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THE EFFECTS OF INDUSTRIAL VALUE ADDED AND ECONOMIC GROWTH ON CARBON EMISSIONS IN TÜRKİYE: FOURIER-SHIN COINTEGRATION TEST

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Abstract

In developing economies such as Türkiye, industrialization and economic growth play a crucial role in shaping both macroeconomic performance and environmental quality. Rapid industrial expansion may intensify environmental pressures through rising carbon emissions. Therefore, understanding the long-run dynamics among industrialization, economic growth, and CO2 emissions is essential for designing sustainable economic policies. This study analyzes the relationship between carbon emissions, industrial value added, and real GDP in Türkiye using econometric models based on the Fourier approach. The main objective is to determine whether Türkiye's growth and industrialization process has followed a carbon-intensive path in the long run.

Using annual data covering 1970–2024, the stationarity properties of lnCO2, lnGDP, and IND are examined through the Augmented Dickey–Fuller (ADF) and Fourier KPSS (FKPSS) tests. The long-run relationship among the variables is investigated using the Fourier-Shin cointegration test, which captures smooth structural changes without pre-specifying break dates. Following confirmation of cointegration, long-run coefficients are estimated via Dynamic Ordinary Least Squares (DOLS) with Newey–West corrections. The results indicate that industrial value added and economic growth have a positive and statistically significant impact on CO2 emissions in the long run, suggesting that Türkiye's growth trajectory remains carbon-intensive.

Keywords

Carbon Emissions
Industrial Value Added
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TÜRKİYE'DE SANAYİ KATMA DEĞERİ VE EKONOMİK BÜYÜMENİN KARBON EMİSYONLARI ÜZERİNDEKİ ETKİLERİ: FOURİER-SHİN EŞBÜTÜNLEŞME TESTİ

Öz

Türkiye gibi gelişmekte olan ekonomilerde sanayileşme ve ekonomik büyüme hem makroekonomik performansı hem de çevresel kaliteyi doğrudan etkilemektedir. Hızlı sanayi genişlemesi ve üretim artışı, karbon emisyonlarındaki yükseliş yoluyla önemli çevresel baskılar oluşturabilmektedir. Bu nedenle sanayileşme, ekonomik büyüme ve CO2 emisyonları arasındaki uzun dönemli ilişkinin incelenmesi, sürdürülebilir ekonomi politikalarının geliştirilmesi açısından büyük önem taşımaktadır. Bu çalışmada, Türkiye'de karbon emisyonları, sanayi katma değeri ve reel gayri safi yurt içi hasıla arasındaki ilişki Fourier yaklaşımına dayalı ekonometrik yöntemlerle analiz edilmektedir.

1970–2024 dönemini kapsayan yıllık veriler kullanılarak lnCO2, lnGDP ve IND değişkenlerinin durağanlık özellikleri Augmented Dickey–Fuller (ADF) ve Fourier KPSS (FKPSS) testleri ile incelenmiştir. Değişkenler arasındaki uzun dönemli ilişki, yumuşak yapısal değişimleri dikkate alan Fourier-Shin eşbütünleşme testi ile araştırılmıştır. Eşbütünleşme ilişkisinin varlığı tespit edildikten sonra uzun dönem katsayıları Dinamik En Küçük Kareler (DOLS) yöntemiyle tahmin edilmiştir. Bulgular, sanayi katma değeri ve ekonomik büyümenin uzun dönemde CO2 emisyonlarını pozitif ve istatistiksel olarak anlamlı biçimde artırdığını göstermektedir. Sonuçlar, Türkiye'nin büyüme sürecinin karbon yoğun niteliğini sürdürdüğüne işaret etmektedir.

Anahtar Kelimeler

Karbon Emisyonları
Sanayi Katma Değeri
Ekonomik Büyüme
Fourier-Shin Eşbütünleşme Testi

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INTRODUCTION

The relationship between economic growth and environmental sustainability has become one of the defining empirical and policy challenges of contemporary development economics. Industrialization, long regarded as the primary engine of growth in emerging economies, simultaneously represents one of the most carbon-intensive phases of structural transformation. As production shifts toward manufacturing and energy-using industries, rising energy demand often translates into increasing carbon dioxide (CO_2) emissions. Whether economic expansion inevitably follows a carbon-intensive trajectory, or whether structural upgrading can gradually decouple growth from emissions, remains a central empirical question.

