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Environmental taxes, growth, and emissions in Türkiye: Evidence from Fourier FMOLS

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ABSTRACT

This study investigates the long-run relationship between environmental degradation, environmentally related tax revenues, economic growth, unemployment, and inflation in Türkiye over the period 1994–2022. Using the Fourier Fully Modified Ordinary Least Squares (Fourier FMOLS) method, the analysis jointly examines the Environmental Kuznets Curve (EKC), the Environmental Phillips Curve (EPC), and an Environmental Laffer Curve-type nonlinear taxation–emissions relationship. Carbon dioxide emissions and carbon intensity are used as alternative indicators of environmental degradation, while environmentally related tax revenues, real GDP per capita, unemployment, and inflation are included as explanatory variables. The findings indicate a statistically significant inverted U-shaped relationship between environmentally related tax revenues and both environmental degradation indicators. The Lind-Mehlum *U* test further confirms that the estimated turning points for environmental tax revenues lie within the observed sample range, providing evidence consistent with an Environmental Laffer Curve-type relationship. The EKC results are more nuanced: while the Fourier FMOLS coefficients suggest a nonlinear income–environment relationship, the *U* test confirms an in-sample inverted U-shaped pattern only for carbon intensity, not for absolute CO_2 emissions. The results also support the EPC framework, as unemployment is negatively associated with both CO_2 emissions and carbon intensity. These findings suggest that environmental degradation in Türkiye is shaped by nonlinear and threshold-sensitive fiscal, economic, and labor market dynamics. The study contributes to the literature by integrating EKC, EPC, and an ELC-type framework in the Turkish context, while emphasizing that environmentally related tax revenues should be interpreted as an imperfect proxy for environmental tax pressure rather than as a direct measure of tax stringency. Policy implications point to the need for green fiscal reform, cleaner production incentives, and employment policies aligned with low-carbon transition objectives.

1. Introduction

Increased economic activity, fossil fuel dependence, and energy-intensive production structures have intensified environmental degradation across both developed and emerging economies. Over the last few decades, rising greenhouse gas emissions, air pollution, and climate-related risks have become central challenges for sustainable development. In this context, the United Nations Sustainable Development Goals (SDGs), particularly Goal 13 on climate action and Goal 11 on sustainable cities and communities, emphasize the need to reconcile economic development with environmental sustainability [1]. For emerging economies, this challenge is particularly important because growth, employment creation, fiscal policy, and environmental protection are closely interconnected.

Türkiye provides a relevant case for examining these interactions. The country signed the Paris Climate Agreement in 2016, ratified it in October 2021, and announced a net-zero emissions target for 2053 [2]. In line with the European Green Deal, Türkiye also introduced the Green Deal Action Plan in 2021, which includes policy actions related to clean energy transition, carbon pricing mechanisms, green technology investments, and sustainable production practices [3]. In addition, Türkiye updated its 2030 emissions target in 2022 and declared a 41% reduction from the projected increase in greenhouse gas emissions [4]. These policy developments indicate that environmental sustainability has become an increasingly important component of Türkiye's development strategy.

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Despite these policy commitments, Türkiye's greenhouse gas emissions have followed a strong upward trend over the last three decades. As shown in Fig. 1, total greenhouse gas emissions increased from approximately 220 million tons of CO_2 equivalent in 1990 to >570 million tons in 2021, before declining slightly to 558.3 million tons of CO_2 equivalent in 2022 [5]. This corresponds to an increase of >150% over the period. Per capita greenhouse gas emissions also rose from 4.1 tons of CO_2 equivalent in 1990 to 6.8 tons in 2021 [5]. This trend suggests that Türkiye's growth process has remained closely associated with rising environmental pressure, making the design of effective environmental and fiscal policies particularly important.

These developments raise important questions about the relationship between economic growth, labor market conditions, environmental taxation, and environmental degradation in Türkiye. One of the most widely discussed approaches in this field is the Environmental Kuznets Curve (EKC) hypothesis, which proposes an inverted U-shaped relationship between income and environmental degradation. According to this hypothesis, environmental degradation initially increases with economic growth, but after a certain income threshold, further increases in income may reduce environmental pressure through structural transformation, technological progress, and stronger environmental preferences [6,7].

A second relevant perspective is the Environmental Phillips Curve (EPC) hypothesis, which focuses on the relationship between unemployment and environmental degradation. The EPC suggests that lower unemployment and higher economic activity may be associated with higher emissions, while periods of higher unemployment may coincide with lower emissions due to reduced production and energy demand [8]. However, this relationship should not be interpreted as a permanent policy trade-off between employment and environmental quality. Rather, it may reflect the current carbon intensity of production structures and the extent to which green technologies, renewable energy, and low-carbon employment opportunities have developed.

In addition to growth and employment dynamics, environmental taxation is one of the most important policy instruments used to internalize environmental externalities. Environmental taxes can increase the cost of polluting activities and create incentives for firms and consumers to adopt cleaner technologies and reduce emissions. However, the effectiveness of such taxes may depend on their level, design, coverage, and the behavioral responses they generate. In Türkiye, environmentally related taxes are largely concentrated in areas such as fuel consumption, motor vehicles, transportation, and energy use. Therefore, environmental tax revenues do not necessarily represent a direct carbon tax rate or a pure measure of environmental policy stringency. Nevertheless, they can be used as a proxy for environmental tax pressure, provided that their limitations are clearly acknowledged.

Building on this discussion, this study explores whether the relationship between environmentally related tax revenues and environmental degradation follows a nonlinear pattern. More specifically, the study proposes an Environmental Laffer Curve-type relationship, according to which the effect of environmental taxation on emissions may depend on threshold dynamics. At relatively low levels, environmental tax revenues may be associated with higher emissions because they may reflect the expansion of taxed polluting activities rather than strong behavioral change. Beyond a certain level, however, environmental taxation may begin to exert stronger incentive effects by encouraging cleaner production, lower fossil fuel consumption, and technological adjustment. In this sense, the Environmental Laffer Curve approach developed in this study should be understood not as a direct replication of the traditional Laffer Curve, but as a conceptual extension that investigates a possible nonlinear tax–emissions relationship.

This study contributes to the literature in three main ways. First, it jointly examines the EKC, EPC, and an Environmental Laffer Curve-type nonlinear taxation–emissions relationship within the same empirical framework for Türkiye. Second, it evaluates environmental degradation using two alternative indicators, namely CO_2 emissions and carbon intensity, thereby providing a broader perspective on both absolute emissions and emissions efficiency. Third, it emphasizes the fiscal dimension of environmental policy by examining whether environmentally related tax revenues are associated with nonlinear changes in environmental degradation. By doing so, the study offers evidence on the role of fiscal instruments in Türkiye's green transition process while also recognizing that environmental tax revenues are an imperfect proxy for tax stringency.

Using annual data for the period 1994–2022, the study analyzes the long-run relationship between environmental degradation, environmentally related tax revenues, economic growth, unemployment, and inflation in Türkiye. The empirical analysis allows for nonlinear effects through squared income and environmental tax terms and accounts for smooth structural changes over time. Rather than claiming to estimate an optimal environmental tax rate, the study aims to identify whether threshold-sensitive nonlinear patterns exist in the Turkish case. The findings are expected to provide useful insights for the design of environmental taxation, green fiscal reform, and sustainable development policies in emerging economies.

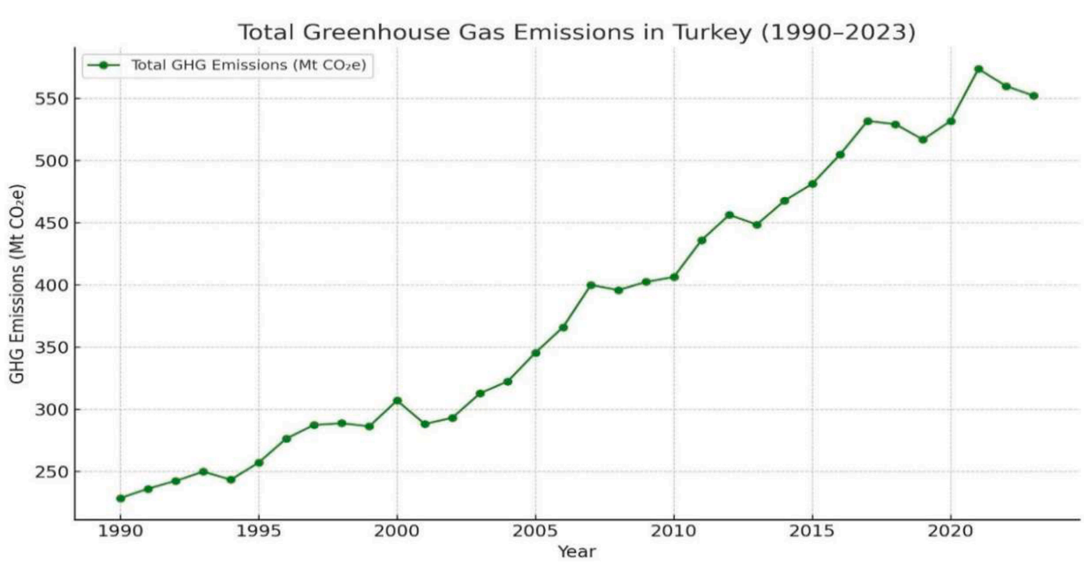

Fig. 1. Total greenhouse gas emissions (CO_2 equivalent, Mt) in Türkiye by year. Source: TurkStat [5].

