtained in Türkiye ($\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 < 0$) clearly reveals how this three-stage pressure cycle is shaped throughout the income level. This mechanism forms the fundamental analytical framework that explains, in the remainder of the discussion, the processes through which the findings emerge.

This study examines the macroeconomic dynamics determining environmental sustainability in Türkiye within the framework of the LCC approach and assesses the nonlinear nature of the economic growth–environment relationship through this three-stage pressure cycle. The findings show that environmental pressures are shaped by income levels and that

this structure is directly related to Türkiye's production, energy, and consumption patterns. Furthermore, the findings reveal that structural variables such as energy efficiency (FFE) and openness to trade (TO) create conditional effects on LCF, indicating that environmental sustainability is determined not only by economic growth but also by policy mixes.

The first phase ($\beta_1 < 0$), reflects a growth structure in Türkiye where scale effects are clearly dominant. During this period, economic activities largely relied on energy-intensive sectors and fossil fuels. Indeed, Shokoohi et al. [33] confirm this negative scale effect in the early stages of industrialization, noting that energy intensity in Türkiye has an increasing effect on both CO₂ and the Ecological Footprint. According to International Energy Agency [14] data, approximately 83% of Türkiye's primary energy supply and two-thirds of its electricity production come from fossil sources. This structure explains the steady increase in energy-related emissions since the 1990s, driven by rising industrial production, increasing numbers of motor vehicles, and growing energy demand. Therefore, Türkiye's fossil-fuel-heavy and energy-intensive growth model constitutes the fundamental reason for the decline in LCF observed in the first phase of the inverted-N curve.

The middle phase ($\beta_2 > 0$) represents a period in Türkiye when compositional and technical effects temporarily alleviated environmental pressures. Following the 2007 Energy Efficiency Law, energy intensity decreased by 24% between 2007 and 2022 (WDI, 2023) [78]. This improvement parallels Aslan's [12] finding that non-renewable energy efficiency in Türkiye has an enhancing (improving) effect on LCF. Renewable energy capacity grew rapidly during this period; total installed capacity rose from 27.9 GW in 2014 to 58.5 GW in 2023 [79]. The share of wind and solar power in electricity generation reached 16% in 2023, up from less than 1% in 2010 [80]. Environmental management practices in industry have also become more widespread; the number of ISO 14001 certifications increased significantly between 2010 and 2020 [81]. These developments support the upward movement in the middle section of the inverted-N curve and indicate that partial technical decoupling has occurred in some sectors. However, due to the low share of renewable energy in primary energy supply and the uneven distribution of efficiency gains across sectors, this improvement does not signal a permanent transformation. This is consistent with Yurtkuran's [52] finding that renewable energy use in Türkiye has not yet produced the expected reduction in emissions.

The third stage ($\beta_3 < 0$) shows a structure in which the scale effect has become dominant again due to the acceleration of energy demand driven by consumption and transportation at high income levels. In Türkiye, residential electricity consumption increased by approximately 204% between 2000 and 2021, while CO₂ emissions linked to the transportation sector increased by 222% [82,83]. The share of coal in electricity production rose again after 2010, reaching 36% in 2023, indicating the continuation of a fossil fuel-based energy structure [84]. The real increase of 222% in household final consumption expenditures during the same period [85] clearly demonstrates why consumption-based pressures have intensified. These indicators numerically confirm that the main reason for the LCF's renewed decline in the final stage of the inverted-N curve is increased consumption, transportation demand, and a return to fossil fuels. This result supports the studies by Halkos and Polemis [22], which predict that pollution may increase again at high income levels, and by Güzel [25] and Topal [26], which point to similar risks for Türkiye.

The three-stage inverse-N structure in Model 1 continues in Model 2. The signs of the $\ln GDP$, $\ln GDP^2$, and $\ln GDP^3$ coefficients ($\mu_1 < 0$, $\mu_2 > 0$, $\mu_3 < 0$) show that this nonlinear structure is consistent in both models. The difference in Model 2 is that it makes growth effects dependent on openness and energy efficiency conditions. The positive value of the FFE $\times$ TO coefficient (0.007947) indicates that the improving effect of energy efficiency increases on LCF strengthens as the level of openness to the outside world rises.

The impact of openness on environmental sustainability is evident through Türkiye's foreign trade structure, which is based on sectors with high energy and carbon intensity. The total share of metals, chemicals, plastics, and mineral products in Türkiye's exports is approximately 26% in 2024 [86]. The fact that the embedded carbon intensity of the export basket is approximately 35% above the OECD average [87] indicates that these sectors are key contributors to increasing environmental pressure. This structure is consistent with Model 1, where openness has a negative effect on LCF. This finding is consistent with the findings of Durgun Kaygısız [48], who argues that trade increases emissions for Türkiye, and Khan et al. [47], who support the "pollution haven" hypothesis in developing countries.