The existing literature provides mixed evidence regarding the industry–growth–emissions nexus. A dominant strand of research supports the "scale effect" hypothesis, arguing that industrial expansion and income growth increase emissions, particularly in energy-intensive production systems. Cross-country evidence from E7 economies indicates that GDP per capita and industrialization significantly increase CO_2 emissions when energy consumption remains fossil-fuel dependent (Efeoğlu, 2022, s. 2104-2106). Similarly, multi-country panel results suggest that industrialization frequently intensifies environmental degradation unless accompanied by renewable energy expansion and financial development (Elfaki et al., 2022, s. 31478). In the Turkish context, ARDL-based studies document a positive long-run association between industrialization, growth, and carbon emissions (Karaca and Çımat, 2023, s. 52; Pata, 2018, s. 7742-7745), while nonlinear approaches also confirm a persistent growth–emissions linkage (Bayramoğlu and Koç-Yurtkur, 2016, s. 35). Complementary evidence further highlights electricity consumption as a key transmission channel connecting industrial expansion to emissions in Türkiye (Kazanasmaz et al., 2023, s. 250-254).

However, another strand of literature challenges the inevitability of carbon-intensive growth. Studies focusing on structural transformation and decoupling emphasize that industrialization does not mechanically increase emissions; rather, its impact depends on energy composition, technological upgrading, and efficiency improvements. For instance, panel evidence for ASEAN+3 economies suggests that industrialization may coincide with lower emissions under specific structural conditions (Elfaki et al., 2022, s. 31479). Similarly, research on China indicates that improvements in energy intensity and investment structure can alter the direction of the growth–emissions relationship (Wang and Jiang, 2019, s. 1196; Wang and Su, 2019, s. 2), while threshold effects imply that the environmental impact of industrialization may weaken at higher income levels (Dong et al., 2019, s. 62). These findings underscore that the relationship is context-specific and sensitive to structural change.

Despite this extensive body of research, two important gaps remain in the Türkiye-focused literature. First, most empirical studies rely on linear cointegration or ARDL-based frameworks (Karaca and Çımat, 2023, s. 52-55; Pata, 2018, s. 7742-7745), which typically assume stable deterministic components or, at best, discrete structural breaks. Yet Türkiye's economic history between 1970 and 2024 is characterized by gradual transformations, including trade liberalization, energy market reforms, industrial upgrading, and

macroeconomic restructuring. Such processes are unlikely to be adequately captured by models that assume abrupt regime shifts or purely linear dynamics.

Second, while industrialization is frequently proxied by industrial value added, few studies explicitly evaluate whether the structural role of industry in Türkiye's growth model has remained persistently carbon-intensive once smooth structural shifts are taken into account. The omission of flexible deterministic modeling may bias long-run inference when nonlinear trends are present (Becker et al., 2006, s. 383-385; Tsong et al., 2016, s. 1087).

To address these limitations, the present study investigates the long-run relationship among carbon emissions ($\ln CO_2$), industrial value added (IND), and economic growth (lnGDP) in Türkiye over the period 1970–2024 within a Fourier-based cointegration framework. By incorporating trigonometric terms into both stationarity and cointegration testing procedures (Becker et al., 2006, s. 383-386; Tsong et al., 2016, s. 1088), the analysis allows for smooth structural shifts without requiring prior knowledge of break dates. This approach provides a more flexible and robust specification compared to conventional linear models.

The contribution of this study is threefold. First, it extends the Türkiye literature by employing the Fourier-Shin cointegration test, which directly tests the null hypothesis of cointegration while accounting for gradual structural transformations. Second, it utilizes a long and up-to-date dataset covering more than five decades of economic change. Third, by focusing explicitly on industrial value added as a structural determinant of emissions, the study clarifies whether Türkiye's growth trajectory has remained aligned with a high-carbon industrial model or shows signs of structural decarbonization.