2. Literature review

The relationship between economic growth and environmental degradation has been one of the central debates in environmental economics. The Environmental Kuznets Curve (EKC) hypothesis suggests that environmental degradation initially increases with economic growth, but after a certain income threshold, further increases in income may contribute to environmental improvement through structural transformation, technological progress, stronger institutions, and rising environmental awareness. The hypothesis was first discussed by Grossman and Krueger [6], later developed by Shafik and Bandyopadhyay [9] and Panayotou [7], and has since become a widely used framework for examining the growth–environment nexus.

Empirical findings on the EKC hypothesis, however, remain mixed. While several studies have found evidence of an inverted U-shaped relationship between income and environmental degradation indicators such as CO_2 emissions or ecological footprint [10,11], others have reported weak, insignificant, or even non-inverted U-shaped relationships [12,13]. These differences are generally attributed to country-specific characteristics, sample periods, environmental indicators, energy structures, and econometric methods. Carson [14], for instance, argues that the EKC literature does not always provide a sufficiently clear explanation of the mechanisms through which income growth improves environmental quality. Similarly, the validity of the EKC may depend on the existence of effective environmental regulation, technological upgrading, renewable energy diffusion, and institutional capacity rather than income growth alone.

Recent country-specific studies also confirm that the EKC should not be treated as a universal empirical regularity. Kilinc-Ata and Likhachev [15], for example, examined the relationship between CO_2 emissions, economic growth, energy consumption, population, trade openness, and financial development in the Russian Federation for the period 1990–2020 using the ARDL bounds testing approach. Their findings revealed that energy consumption and population increased CO_2 emissions, while GDP, financial development, and trade openness reduced emissions in the long run. However, the signs of GDP and GDP^2 indicated a U-shaped relationship rather than the conventional inverted U-shaped EKC, suggesting that the EKC hypothesis was not fully supported in the Russian case. This finding is important because it shows that resource-dependent economies may not automatically move toward lower emissions after reaching higher income levels.

Similarly, Kilinc-Ata [16] investigated the determinants of CO_2 emissions in Oman for the period 1990–2023 using an ARDL model. The study considered GDP, energy consumption, financial development, foreign direct investment, urbanization, and population as explanatory variables. The results showed that urbanization and GDP reduced CO_2 emissions, whereas population growth, energy use, FDI, and financial development increased emissions. The study also emphasized the importance of clean energy technologies, stronger environmental regulation, reduced energy consumption, and net-zero policy targets for fossil-fuel-dependent economies. These findings are relevant for the present study because Türkiye, like other emerging and energy-importing economies, faces the challenge of sustaining economic growth while reducing the carbon intensity of production.

In addition to the EKC framework, the decoupling literature provides another important perspective on the relationship between economic growth and emissions. Decoupling refers to the ability of an economy to continue growing without a proportional increase in environmental pressure. Kilinc-Ata, Xavier, and Bhat [17] compared CO_2 emissions decoupling in the European Union and Gulf Cooperation Council countries over the period 1990–2023 using the Decoupling Consistency Index and Logarithmic Mean Divisia Index decomposition. Their results showed that the EU achieved absolute decoupling due to sustained reductions in energy intensity and CO_2 intensity, while GCC countries experienced only partial decoupling because efficiency gains were often offset by rapid economic expansion and population growth. This evidence suggests that the relationship between growth and emissions is strongly shaped by energy structure, policy design, technological capacity, and institutional differences. Therefore, the EKC should be interpreted together with broader decoupling and decomposition perspectives.

The Environmental Phillips Curve (EPC) hypothesis has recently emerged as another framework for understanding the interaction between macroeconomic activity and environmental degradation. The EPC suggests that there may be a negative relationship between unemployment and emissions: when unemployment declines and economic activity expands, production, transportation, and energy demand may rise, thereby increasing emissions; when unemployment rises during economic slowdowns, emissions may temporarily decline. Kashem and Rahman [8] introduced this concept using data from OECD and newly industrialized Asian economies and found a statistically significant negative relationship between unemployment and per capita carbon emissions. Later studies have also examined the EPC for different country groups and methodological settings [18–20].

Nevertheless, the EPC should be interpreted cautiously. A negative coefficient on unemployment does not necessarily imply a stable or desirable trade-off between employment and environmental quality. It may instead reflect cyclical reductions in production and energy demand during periods of economic slowdown. In this sense, EPC-type relationships may be stronger in economies where production remains energy-intensive and fossil-fuel dependent. The literature also emphasizes that green employment, renewable energy investments, technological innovation, and energy efficiency improvements can weaken this apparent trade-off over time [21]. Therefore, the EPC provides a useful but conditional framework for examining whether Türkiye's labor market dynamics are linked to environmental degradation.

Another strand of the literature focuses on environmental policy instruments, environmental taxation, and clean energy transition. Environmental taxes are designed to internalize negative environmental externalities by increasing the cost of pollution-intensive activities. In theory, these taxes should encourage firms and households to reduce fossil fuel consumption, adopt cleaner technologies, and shift toward less carbon-intensive production and consumption patterns. However, empirical findings on the environmental effectiveness of such taxes are mixed. Some studies find that environmental taxes reduce emissions, but the magnitude of the effect is often limited. For example, Cural and Saygı [22] show that environmental taxes in European Union countries are associated with only limited reductions in carbon emissions. Özkaya [23] similarly reports statistically significant but relatively small emission-reducing effects of environmental tax revenues in European countries. Sun and Lin [24], in their study on China, find that environmental taxation has a negative but small effect on greenhouse gas emissions.

The effects of environmental taxation have also been examined in relation to economic growth, renewable energy, and sustainable development. Kurt [25], using data from 27 European Union countries, shows that the growth effects of renewable energy consumption may vary depending on the level of environmental taxation. This finding is relevant because it indicates that environmental taxes may interact with energy transition dynamics in a nonlinear manner. Atay-Polat and Ergün [26], focusing on Türkiye, argue that environmental taxes can support sustainable growth in the long run by reducing carbon emissions and encouraging green energy investments. Similarly, Özbek [27] provides Türkiye-specific evidence that a 1% increase in environmental taxes reduces CO_2 emissions by 0.07%, whereas a 1% increase in per capita income increases emissions by 0.41%. These studies suggest that environmental taxes may contribute to environmental improvement when they are properly designed; however, their effects are often modest and depend on broader economic, institutional, and energy-related conditions.

The mixed effectiveness of environmental taxation is also linked to the type and design of policy instruments. Kilinc-Ata and Proskuryakova

[28], examining 16 Asia-Pacific economies over the period 2000–2021, analyzed the role of renewable energy policy instruments such as feed-in tariffs, quotas, tenders, and tax incentives in the green energy transition. Their findings show that feed-in tariffs, quotas, and tenders play an important role in supporting renewable energy transition, whereas tax incentives are not found to be statistically effective. This result is particularly important for the present study because it suggests that fiscal incentives and tax-based instruments do not automatically generate strong environmental outcomes. Their effectiveness depends on policy design, implementation capacity, coverage, and monitoring mechanisms.

In this regard, environmental taxes should not be evaluated only through their revenue-generating function. The environmental impact of such taxes depends on whether they create sufficient behavioral and technological responses. Low or poorly targeted environmental taxes may generate fiscal revenue without substantially changing polluting behavior. Conversely, stronger or better-designed environmental taxation may encourage fuel switching, energy efficiency, renewable energy adoption, and cleaner production. This distinction is particularly relevant for Türkiye because environmentally related taxes are largely concentrated in fuel consumption, motor vehicles, transportation, and energy use rather than being designed as a direct carbon tax. Therefore, environmental tax revenues may reflect both environmental policy pressure and the size of the underlying taxed polluting activities.

Recent studies also emphasize that environmental outcomes depend on broader policy uncertainty, energy intensity, and the ability of economies to adapt to structural changes. Kilinc-Ata et al. [29] investigated the effect of economic policy uncertainty on load capacity factors in China and the United States using the Fourier Bootstrap ARDL approach. The study found that economic policy uncertainty temporarily improved environmental quality in China, while its long-run effect differed for the United States. It also showed that energy intensity plays a crucial role in environmental degradation. This study is relevant for two reasons. First, it demonstrates that environmental quality is affected by macroeconomic uncertainty and energy intensity, not only by income or taxation. Second, it highlights the usefulness of Fourier-based methods in capturing smooth structural changes in environmental-economic relationships.

The use of Fourier-based approaches has become increasingly common in environmental economics because environmental and macroeconomic series often contain structural shifts caused by energy crises, policy reforms, financial crises, technological changes, and international climate agreements. Fourier methods allow such shifts to be modeled as smooth and gradual changes without requiring the exact break dates to be known in advance. This is important for countries such as Türkiye, where the sample period includes several macroeconomic crises, energy price shocks, policy reforms, and climate-related institutional changes. Therefore, Fourier-based methods provide a useful empirical tool for examining long-run environmental relationships under structural change.