In Model 2, the fact that the energy efficiency indicator FFE is not significant on its own, but the interaction term $FFE \times TO$ yields a positive result, suggests that energy efficiency gains are reinforced by technological improvements acquired through foreign trade. This result is consistent with the studies by Chen et al. [54], which suggest that trade can reduce pollution through its "technical effect", and Çütcü et al. [57], which report that technology imports improve standards in Türkiye. The fact that approximately 21% of Türkiye's imports in 2023 consisted of machinery and electrical equipment [88] indicates that foreign trade provides a channel that supports technological renewal. Taken together, these findings reveal that Türkiye's current foreign trade structure increases environmental pressure, but that the positive effects of technology-intensive imports on energy efficiency can partially offset this pressure under certain conditions.

For Türkiye, these results indicate that scale, composition, and technical effects, which vary according to income level, should be translated into separate targets in policy design. Specifically, policies that reduce energy demand should be prioritized during periods when scale effects are dominant, applications that accelerate inter-sectoral transformation should be prioritized during phases where composition effects are prominent, and tools that encourage efficiency investments should be prioritized during phases where technical effects are strengthened. Furthermore, the conditional effect in Model 2 reveals that energy efficiency and openness to trade, when considered together, support environmental sustainability more effectively, thus demonstrating that technology-intensive imports have the potential to reduce environmental pressures when implemented in coordination with efficiency programs.

6. Conclusions

This study analyzes the relationship between energy efficiency and environmental sustainability in Türkiye during the period 1982–2023, focusing on the moderating role of openness in this relationship within the framework of the Load Capacity Curve (LCC) hypothesis. Empirical findings reveal that environmental sustainability is sensitive to the level of energy efficiency and that this effect is conditioned by openness to trade. In this respect, the study shows that the environmental consequences of energy efficiency must be considered in conjunction with openness to trade.

The results show that increases in energy efficiency support environmental sustainability, but this effect can be strengthened or weakened depending on the level of openness to the outside world. In particular, the interaction between energy efficiency and openness to the outside world ($FFE \times TO$) creates a mechanism that supports environmental sustainability through technology transfer and knowledge diffusion channels.

When the economic growth variable is taken into account in the study, the findings show that the relationship between growth and environmental sustainability in Türkiye is not linear and exhibits a three-stage inverted-N shape. This result indicates that, despite gains in energy efficiency, environmental pressures can re-emerge after a certain income

level. At low income levels, the scale effect associated with industrialization increases environmental pressures, while at middle income levels, the technical effect based on energy efficiency comes to the fore. In contrast, the environmental degradation observed at high income levels shows that pressures from consumption and transportation can outweigh gains in energy efficiency.

Within this framework, the findings reveal that trade policies that do not focus on energy efficiency may be limited in terms of environmental sustainability. Conversely, openness strategies aligned with energy efficiency-focused technology and industrial policies may play a supportive role in environmental sustainability. Therefore, the study demonstrates that the interaction between energy efficiency and trade openness is one of the determining factors of environmental sustainability in Türkiye.

In light of these empirical findings, the following concrete policy recommendations are presented with the aim of strengthening the energy efficiency–trade interaction and reversing the decline in the third stage of the inverse-N curve in Türkiye:

1. **Taxation of Consumption-Related Emissions (Third-Stage Intervention):** The analysis results show that the main reason for the renewed increase in pollution at high income levels is consumption and transportation demand. Therefore, policymakers should abandon strategies focused solely on industrial emissions and shift towards demand-side policies. Increasingly progressive carbon taxes or “ecological footprint taxes” on luxury goods and high-emission vehicles should be implemented to curb the excessive consumption pressure created by income growth.
2. **The “Green Filter” Era in Trade Policy:** To neutralize the negative impact of trade (Model 1) and strengthen the technology transfer effect (Model 2), “Minimum Energy Efficiency Standards” should be introduced into the import regime. The entry of energy-intensive, old-technology machinery and equipment into the country should be restricted; conversely, customs duty reductions or VAT exemptions should be applied to imports of high-tech capital goods that enable digitalization and energy savings in industry.
3. **Policy Integration and Carbon Border Adjustment Mechanism (CBAM) Compliance:** The interactive effect of energy efficiency and trade demonstrates that these two areas cannot be managed independently of each other. The Carbon Border Adjustment Mechanism (CBAM) process of the EU, Türkiye’s largest trading partner, should be used as an opportunity for the technological transformation of industry, rather than as a threat. Incentives provided to exporting companies should be conditional on “reducing their carbon footprint” and “investing in energy efficiency.” In this way, trade can be transformed from a channel that exports pollution to one that imports clean technology.
4. **Lessons from the Circular Economy and Second Stage:** To make the improvement achieved at the middle-income level sustainable, the 2007 Energy Efficiency Law should be updated and integrated with the “Circular Economy Action Plan.” The pressure of growth on resource consumption (scale effect) should be reduced by making recycling and industrial symbiosis practices mandatory to increase raw material efficiency in industry.

Future studies could examine this analysis in more detail by breaking it down by sector (e.g., transportation vs. manufacturing) to identify which sectors contribute to the Inverted-N structure. Furthermore, examining the differentiated effects of renewable energy types (solar, wind, biomass) on this curve would make significant contributions to the literature.

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Abbreviations

The following abbreviations are used in this manuscript:

EKC	Environmental Kuznets Curve
GDP	Gross Domestic Product
LCC	Load Capacity Curve
LCF	Load Capacity Factor
UNDP	United Nations Development Programme

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