Understanding this relationship is not merely of academic interest. If economic growth and industrial expansion systematically increase emissions, then decarbonization policies must focus on energy transformation and green industrial strategies. Conversely, if structural upgrading weakens the growth–emissions elasticity over time, identifying the enabling mechanisms becomes crucial for sustainable policy design.

The remainder of the paper proceeds as follows. The next section reviews the related literature in greater detail. Subsequently, the data and methodology are presented, followed by the empirical findings and policy implications.

1. Literature Review

The relationship between industrialization, economic growth, and carbon dioxide (CO_2) emissions has been extensively examined in both single-country time-series and multi-country panel frameworks. The existing literature converges around two dominant perspectives: first, the "scale effect" argument, which suggests that industrial expansion and income growth increase carbon emissions; and second, the "decoupling" perspective, which investigates whether economic growth can gradually detach from carbon-intensive production patterns. Additionally, several studies emphasize the mediating roles of energy consumption, investment dynamics, and sectoral composition in shaping emission outcomes.

1.1. Industrialization and Growth as Drivers of Carbon Emissions

A substantial body of evidence indicates that industrialization and economic growth tend to increase CO_2 emissions, particularly in developing and emerging economies. Wang et al. (2011), focusing on China's heavy industrial structure, demonstrate through an error correction model that growth in heavy industrial output significantly increases carbon emissions in both the short and long run. Their findings highlight the environmental consequences of structural shifts toward energy-intensive industrial production.

Similarly, Zhu et al. (2017) analyze the manufacturing center Tianjin and show that rapid industrialization and urbanization significantly increased CO_2 emissions between 1997 and 2012. While improvements in energy intensity partially restrained emission growth, final demand expansion and investment were identified as major contributors to rising emissions. These results underscore that industrialization influences emissions not only through output expansion but also through demand-side and structural transformation mechanisms.

Comparable findings emerge from other developing country contexts. Using quarterly data for Bangladesh, Shahbaz et al. (2014) apply the ARDL bounds testing approach and find long-run cointegration among industrialization, electricity consumption, and CO_2 emissions. Their results indicate that electricity consumption significantly contributes to carbon emissions and that causal relationships exist among the variables. In the case of India, Koçak (2024) reports that economic growth and industrialization increase carbon emissions in the long run, while trade activities do not exert a statistically significant effect. These results collectively suggest that industrial-led growth remains strongly carbon-intensive in many developing economies.

The Turkish literature largely aligns with this pattern. Karaca and Çimat (2023), employing the ARDL bounds testing procedure for Türkiye, find that industrialization and energy consumption increase CO_2 emissions in the long run. Pata (2018) similarly concludes that industrialization and urbanization positively affect per capita CO_2 emissions in Türkiye. Furthermore, Bayramoğlu and Koç-Yurtkur (2016), using both linear and nonlinear cointegration techniques, detect a nonlinear long-run positive relationship between economic growth and carbon emissions in Türkiye. These findings suggest that Türkiye's growth process has historically been accompanied by rising environmental pressure.

In addition, Kazanasmaz et al. (2023) examine the dynamic relationship between economic growth, electricity consumption, and CO_2 emissions in Türkiye using VECM and Granger causality analysis. Their results indicate that electricity consumption positively affects economic growth in the long run, and unidirectional causality runs from electricity consumption to both economic growth and CO_2 emissions. This highlights energy consumption as a key transmission channel linking industrial expansion and carbon emissions.

1.2. Decoupling and Structural Transformation Perspectives

While many studies document emission-increasing effects of industrialization, another strand of the literature explores whether economic growth can decouple from carbon emissions under certain structural and policy conditions. Wang and Jiang (2019) apply the

Tapio decoupling model and structural decomposition analysis (LMDI) for China and show that decoupling elasticity exhibits time-varying patterns. They identify investment effects as a major driver of emission increases, whereas improvements in energy intensity contribute to emission reductions. Their results suggest that structural and technological changes critically determine the direction of the growth–emissions relationship.