Within this broader literature, the present study explores an Environmental Laffer Curve-type nonlinear relationship between environmentally related tax revenues and environmental degradation. The concept is inspired by the traditional Laffer Curve logic, but it should not be interpreted as a direct replication of the relationship between tax rates and tax revenues. Instead, the ELC-type framework in this study refers to the possibility that the association between environmental tax revenues and emissions may be nonlinear. At low levels, rising environmental tax revenues may reflect the expansion of pollution-related tax bases such as fuel consumption, vehicle ownership, transportation, and energy use. Beyond a certain threshold, however, stronger environmental tax pressure may begin to generate incentive effects by encouraging cleaner technologies, lower fossil fuel consumption, and behavioral adjustment.

This approach is consistent with the broader literature on nonlinear, threshold, and asymmetric effects of environmental policies, carbon pricing, and environmental taxation. However, the present study differs from previous research by jointly examining three interrelated hypotheses — the EKC, EPC, and an ELC-type nonlinear taxation–emissions relationship — within the same empirical framework for Türkiye. By using both CO_2 emissions and carbon intensity as alternative indicators of environmental degradation, the study aims to provide evidence not only on the level of emissions but also on emissions efficiency relative to economic output. In this respect, the contribution of the study is not to claim that nonlinear environmental tax effects have never been discussed before, but to examine whether environmentally related tax revenues exhibit a threshold-sensitive association with environmental degradation in the Turkish context.

Overall, the reviewed literature indicates three important points. First, the EKC hypothesis remains empirically contested, and its validity depends on country-specific energy structures, environmental policies, technological capabilities, and institutional conditions. Second, EPC-type relationships should be interpreted as conditional macro-environmental associations rather than as a permanent conflict between employment and environmental quality. Third, environmental taxation and fiscal instruments may contribute to emissions reduction, but their effectiveness depends on design, stringency, coverage, and the extent to which they induce behavioral and technological change. Against this background, the present study contributes to the literature by examining the nonlinear links between environmental degradation, growth, unemployment, and environmentally related tax revenues in Türkiye while explicitly acknowledging the limitations of revenue-based tax measures and the importance of threshold effects.

3. Materials and methods

3.1. Theoretical framework

The theoretical framework of this study is built on the interaction between economic activity, labor market conditions, fiscal-environmental policy instruments, and environmental degradation. In the environmental economics literature, the Environmental Kuznets Curve (EKC) emphasizes the nonlinear relationship between income and environmental degradation, while the Environmental Phillips Curve (EPC) focuses on the macroeconomic trade-off between unemployment and emissions. In addition to these two frameworks, this study explores an Environmental Laffer Curve-type relationship, which refers to a possible nonlinear association between environmentally related tax revenues and environmental degradation. Rather than treating this relationship as a direct replication of the traditional Laffer Curve, the study conceptualizes it as a threshold-sensitive fiscal-environmental mechanism in which the environmental effect of tax-related revenues may vary depending on the level, design, and behavioral impact of environmental taxation.

The EKC hypothesis argues that environmental degradation may initially increase during the early stages of economic development but may decline after income reaches a certain threshold. In the early stages of growth, industrialization, fossil fuel consumption, transportation activity, and energy-intensive production generally expand. As a result, economic growth tends to increase emissions and environmental pressure through the scale effect. In this phase, the priority of policymakers and society is often income growth, employment creation, and industrial expansion, while environmental quality may remain secondary.

However, after a certain income level, the relationship between growth and environmental degradation may begin to change. Rising income can increase social demand for environmental protection, while structural transformation may shift the economy from heavy industry toward services and higher-value-added sectors. At the same time, technological progress, renewable energy use, improvements in energy efficiency, and stricter environmental regulations can reduce the emission intensity of production. These mechanisms may cause environmental degradation to decline after a turning point, generating the inverted U-shaped relationship proposed by the EKC hypothesis [6,7]. Nevertheless, the EKC should not be interpreted as an automatic process in which growth inevitably solves environmental problems. The transition toward the downward segment of the EKC depends on institutional quality, environmental regulation, clean technology adoption, and effective policy interventions. Therefore, the EKC framework is better understood as a conditional relationship rather than a universal law.

The EPC hypothesis extends the macroeconomic relationship between growth, unemployment, and economic activity to the environmental context. In general, lower unemployment is associated with higher production, stronger aggregate demand, and greater use of energy and transportation services. If the production structure is carbon-intensive, periods of low unemployment and high economic activity may coincide with higher emissions. Conversely, higher unemployment may reflect economic slowdown, lower production, and reduced energy demand, which can temporarily reduce emissions. In this sense, the EPC suggests a negative association between unemployment and environmental degradation: when unemployment decreases, emissions may increase; when unemployment rises, emissions may decline.

The theoretical basis of the EPC can be linked to Okun's Law and the traditional Phillips Curve. Okun's Law implies that lower unemployment is generally associated with higher output, while the Phillips Curve relates labor market tightness to macroeconomic pressure. From an environmental perspective, stronger output and lower unemployment may increase fossil fuel consumption, industrial production, and transportation-related emissions. This mechanism is especially relevant for economies where energy production and industrial activity remain dependent on fossil fuels. However, the EPC should not be interpreted as a desirable or permanent conflict between employment and environmental quality. Rather, it reflects the current structure of production and energy use. In the long run, green employment, renewable energy investments, clean technologies, and improvements in energy efficiency may weaken or even eliminate this trade-off by allowing economies to reduce emissions while maintaining employment growth.

The third theoretical component of the study concerns the relationship between environmental taxation and environmental degradation. From the perspective of Pigouvian taxation, environmental taxes are designed to internalize negative externalities by increasing the cost of pollution-intensive activities. In theory, such taxes should encourage firms and households to reduce fossil fuel consumption, invest in cleaner technologies, and shift toward less carbon-intensive behavior. However, the empirical effectiveness of environmental taxation depends on tax design, coverage, enforcement, the availability of clean alternatives, and the behavioral responses of economic agents. Low or narrowly designed taxes may generate fiscal revenue without sufficiently changing polluting behavior, while stronger and better-targeted environmental taxes may induce technological adjustment and emission reductions.

This study proposes an Environmental Laffer Curve-type framework to examine whether the association between environmentally related tax revenues and environmental degradation is nonlinear. The term is inspired by the traditional Laffer Curve, which describes a nonlinear relationship between tax rates and tax revenues. However, the framework used in this study differs from the classical Laffer mechanism. The traditional Laffer Curve focuses on the revenue-maximizing tax rate, whereas the present study focuses on whether environmentally related tax revenues are associated with a turning point in environmental degradation. Therefore, the ELC-type relationship should not be interpreted as an attempt to estimate an optimal tax rate or a welfare-maximizing environmental tax level.

The key distinction is that the empirical variable used in this study is not a statutory environmental tax rate but environmentally related tax revenues. This distinction is theoretically important. Environmental tax revenues may reflect not only tax pressure but also the size of the underlying tax base, including fuel consumption, vehicle ownership, transportation activity, and energy use. Therefore, at relatively low or intermediate levels, rising environmental tax revenues may be associated with higher emissions because they may reflect the expansion of pollution-intensive taxed activities rather than effective behavioral change. In other words, a positive association between environmental tax revenues and emissions does not necessarily imply that environmental taxes cause environmental degradation; it may indicate that the tax base itself is closely linked to polluting economic activities.

Beyond a certain threshold, however, higher environmental tax pressure may begin to generate stronger incentive effects. If environmental taxes become sufficiently binding and are accompanied by regulatory support, technological alternatives, and clean energy investment, firms and households may respond by reducing fossil fuel consumption, improving energy efficiency, adopting cleaner technologies, or changing consumption and transportation behavior. Under these conditions, further increases in environmentally related tax revenues may coincide with lower emissions or reduced carbon intensity. This gives rise to the possibility of an inverted U-shaped relationship between environmentally related tax revenues and environmental degradation.

Fig. 2 illustrates this conceptual ELC-type relationship. The upward segment of the curve represents the possibility that environmental tax revenues initially move together with environmental degradation because they partly capture the expansion of pollution-related tax bases. The downward segment represents the possibility that, after an empirical threshold, environmental tax pressure becomes strong enough to induce behavioral and technological adjustment. Therefore, the threshold shown in Fig. 2 should be interpreted as a conceptual turning point, not as an optimal tax rate. In the empirical analysis, the existence of such a turning point must be tested through the estimated coefficients and verified by checking whether the implied threshold lies within the observed sample range.

The Turkish economy provides an appropriate case for examining this relationship because environmentally related taxes have historically played an important fiscal role, but their structure differs from a direct carbon tax system. In Türkiye, environmental tax revenues are largely associated with energy use, fuel consumption, transportation, and motor vehicles. Therefore, these revenues may simultaneously reflect environmental policy pressure and the scale of carbon-intensive economic activity. This dual character makes it necessary to interpret the environmental tax variable carefully.

Fig. 3 presents the share of environmental tax revenues in GDP in Türkiye over the period 1994–2022. The ratio increased significantly from the mid-1990s to the early 2000s and reached its highest levels in the first half of the 2000s. After this period, however, the share of environmental tax revenues in GDP gradually declined and remained lower in the late 2010s and early 2020s. These changes indicate that the fiscal weight of environmentally related taxation has not followed a stable linear path over time.

Similarly, Fig. 4 shows the share of environmental tax revenues in total tax revenues in Türkiye. This ratio increased sharply in the early 2000s, mainly reflecting the fiscal importance of taxes related to fuel consumption and motor vehicles, but later declined. The downward trend after the mid-2000s suggests that the relative role of environmentally related taxes in the overall tax system weakened over time. These descriptive patterns provide useful background for understanding the fiscal-environmental context of Türkiye. However, they should be interpreted as descriptive indicators rather than direct evidence of the ELC-type relationship tested in the empirical model.

In light of these theoretical considerations, the present study does not claim to identify an optimal environmental tax rate. Instead, it investigates whether the relationship between environmentally related tax revenues and environmental degradation exhibits a statistically meaningful nonlinear pattern. If the coefficient of environmental tax revenues is positive and the coefficient of its squared term is negative, this would suggest an inverted U-shaped association. However, such a finding can only be interpreted as evidence of an ELC-type relationship if the estimated turning point lies within the observed data range and the

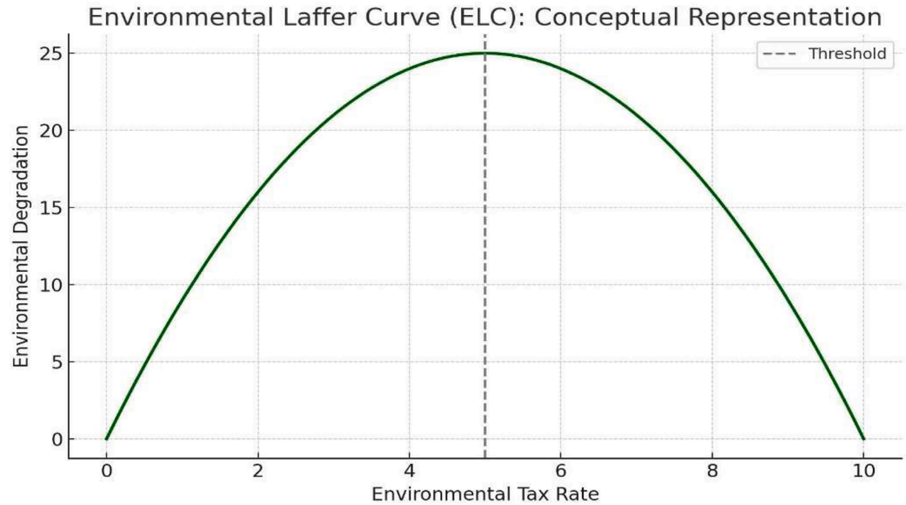

Fig. 2. Conceptual representation of the Environmental Laffer Curve hypothesis.

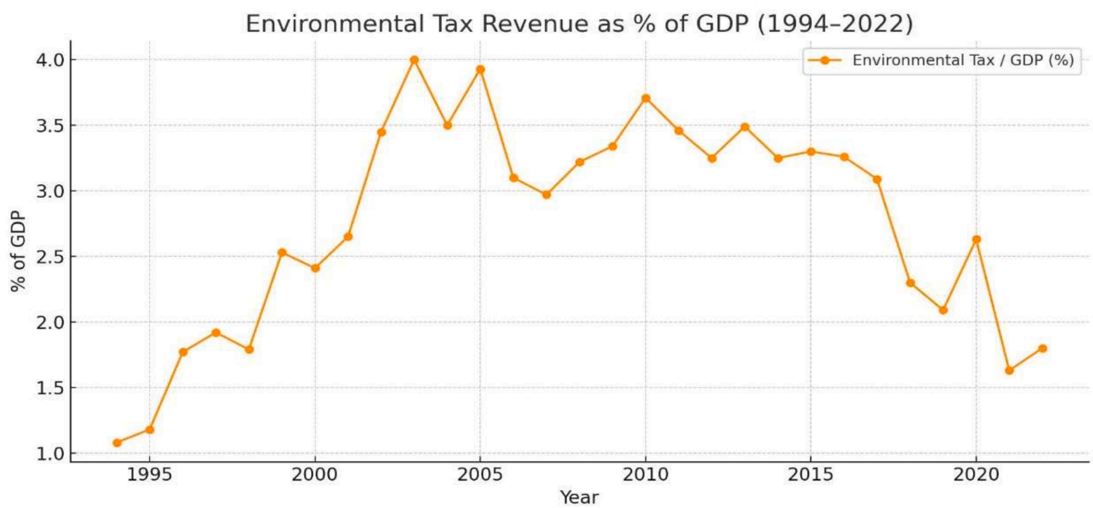

Fig. 3. Change in the share of environmental tax revenues in GDP over time in Türkiye (%). Source: Compiled from OECD environmentally related tax revenue statistics [30].

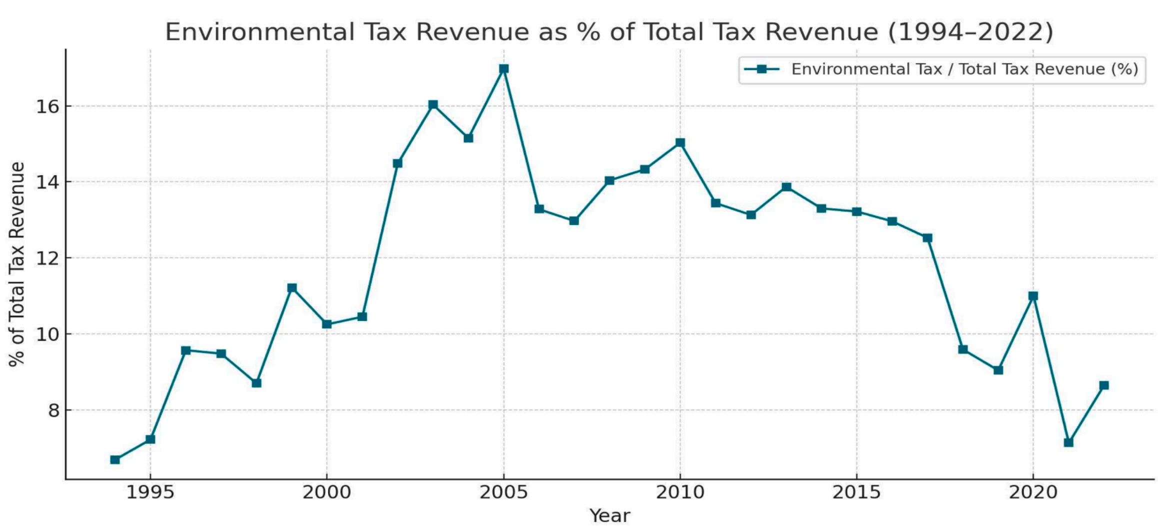

Fig. 4. Share of environmental tax revenues in total tax revenues in Türkiye (%). Source: Compiled from OECD environmentally related tax revenue statistics [30].

nonlinear pattern is empirically validated. Therefore, the ELC-type framework in this study is used as an exploratory and threshold-sensitive approach to examine the fiscal dimension of environmental degradation in Türkiye.

Overall, the theoretical framework suggests that environmental degradation in Türkiye may be shaped by three interrelated mechanisms. First, economic growth may affect emissions nonlinearly through the EKC mechanism. Second, unemployment may be negatively associated with emissions through the EPC mechanism, reflecting the link between economic activity and environmental pressure. Third, environmentally related tax revenues may exhibit a nonlinear association with environmental degradation, reflecting both the expansion of pollution-related tax bases and the potential incentive effects of environmental taxation beyond a certain threshold. By considering these mechanisms jointly, the study provides a broader framework for analyzing the interaction between growth, labor market dynamics, fiscal policy, and environmental sustainability in Türkiye.

3.2. Data and methodology

This study uses annual data covering the period 1994–2022 for the Turkish economy. The primary dependent variable of the study is represented by two different environmental degradation indicators: carbon dioxide emissions per capita (LCO_2) and, alternatively, carbon intensity (CINT, carbon intensity of GDP, kg CO_2e per constant 2015 US$ of GDP). These two indicators reflect the level of environmental pollution and emission efficiency relative to economic growth and are considered suitable for empirical testing of both the EKC and ELC hypotheses [31].

Among the independent variables, real per capita GDP (log(GDP)-LGDP) and its square ($LGDP^2 = (\log GDP)^2$), representing real economic growth, were included to examine potential nonlinear effects on environmental degradation. This approach is widely adopted in the literature for testing the EKC hypothesis [32]. The environmental tax variables, which constitute the original aspect of the study, are modeled as the total of environmentally qualified tax revenues (log(REV)-LREV) and its square ($LREV^2 = (\log REV)^2$). Through these variables, the study tests the ELC hypothesis, which aims to be introduced to the literature for the first time. According to this hypothesis, an increase in environmental tax revenues increases environmental degradation up to a threshold, after which it decreases. Thus, a nonlinear inverse U-shaped relationship between environmental tax pressure and environmental quality is proposed.