Wang and Su (2019) further investigate the role of urbanization and industrialization in decoupling economic growth from carbon emissions in China. Using the Tapio model, Johansen cointegration, and Granger causality analysis, they find that urbanization promotes emission increases in both the short and long run, while industrialization may inhibit decoupling in early stages due to scale effects. Consumption structure also plays a key role in restraining emission growth. These findings emphasize that decoupling is conditional and often incomplete during early phases of industrial expansion.

Du et al. (2019), analyzing China's construction industry across 30 provinces, report that economic development levels are positively correlated with carbon emissions in most regions, and decoupling patterns vary spatially. Their spatial findings reinforce the argument that industrial sectors and regional heterogeneity shape emission trajectories differently.

The dynamic nature of the growth–emissions nexus is further supported by Jiang and Yu (2023), who employ a mixed-frequency VAR framework for China. They find bidirectional causality between economic growth and carbon emissions, suggesting mutual reinforcement rather than a one-directional relationship. Such evidence implies that policy interventions targeting emissions may also influence growth dynamics.

Studies focusing on developed economies provide additional nuance. Dong et al. (2019) show that the impact of industrialization on carbon emissions depends on income levels. In low- and middle-income stages, industrialization increases emissions; however, this promotional effect weakens at higher income levels. This threshold behavior suggests that structural upgrading and technological advancements may gradually mitigate the environmental cost of growth.

Recent evidence further highlights the time-varying nature of the growth–emissions relationship. Sağlam et al. (2025), examining France over the period 1890–2019, employ Fourier-based econometric techniques to analyze the Environmental Kuznets Curve (EKC) hypothesis and the dynamics of decoupling between economic growth and carbon emissions. Their findings reveal a stable long-run linkage among CO_2 emissions, energy consumption, and economic activity, while the EKC relationship appears only during specific historical periods. Moreover, the results suggest that decoupling is contingent upon energy efficiency improvements, technological innovation, and structural transformation. These findings reinforce the argument that the growth–emissions nexus is not static but evolves over time in response to policy interventions and technological change.

1.3. Panel Evidence and Heterogeneity

Panel data studies further reveal that the impact of industrialization is not uniform across countries. Elfaki et al. (2022), analyzing ASEAN+3 economies using a PMG-ARDL framework, report that energy consumption and financial development increase

environmental degradation, while economic growth and industrialization may reduce it under certain model specifications. However, robustness checks indicate methodological sensitivity, implying that results may vary depending on estimator choice.

Similarly, Efeoğlu (2022) examines E7 economies and finds that GDP per capita, industrialization, and energy consumption increase CO_2 emissions, while renewable energy and financial development reduce emissions. Arı and Zeren (2011), in a panel analysis of Mediterranean countries, detect an N-shaped relationship between income and CO_2 emissions and confirm that energy consumption and population density positively affect emissions. These panel findings highlight that the industrialization–emissions relationship is shaped by structural, technological, and institutional differences across economies.

1.4. Positioning of the Present Study

Overall, the reviewed literature yields three central conclusions. First, industrialization and economic growth frequently increase CO_2 emissions, especially in energy-intensive and developing economies. Second, energy consumption, investment dynamics, and structural composition serve as key transmission mechanisms linking growth and emissions. Third, nonlinearities, decoupling patterns, and methodological differences lead to heterogeneous empirical outcomes.

In the Turkish context, previous studies predominantly rely on ARDL or linear/nonlinear cointegration approaches (Bayramoğlu and Koç-Yurtkur, 2016; Karaca and Çimat, 2023; Pata, 2018) and although they establish long-run linkages, gradual structural transformations are typically not modeled flexibly. Given that Türkiye underwent substantial economic restructuring between 1970 and 2024—including industrial expansion, trade liberalization, energy market reforms, and technological shifts—structural changes are likely to have occurred smoothly rather than through sharp breaks.