The control variables used were the unemployment rate (%) and inflation rate (CPI based on the Consumer Price Index, CPI). The unemployment rate aims to measure the interaction between environmental quality and the labor market, referencing the EPC hypothesis, while the inflation is included to reflect the socioeconomic conditions that may affect environmental degradation.

The data were compiled from the World Bank (World Development Indicators), OECD Tax Statistics, and TurkStat databases. We calculated the ratios of environmental tax revenues to total tax revenues based on OECD environmental tax statistics.

The findings related to the descriptive statistics in Table 1 summarize the distribution of the key variables included in the study within the context of the Turkish economy during the period 1994–2022. Carbon emissions (LCO_2) and carbon intensity (CINT), used as dependent variables, provide a general idea of the level of environmental degradation and the pressure of emissions on economic production during the period. The logarithm (LREV) and square of environmental tax revenues showed a gradual increase over time with a relatively low standard deviation. Similarly, LGDP and its square, used to represent economic growth, showed limited variability, indicating that economic stability was maintained at a certain level. Among the socioeconomic control variables, the unemployment rate (UNEMP), and consumer price index (CPI) have fluctuated with a wider variance over the period. This suggests that macroeconomic and social conditions have influenced environmental degradation with varying intensities over time. Overall, descriptive statistics indicate that the variables provide a balanced structure in terms of empirical representation in the model setup and exhibit a distribution suitable for the estimation process.

Table 1
Descriptive Statistics.

Variable	Obs	Mean	Std.	Min	Max
LCO_2	29	5.661	0.310	5.098	6.133
CINT	29	0.481	0.049	0.363	0.549
LREV	29	10.513	0.592	8.982	11.149
$LREV^2$	29	110.859	12.046	80.673	124.299
LGDP	29	9.031	0.300	8.561	9.551
$LGDP^2$	29	81.653	5.437	73.284	91.217
UNEMP	29	9.997	2.005	6.495	14.026
CPI	29	32.420	32.438	6.251	105.215

Prior to the empirical analysis, the stationarity properties of the variables were examined using the Dickey-Fuller Generalized Least Squares (DF-GLS) unit root test proposed by Elliott, Rothenberg, and Stock [33], together with the Zivot-Andrews (ZA) unit root test, which allows for a single endogenous structural break [34]. The DF-GLS test was preferred instead of the conventional Augmented Dickey-Fuller (ADF) test because it has higher power in small samples and provides more reliable inference for limited annual time-series observations. Since this study uses annual data for Türkiye over the period 1994–2022, the use of DF-GLS is considered appropriate for determining the integration properties of the series.

In addition, the ZA test was employed to account for possible structural breaks in the variables. This is particularly important in the case of Türkiye, as the sample period includes major macroeconomic crises, policy changes, energy price shocks, and environmental policy developments that may affect the time-series behavior of the variables. Ignoring such breaks may lead to biased unit root conclusions and misleading inference regarding the order of integration.

The unit root results indicate that the variables become stationary after first differencing and that none of the series is integrated of order two, I(2). Based on this evidence, the variables are treated as integrated of order one, I(1), for the purpose of long-run analysis. Accordingly, the multivariate Johansen cointegration test [35] was applied to examine whether a stable long-run equilibrium relationship exists among environmental degradation, environmentally related tax revenues, economic growth, unemployment, and inflation. The Johansen test is widely used in multivariate time-series analysis because it allows the identification of potential cointegrating relationships among non-stationary variables and can detect more than one cointegrating vector in the system.

After establishing the existence of cointegration, the long-run coefficients were estimated using the Fourier Fully Modified Ordinary Least Squares (Fourier FMOLS) method. Fourier FMOLS is an extension of the conventional FMOLS estimator and incorporates Fourier terms to capture unknown and smooth structural shifts in the long-run relationship. While the FMOLS estimator corrects for potential endogeneity and serial correlation in cointegrated systems, the Fourier extension allows structural changes to be modeled without requiring the exact break dates to be known in advance. This feature is particularly useful for Türkiye, where the relationships among environmental degradation, economic growth, environmental taxation, and macroeconomic variables may have been affected by gradual policy shifts, economic crises, and changes in the energy and environmental policy environment.

In the Fourier FMOLS specification, sine and cosine terms are added to the deterministic component of the model in order to approximate smooth structural changes over time. These Fourier terms allow the model to account for gradual breaks, cyclical movements, and regime-like shifts that may not be captured by conventional linear specifications. Therefore, the Fourier FMOLS approach provides a flexible framework for estimating long-run coefficients under the presence of unknown structural changes while maintaining the advantages of the

FMOLS estimator in cointegrated systems [36,37].

The general structure of the model can be expressed as follows:

$$Y_t = \beta_0 + \beta_1 X_{1t} + \ldots + \beta_k X_{kt} + \theta_1 \sin\left(\frac{2\pi kt}{T}\right) + \theta_2 \cos\left(\frac{2\pi kt}{T}\right) + e_t \quad (1)$$

- Y_t is dependent variable (logCO_2 and CI)
- X_{it} represents independent variables
- $\sin\left(\frac{2\pi kt}{T}\right)$ and $\cos\left(\frac{2\pi kt}{T}\right)$ indicates the Fourier terms used to capture smooth structural shifts or breaks
- θ_1 and θ_2 show the coefficients of the sinusoidal components
- k is the selected frequency (number of Fourier components used in the transformation)

Fourier terms add periodic components to the deterministic structure of the model, enabling the indirect modeling of structural effects such as changes in policy regimes, transformations in environmental regulations, or international agreements. This method is particularly advantageous in situations where the timing of structural breaks is unknown or where there may be numerous breaks.

In Fourier-based regression approaches, the frequency parameter (k) associated with the Fourier components is typically examined over a small range of integer values, and the value that yields the most accurate model representation is chosen as the optimal frequency. Previous studies have commonly identified the best-performing regression model by considering the minimum sum of squared residuals (SSR) criterion [36]. Following this approach, the models analyzed in this study were independently estimated for k values ranging from 0 to 5, with a step size of 0.01. The frequency parameter corresponding to the lowest SSR value was then selected as the optimal k value.

Fourier FMOLS absorbs the effects of these structural transformations, providing both unbiased and consistent long-term coefficient estimates [38]. In this study, the optimal frequency parameter (k) was selected as the value that minimized the sum of squared residuals (SSR), following the procedure suggested by Enders and Lee [36]. The coefficients obtained from Fourier FMOLS estimates enabled testing the nonlinear structure of the effect of environmental tax revenues on environmental degradation (ELC hypothesis), the environmental impact of economic growth (EKC hypothesis), and the relationship between unemployment and environmental variables (EPC hypothesis) within the same model.

Two different models were constructed in this study; Model 1 is a model with LCO_2 as the dependent variable, while Model 2, constructed for robustness checking, is a model with CINT as the dependent variable.

Model 1: $LCO_{2_t} = \beta_0 + \beta_1 LREV_t + \beta_2 LREV_t^2 + \beta_3 LGDP_t + \beta_4 LGDP_t^2 + \beta_5 UNEMP_t + \beta_6 URBAN_t + \beta_7 CPI + e_t$

Model 2: $CINT_t = \beta_0 + \beta_1 LREV_t + \beta_2 LREV^2{}_t + \beta_3 LGDP_t + \beta_4 LGDP^2{}_t + \beta_5 UNEMP_t + \beta_6 URBAN_t + \beta_7 CPI + u_t$

4. Results

In order to determine the stationarity properties of the variables used in this study, the DF-GLS unit root test and the ZA unit root test with an endogenous structural break were employed. The DF-GLS test was preferred instead of the conventional ADF test because it has greater power in small samples and is therefore more suitable for annual time-series data with a limited number of observations. The ZA test was additionally used to account for possible structural breaks in the series.

The DF-GLS results indicate that the null hypothesis of a unit root cannot generally be rejected for the variables at their levels. In both the constant and constant-plus-trend specifications, LCO_2, CINT, LREV, $LREV^2$, LGDP, $LGDP^2$, UNEMP, and CPI do not provide strong evidence of level stationarity. Similarly, the ZA test results do not provide robust evidence that the variables are stationary at level once structural breaks are taken into account. Although some test statistics are relatively close to conventional critical values, the overall evidence suggests that the variables are predominantly non-stationary in levels.

When the first differences of the variables are considered, the results provide stronger evidence of stationarity. According to the DF-GLS test, the first differences of LCO_2, CINT, LGDP, $LGDP^2$, and UNEMP are statistically significant under at least one deterministic specification. Similarly, ΔLREV and $\Delta LREV^2$ become strongly stationary in the constant-plus-trend specification, while ΔCPI is also stationary in the trend specification. The ZA test results further support the stationarity of the first-differenced variables, particularly for ΔLCO_2, ΔCINT, ΔLREV, $\Delta LREV^2$, ΔLGDP, $\Delta LGDP^2$, and ΔCPI. These findings indicate that the variables become stationary after first differencing.

Overall, the unit root test results suggest that the variables are integrated of order one, I(1), or at least do not exhibit integration beyond the first order. Importantly, there is no evidence that any of the variables is integrated of order two, I(2). This finding supports the continuation of the long-run analysis through a cointegration framework. Accordingly, the Johansen cointegration test is applied to examine whether a stable long-run equilibrium relationship exists among environmental degradation, environmentally related tax revenues, economic growth, unemployment, and inflation Table 2.

The results of the Johansen cointegration test are presented in Table 3. Both trace and maximum eigenvalue statistics were evaluated together with their corresponding 5% critical values. For Model 1, the trace statistics exceed the relevant critical values at all reported ranks, indicating rejection of the null hypothesis of no cointegration and supporting the existence of a long-run relationship among the variables. For Model 2, the trace statistics also exceed the corresponding critical values from r = 0 to r = 5, while the null is not rejected at r = 6. These findings provide evidence of cointegration in both model specifications.

The maximum eigenvalue statistics also support the presence of cointegration. For Model 1, the null hypotheses are rejected at the lower ranks, particularly from r = 0 to r = 2, while the evidence becomes weaker at higher ranks. For Model 2, the maximum eigenvalue statistics exceed the relevant critical values from r = 0 to r = 5, but not at r = 6. Overall, both the trace and maximum eigenvalue tests confirm that the variables in the two models are linked through a long-run equilibrium relationship. Therefore, the use of a long-run estimator such as Fourier FMOLS is empirically justified.

Table 2
Unit Root Test Results.

	DF-GLS		ZA	
	constant	constant+trend	constant	constant+trend
LCO_2	0.451	−2.674	−4.393	−4.531
CINT	−0.015	−2.201	−2.956	−3.209
LREV	−0.326	−0.542	−3.171	−2.474
$LREV^2$	−0.388	−0.578	−3.017	−2.353
LGDP	0.805	−2.918	−3.711	−3.71
$LGDP^2$	0.831	−2.833	−3.729	−3.629
UNEMP	−1.779	−3.038	−4.071	−4.228
CPI	−1.206	−0.249	−0.218	−0.491
ΔLCO_2	−4.435***	−4.248***	−5.91***	−6.129***
ΔCINT	−3.513***	−3.74**	−5.255**	−5.196**
ΔLREV	−1.777	−6.052***	−6.663***	−6.514***
$\Delta LREV^2$	−1.767	−5.872***	−6.565***	−6.530***
ΔLGDP	−3.188***	−3.385*	−4.964**	−5.462**
$\Delta LGDP^2$	−3.215***	−3.428**	−4.928**	−5.387**
ΔUNEMP	−3.403***	−3.978***	−4.917**	−4.815
ΔCPI	−0.017	−3.553**	−3.914	−5.193**

Notes: For the DF-GLS unit root test, the maximum lag length was set to 2, and the optimal lag length was chosen by the Schwarz criterion. Δ is the difference operator.

*** $p < 0.01$,.
** $p < 0.05$,.
* $p < 0.1$.

Table 3
Cointegration Results.

Rank	Trace Statistic		Max Eigenvalue Statistic		Critical Value at 5%			
	Model 1	Model 2	Model 1	Model 2	Trace-Model 1	Trace-Model 2	Eigenvalue-Model 1	Eigenvalue-Model 2
0	316.523	277.4409	122.3284	123.1743	146.76	124.24	49.42	45.28
1	184.8389	154.2667	50.2396	47.4405	114.9	94.15	43.97	39.37
2	131.4596	106.8262	39.8667	43.0006	87.31	68.52	37.52	33.46
3	89.1623	63.8256	28.0654	30.1632	62.99	47.21	31.46	27.07
4	56.4944	33.6623	18.2193	18.4403	42.44	29.68	25.54	20.97
5	32.6439	15.2220	15.0913	15.182	25.32	15.41	18.96	14.07
6	15.0673	0.04	0.0016	0.04	12.25	3.76	12.52	3.76

It should also be noted that the revised table reports the actual maximum eigenvalue test statistics rather than eigenvalue coefficients. This correction improves the transparency of the cointegration analysis and addresses potential ambiguity in the previous version of the table.

Considering that the dependent variable in Model 1 is logarithmic CO_2 emissions and in Model 2 it is carbon intensity, it is seen that meaningful and permanent relationships are established between these two indicators representing environmental degradation and economic growth, environmental taxes, and social indicator-type variables. Therefore, the theoretical and statistical basis for moving on to long-term analyses of both models is considered appropriate.

To determine the appropriate lag length for the Johansen cointegration analysis, an unrestricted Vector Autoregression (VAR) model was initially estimated. The information criteria suggested optimal lag lengths ranging from 2 to 4. However, given the limited sample size, estimating models with three or more lags resulted in a substantial loss of degrees of freedom. Therefore, a lag length of 2 was adopted for the subsequent analysis.

As a sensitivity analysis, the Johansen cointegration test was also estimated using a lag length of 1. Although these results are not reported for brevity, the lag-1 specification identified two cointegrating vectors. In addition, a residual-based cointegration test was conducted to provide complementary evidence on the long-run relationship. Taken together, these findings provide further support for the existence of a stable long-run cointegrating relationship among the variables.

Table 4 presents the long-run estimates obtained from the Fourier FMOLS method. Model 1 uses CO_2 emissions as the dependent variable, while Model 2 uses carbon intensity as an alternative indicator of environmental degradation. In both models, the coefficient of LREV is positive and statistically significant, whereas the coefficient of $LREV^2$ is negative and statistically significant. This pattern indicates an inverted U-shaped association between environmentally related tax revenues and environmental degradation. Therefore, the results provide evidence consistent with the Environmental Laffer Curve-type relationship proposed in this study. However, this finding should be interpreted as a nonlinear tax revenue–emissions association rather than as evidence of an optimal environmental tax rate.

The results also support the EKC hypothesis. The coefficient of LGDP is positive and statistically significant in both models, while $LGDP^2$ is negative and statistically significant. This suggests that environmental degradation initially increases with economic growth but declines after a certain income threshold. The unemployment coefficient is negative and statistically significant in both specifications, providing evidence consistent with the EPC hypothesis. This result implies that higher unemployment may be associated with lower emissions and carbon intensity through reduced production, energy use, and transportation activity. However, this should not be interpreted as a desirable trade-off; instead, it highlights the importance of green employment and low-carbon transformation.

CPI has a negative and statistically significant coefficient in both models. This may reflect the indirect effect of macroeconomic instability on economic activity and energy demand. Nevertheless, inflation should not be interpreted as an environmental policy mechanism. The Fourier sine and cosine terms are statistically significant in both models, confirming the presence of smooth structural shifts and supporting the use of the Fourier FMOLS approach. The selected Fourier frequency parameters are 3.61 and 3.78 for Model 1 and Model 2, respectively. The estimations use the Bartlett kernel and Newey-West bandwidth correction.

Table 4
Long-term Estimation Results.

VARIABLES	Model 1	Model 2		
LREV	0.9625***	0.5049***		
	(0.1416)	(0.0780)		
$LREV^2$	−0.0490***	−0.0267***		
	(0.0070)	(0.0039)		
LGDP	6.6987***	4.3209***		
	(1.0218)	(0.5302)		
$LGDP^2$	−0.3106***	−0.2427***		
	(0.0559)	(0.0290)		
UNEMP	−0.0031*	−0.0029***		
	(0.0016)	(0.0009)		
CPI	−0.0006***	−0.0002**		
	(0.0002)	(0.0001)		
Sin	0.0163***	0.0145***		
	(0.0028)	(2.5052)		
Cos	0.0466***	0.0143***		
	(0.0027)	(0.0013)		
Constant	−34.1115***	−21.0368***		
	(4.8086)	(0.0016)		
Model Summary				
k	3.61	3.78		
Observations	28	28		
R-squared	0.9946	0.9632		
Kernel	Bartlett	Bartlett		
Bandwidth (Newey-West)	7.0268	6.7866		
Diagnostic Tests	Test Statistic	P-value	Test Statistic	P-value
Residual-based cointegration	−5.392	<0.01	−5.459	<0.01
Serial correlation (1 lag)	0.03	0.8686	0.10	0.7548
Serial correlation (2 lags)	1.17	0.3283	1.46	0.2515
Normality	1.95	0.3769	2.82	0.2438

Standard errors in parentheses.
*** $p < 0.01$,.
** $p < 0.05$,.
* $p < 0.1$.

The diagnostic tests also support the reliability of the estimates. The residual-based cointegration tests are statistically significant at the 1% level in both models, confirming the presence of a long-run relationship. The serial correlation tests at the first and second lags are insignificant, indicating no evidence of residual autocorrelation. The normality tests are also insignificant, suggesting that the residuals do not significantly deviate from normality. Overall, the results indicate that the EKC, EPC, and Environmental Laffer Curve-type mechanisms are jointly relevant for explaining Türkiye's long-run environmental dynamics. However, given the limited sample size, the findings should be interpreted as evidence of nonlinear long-run associations rather than definitive causal effects.

As an additional robustness analysis, conventional FMOLS estimations were performed under alternative deterministic trend specifications, including linear, quadratic, and cubic trends. The corresponding results are reported in Appendix Table A1. Overall, the linear and quadratic trend specifications yield broadly similar coefficient estimates and statistical significance. In contrast, the cubic trend specification produces noticeable changes in the magnitude, sign, and statistical significance of several coefficients, indicating that the long-run estimates are sensitive to the specification of deterministic trends. By comparison, the Fourier FMOLS estimates provide a more stable coefficient pattern while explicitly accounting for smooth structural changes, supporting the suitability of the Fourier specification for the empirical analysis Table 5.