Therefore, examining the long-run relationship among carbon emissions ($\ln CO_2$), industrial value added (IND) and economic growth (lnGDP) within a framework that can accommodate gradual structural shifts provides an important contribution. By focusing explicitly on industrial value added as a structural determinant of emissions and employing an approach capable of capturing smooth transformations, the present study extends the Turkish literature and offers more robust inference regarding whether Türkiye's industrial growth path has remained carbon-intensive over the long run.

2. Data and Methodology

2.1. Data

This study investigates the relationship between carbon dioxide (CO_2) emissions, industrial value added, and economic growth in Türkiye. Annual data covering the period 1970–2024 were used in the analysis. The time span was determined according to the availability of consistent data for all variables.

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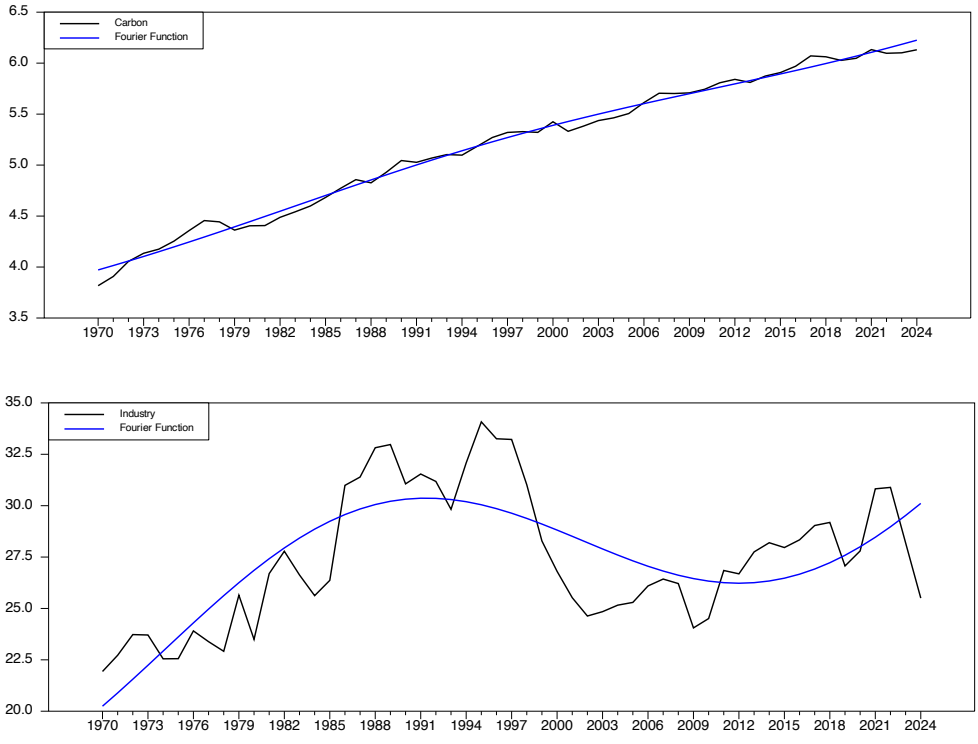
Table 1. Variable Definitions

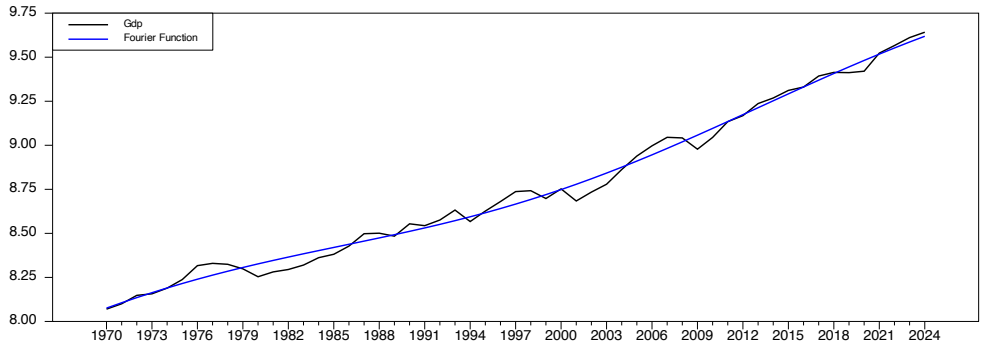
Variables	Symbol	Explanation	Source
Carbon Dioxide Emissions	$\ln CO_2$	CO_2 emissions (total, excluding LULUCF), million tons (natural logarithm)	World Bank (WDI)
Economic Growth	lnGDP	GDP per capita (constant 2015 US$, natural logarithm)	World Bank (WDI)
Industrial Value Added	IND	Industry (including construction), value added (% of GDP)	World Bank (WDI)