The nonlinear relationships were further examined using the Lind and Mehlum [39] *U* test, implemented through the utest Stata routine developed by Lind and Mehlum [40]. This test is important because coefficient signs alone are not sufficient to validate an inverted U-shaped relationship; the estimated turning point must also lie within the observed data range and the slope must change significantly within the relevant interval.

The results provide strong support for the Environmental Laffer Curve-type relationship. The estimated turning point for LREV is 9.402 in the carbon intensity model and 9.809 in the CO_2 emissions model. The corresponding test statistics are statistically significant, with p-values of 0.0197 and 0.0001, respectively. This indicates that the nonlinear relationship between environmentally related tax revenues and environmental degradation is formally supported in both model specifications.

For the EKC hypothesis, the results are more nuanced. In the carbon intensity model, the turning point for LGDP is 8.896 and the *U* test is statistically significant at the 1% level, supporting the existence of an inverted U-shaped relationship. However, in the CO_2 emissions model, the estimated LGDP turning point is 10.789 and lies outside the observed sample range. Therefore, the EKC hypothesis is supported for carbon intensity but not fully validated for CO_2 emissions. This finding suggests that income growth may be more clearly associated with improvements in emissions efficiency than with reductions in absolute CO_2 emissions.

Overall, the *U* test results confirm the ELC-type nonlinear relationship in both models, while EKC evidence is indicator-specific. These findings support a more cautious interpretation of the nonlinear results and indicate that threshold effects are particularly relevant for the relationship between environmentally related tax revenues and environmental degradation.

5. Discussion

This study examines the long-run interactions between environmental degradation, economic growth, unemployment, inflation, and environmentally related tax revenues in Türkiye over the period 1994–2022. By jointly considering the EKC, EPC, and an Environmental Laffer Curve-type nonlinear taxation–emissions relationship, the study provides a multidimensional framework for understanding Türkiye's environmental dynamics. The use of the Fourier FMOLS approach allows the analysis to account for smooth structural shifts, which is particularly relevant for Türkiye given the presence of macroeconomic crises, policy reforms, energy price fluctuations, and environmental policy changes during the sample period. Overall, the findings indicate that environmental degradation in Türkiye is shaped by nonlinear and threshold-sensitive long-run associations rather than by simple linear relationships.

One of the key findings of the study concerns the relationship between environmentally related tax revenues and environmental degradation. The Fourier FMOLS results show that the coefficient of LREV is positive and statistically significant, while the coefficient of $LREV^2$ is negative and statistically significant in both model specifications. This pattern indicates an inverted U-shaped association between environmentally related tax revenues and environmental degradation. The Lind-Mehlum *U* test further confirms that the estimated turning points for LREV lie within the observed sample range and are statistically significant in both the CO_2 emissions and carbon intensity models. Therefore, the evidence provides support for an Environmental Laffer Curve-type nonlinear relationship in the Turkish case.

This finding should be interpreted carefully. The estimated turning point refers to the value of the environmentally related tax revenue variable at which the fitted long-run association with environmental degradation changes direction. It should not be interpreted as a statutory environmental tax rate, a carbon price, a tax stringency indicator, or an economically optimal policy threshold. Since the empirical variable is revenue-based, the positive segment of the curve may partly reflect the expansion of pollution-related tax bases, such as fuel consumption, transportation activity, motor vehicle ownership, and energy use. In this context, rising environmentally related tax revenues may coincide with higher emissions because the taxed activities themselves are carbon-intensive. The downward segment of the estimated relationship indicates that, beyond the revenue-based statistical turning point, the fitted association between environmentally related tax revenues and environmental degradation becomes negative. This does not imply that policymakers should target this numerical threshold directly; rather, it suggests that the relationship between environmental tax revenues and emissions is nonlinear and should be interpreted together with the structure of the underlying tax base.

The Environmental Laffer Curve-type result is particularly relevant for the Turkish context. Türkiye's environmentally related taxes are not equivalent to a comprehensive carbon tax system. They are largely linked to fuel consumption, motor vehicles, transportation, and energy use. Therefore, the estimated turning points should be understood as empirical thresholds for the revenue variable, not as direct indicators of tax policy intensity or environmental tax stringency. This distinction is important because environmentally related tax revenues may increase either because environmental taxation becomes more binding or because the underlying taxed pollution-related activities expand. Accordingly, the policy relevance of the finding lies not in identifying an optimal tax level, but in emphasizing that Türkiye's environmental tax structure should be evaluated in relation to fuel use, vehicle taxation, transport-related emissions, energy demand, and the availability of low-carbon alternatives.

The results for the EKC hypothesis are more nuanced. In the Fourier FMOLS estimates, LGDP has a positive and statistically significant coefficient, while $LGDP^2$ has a negative and statistically significant coefficient in both models. This coefficient pattern initially suggests an inverted U-shaped relationship between income and environmental degradation. However, the Lind-Mehlum *U* test provides a more precise interpretation. The EKC is formally supported only in the carbon intensity model, where the estimated turning point lies within the observed sample range and is statistically significant. In contrast, for the CO_2 emissions model, the estimated income turning point lies outside the observed sample range. Therefore, this study does not claim full EKC validation for both environmental indicators. The evidence supports an in-sample EKC pattern for carbon intensity, whereas the CO_2 emissions

Table 5
Turning Points and Lind-Mehlum *U* test Results.

Variables	LREV			LGDP		
	Turning point	Test Stat	P-value	Turning point	Test Stat	P-value
Dep: CINT	9.402	2.16	0.0197	8.896	4.87	0.0000
Dep: LCO_2	9.809	4.21	0.0001	10.789	Out of sample	

model does not confirm an EKC relationship within the observed sample range.

This distinction is theoretically meaningful. Carbon intensity measures emissions relative to economic output and therefore captures improvements in emissions efficiency. The finding that the EKC is supported for carbon intensity suggests that income growth in Türkiye may be associated with improvements in emissions efficiency after a certain point, possibly due to structural change, technological progress, energy efficiency gains, or policy adaptation. However, the absence of an in-sample EKC turning point for absolute CO_2 emissions indicates that economic growth has not yet generated a sufficiently strong decline in total emissions. In other words, Türkiye may have made progress in reducing the emissions intensity of production, but this has not necessarily translated into an absolute decline in CO_2 emissions. This result is consistent with the broader EKC literature, which emphasizes that the growth–environment relationship is not universal and depends on energy structure, policy quality, technological capacity, and institutional conditions [12,14].

The employment–environment relationship also provides evidence consistent with the EPC hypothesis. The coefficient of unemployment is negative and statistically significant in both model specifications. This suggests that higher unemployment is associated with lower CO_2 emissions and lower carbon intensity in the long run. In the Turkish context, this may reflect the fact that periods of stronger economic activity and lower unemployment are often accompanied by higher production, transportation, and energy demand. Conversely, periods of higher unemployment may coincide with weaker economic activity and lower emissions. This finding is consistent with the argument of Kashem and Rahman [8] and with subsequent studies that document EPC-type relationships in different country groups [18,19].

However, the economic magnitude of the unemployment coefficient should be interpreted cautiously. Although the coefficient is statistically significant, its absolute size is relatively modest. Therefore, the EPC result should be understood as evidence of a statistically detectable long-run association rather than as evidence of a large economic effect. This distinction between statistical and economic significance is important because a small coefficient may still be statistically significant in the model but may have limited practical magnitude. Accordingly, the EPC finding should not be overstated as a strong or stable trade-off between employment and environmental quality.

Moreover, the EPC result should not be interpreted as implying that unemployment is environmentally beneficial or that employment growth is inherently incompatible with environmental sustainability. Rather, it reflects the current carbon-intensive structure of economic activity. The policy implication is not to tolerate unemployment for environmental reasons, but to transform the employment structure through green jobs, renewable energy investments, cleaner production systems, and energy efficiency improvements. If employment growth is increasingly generated in low-carbon sectors, the negative unemployment–emissions association may weaken over time. Therefore, the EPC result highlights the importance of linking labor market policies with green transition strategies.

Inflation, proxied by CPI, has a negative and statistically significant coefficient in both models. This finding may capture the indirect effects of macroeconomic instability on environmental degradation. In Türkiye, periods of high inflation often coincide with reduced real purchasing power, lower investment capacity, economic uncertainty, and weaker demand conditions. These factors may temporarily reduce energy consumption, production, and transportation activity, thereby lowering emissions or carbon intensity. However, as in the case of unemployment, the economic magnitude of the CPI coefficient appears limited. Therefore, the inflation result should be interpreted as a small but statistically significant association rather than as a substantive environmental mechanism. Inflation is not an environmental policy instrument and should not be viewed as a desirable channel for reducing emissions.

The statistical significance of the Fourier sine and cosine terms confirms the presence of smooth structural shifts in the long-run relationships examined in this study. This supports the use of the Fourier FMOLS approach, as conventional linear specifications may fail to capture gradual structural changes caused by policy reforms, energy shocks, institutional adjustments, or macroeconomic crises. The diagnostic tests further strengthen the reliability of the estimates. The residual-based cointegration tests confirm the existence of a long-run relationship in both models, while the serial correlation and normality tests do not indicate major residual problems. These findings suggest that the estimated long-run relationships are statistically coherent, although they should still be interpreted cautiously due to the limited number of annual observations.

Overall, the findings show that Türkiye's environmental degradation cannot be explained by a single mechanism. Environmentally related tax revenues exhibit a nonlinear relationship with both CO_2 emissions and carbon intensity, supporting the Environmental Laffer Curve-type framework. However, the identified turning points refer only to the revenue-based LREV variable and should not be interpreted as optimal tax rates, carbon prices, or policy targets. Economic growth also shows a nonlinear relationship with environmental degradation, but EKC evidence is supported only for carbon intensity, not for absolute CO_2 emissions within the observed sample range. Unemployment is negatively associated with environmental degradation, supporting the EPC framework, but the magnitude of this association is modest and reflects structural and cyclical characteristics of the economy rather than a desirable policy trade-off. Taken together, the results suggest that environmental sustainability in Türkiye requires coordinated fiscal, technological, energy, and labor market policies, while recognizing that the empirical thresholds identified in this study are statistical turning points rather than direct prescriptions for tax policy design.

6. Conclusion

This study examined the long-run relationship between environmental degradation, environmentally related tax revenues, economic growth, unemployment, and inflation in Türkiye over the period 1994–2022. By jointly considering the Environmental Kuznets Curve, the Environmental Phillips Curve, and an Environmental Laffer Curve-type nonlinear taxation–emissions relationship, the study provides a multidimensional perspective on the interaction between macroeconomic conditions, fiscal variables, and environmental outcomes. The use of the Fourier FMOLS approach enabled the analysis to account for smooth structural shifts, while the Lind-Mehlum *U* test provided additional evidence on whether the estimated nonlinear relationships represent valid inverted U-shaped patterns within the observed sample range.

The results provide evidence consistent with an Environmental Laffer Curve-type relationship in Türkiye. In both the CO_2 emissions and carbon intensity models, environmentally related tax revenues have a positive coefficient, while their squared term has a negative coefficient. The Lind-Mehlum *U* test further confirms that the estimated turning points for environmentally related tax revenues lie within the observed sample range and are statistically significant. This indicates that the relationship between environmentally related tax revenues and environmental degradation is nonlinear.

However, this finding should be interpreted carefully. The estimated turning points refer only to the revenue-based LREV variable used in the empirical model. They should not be interpreted as statutory environmental tax rates, carbon prices, tax stringency indicators, or economically optimal policy thresholds. Rather, they represent empirical statistical turning points at which the fitted long-run association between environmentally related tax revenues and environmental degradation changes direction. Since environmental tax revenues may reflect both fiscal policy and the size of pollution-related tax bases, the results should be understood as evidence of a nonlinear revenue–emissions association rather than as a direct guide for determining tax rates.

The findings regarding the EKC hypothesis are more nuanced. Although the Fourier FMOLS estimates suggest an inverted U-shaped relationship between income and environmental degradation in both specifications, the Lind-Mehlum *U* test supports an in-sample EKC pattern only for the carbon intensity model. In the CO_2 emissions model, the estimated income turning point falls outside the observed sample range. Therefore, the study does not claim full EKC validation for both environmental indicators. Instead, the evidence suggests that economic growth in Türkiye may be more clearly associated with improvements in emissions efficiency than with an absolute reduction in CO_2 emissions. This distinction is important because it indicates that Türkiye may have achieved some progress in reducing the carbon intensity of economic output, but not necessarily in reversing the overall upward trend in absolute emissions.

The EPC-related results show a negative association between unemployment and environmental degradation. This finding is consistent with the idea that periods of lower unemployment and stronger economic activity may be associated with higher production, energy use, transportation, and emissions. However, the magnitude of the unemployment coefficient is relatively modest. Therefore, the EPC finding should be interpreted as a statistically detectable long-run association rather than as evidence of a large economic effect. Moreover, this result should not be interpreted as implying that unemployment is environmentally desirable. Instead, it highlights the need to transform the structure of employment and production through green jobs, renewable energy investments, energy efficiency improvements, and cleaner technologies. In this sense, reducing emissions without weakening employment requires a green transition strategy that integrates labor market policy with environmental and energy policy.

From a policy perspective, the findings suggest that environmental sustainability in Türkiye cannot be achieved through economic growth or environmental taxation alone. Since Türkiye's environmentally related tax revenues are largely connected to fuel consumption, motor vehicles, transportation, and energy use, the estimated revenue-based turning points should not be treated as direct policy targets. They do not indicate a specific tax rate, carbon price, or optimal level of environmental taxation. Instead, the findings suggest that Türkiye's environmental tax structure should be evaluated together with the underlying pollution-related tax bases and the extent to which these fiscal instruments encourage behavioral and technological change. A broader green fiscal reform framework should distinguish revenue generation from environmental effectiveness and should be supported by renewable energy policies, technological innovation, public transport investments, energy efficiency measures, and targeted incentives for low-carbon production.

The study also has several limitations that should be considered. First, the analysis relies on a relatively small annual time-series sample covering 1994–2022. Although the Fourier-based approach helps account for smooth structural changes, the limited number of observations requires cautious interpretation of the results. Second, the study focuses on a single country, which limits the generalizability of the findings to other economies with different fiscal, energy, and institutional structures. Third, environmentally related tax revenues are used as a proxy for environmental tax pressure. This measure is useful given data availability, but it does not directly represent statutory tax rates, effective carbon prices, environmental policy stringency, or carbon taxation. Fourth, possible endogeneity and reverse causality cannot be fully ruled out, since environmental tax revenues, economic activity, fossil fuel consumption, and emissions may be jointly determined. Therefore, the results should be interpreted as long-run associations rather than definitive causal effects.

Future studies could improve this analysis by using longer time horizons, panel data approaches, sector-specific tax indicators, effective environmental tax rates, fuel tax measures, carbon pricing indicators, or emissions trading variables where available. Further research could also incorporate variables such as renewable energy adoption, green innovation, institutional quality, energy efficiency, and environmental regulation intensity to better identify the mechanisms through which fiscal policy, economic growth, and labor market dynamics interact with environmental outcomes. Comparative studies including other emerging economies could also help assess whether the Environmental Laffer Curve-type relationship observed for Türkiye is country-specific or reflects a broader pattern among economies with similar fiscal and energy structures. Overall, the findings suggest that Türkiye's environmental transition requires coordinated fiscal, technological, energy, and labor market policies, while recognizing that the empirical thresholds identified in this study are statistical turning points in environmental tax revenues rather than direct prescriptions for environmental tax policy design.

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Data availability statement

Data can be obtained from authors upon request.

CRediT authorship contribution statement

Hakan Yıldız: Writing – review & editing, Validation, Methodology, Formal analysis. **Serkan Şengül:** Writing – original draft, Supervision, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table A1

Table A1
Conventional FMOLS Estimates under Alternative Deterministic Trend Specifications.

	Dependent Variable: LCO2			Dependent Variable: CINT		
VARIABLES	Linear Trend	Quadratic Trend	Cubic Trend	Linear Trend	Quadratic Trend	Cubic Trend
LREV	0.022	0.154	1.890***	0.027	0.052	0.802***
	(0.237)	(0.231)	(0.307)	(0.111)	(0.104)	(0.151)
LREV^2	−0.006	−0.012	−0.095***	−0.004	−0.005	−0.041***
	(0.012)	(0.011)	(0.015)	(0.005)	(0.005)	(0.007)
LGDP	8.549***	8.734***	−1.395	4.267***	3.620***	−0.554
	(1.910)	(2.583)	(2.047)	(0.892)	(1.166)	(1.007)
LGDP^2	−0.450***	−0.461***	0.107	−0.252***	−0.215***	0.019
	(0.107)	(0.146)	(0.115)	(0.050)	(0.066)	(0.057)
CPI	−0.001***	−0.001**	−0.000**	−0.000	−0.000	−0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
UNEMP	−0.009***	−0.009**	−0.001	−0.003**	−0.003**	−0.000
	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)	(0.001)
trend	0.027***	0.028***	−0.016*	0.008***	0.010***	−0.009**
	(0.004)	(0.007)	(0.008)	(0.002)	(0.003)	(0.004)
trend^2		−0.000	0.003***		−0.000	0.001***
		(0.000)	(0.001)		(0.000)	(0.000)
trend^3			−0.000***			−0.000***
			−0.000***			0.000
Constant	−34.657***	−36.188***	0.000	−17.446***	−14.732***	(0.000)
	(8.455)	(11.691)	(8.843)	(3.948)	(5.280)	(4.350)
Observations	28	28	28	28	28	28
R-squared	0.985	0.989	0.990	0.881	0.907	0.905
Kernel	Bartlett	Bartlett	Bartlett	Bartlett	Bartlett	Bartlett
Bandwidth(neweywest)	6.8879	8.8699	10.6911	6.8844	8.8367	10.6469

Standard errors in parentheses.
*** $p < 0.01$,.
** $p < 0.05$,.
* $p < 0.1$.

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