Source: Variable definitions and data are compiled by the author using annual data retrieved from the World Bank's World Development Indicators (WDI) database.

Before proceeding to the formal econometric analysis, the time paths of the variables are examined in order to gain preliminary insights into their long-run behavior and potential nonlinear patterns. Visual inspection of the series helps identify trend characteristics and possible smooth structural shifts, which justify the use of Fourier-based econometric techniques in the subsequent analysis.

Figure 1. Time Paths of Variables and Their Corresponding Fourier Approximations (1970–2024)





Source: Constructed by the author using annual data retrieved from the World Bank's World Development Indicators (WDI) database covering the period 1970–2024.

Figure 1 presents the time paths of carbon emissions ($\ln CO_2$), industrial value added (IND) and GDP per capita (lnGDP), together with their corresponding Fourier approximations. The black lines represent the original series, while the blue lines illustrate the smooth deterministic components captured by the Fourier functions.

As observed, both carbon emissions and GDP per capita exhibit a clear upward trend over the sample period, reflecting the long-term expansion of economic activity in Türkiye. In contrast, industrial value added displays a more fluctuating pattern, indicating structural transformations within the industrial sector. The Fourier approximations successfully capture the smooth nonlinear movements embedded in the series, suggesting the presence of gradual structural shifts rather than abrupt breaks. These graphical findings support the use of Fourier-based econometric techniques in the subsequent analysis.

2.2. Model Specification

The empirical model is specified as follows:

$$\ln(CO2_t) = \beta_0 + \beta_1 IND_t + \beta_2 \ln(GDP_t) + \varepsilon_t \quad (1)$$

where t denotes time (1970–2024) and ε_t represents the stochastic error term. The model specifies carbon emissions as a function of industrial value added and economic growth. While carbon emissions and GDP per capita are expressed in natural logarithms to allow elasticity-based interpretation, industrial value added (IND) is included in percentage form as it represents the share of industry in total GDP. Log-transforming a percentage share would alter its economic meaning. Therefore, the coefficient of IND should be interpreted as the effect of a one-percentage-point change in the industrial share on carbon emissions.

Although energy consumption is frequently identified in the literature as a key transmission channel linking industrialization and economic growth to carbon emissions, it is intentionally excluded from the baseline specification in this study. The primary objective is to isolate the direct structural impact of industrial value added on carbon emissions, independent of intermediate channels. Since energy demand is largely derived from industrial production and economic expansion, including energy consumption in the same specification may introduce multicollinearity and obscure the structural contribution of industrial activity itself. Nevertheless, this modeling choice represents a parsimonious specification, and future

research may extend the framework by incorporating energy-related variables within a broader multivariate setting.

From a theoretical perspective, industrial expansion and economic growth are expected to increase energy demand and production activities, thereby leading to higher carbon emissions. Therefore, the coefficients β_1 and β_2 are expected to be positive.

2.3. Methodology

This study adopts a structured time-series econometric framework to investigate the dynamic relationship among industrial value added, economic growth, and carbon emissions in Türkiye. Given the potential presence of nonlinear deterministic components and smooth structural shifts, both conventional and Fourier-based techniques are employed to ensure robust inference.

As a preliminary step, the Augmented Dickey-Fuller (ADF) unit root test developed by Dickey and Fuller (1979) is employed to determine the order of integration of the variables. The ADF test examines the null hypothesis of a unit root against the alternative of stationarity by incorporating lagged difference terms to eliminate serial correlation.

2.3.1. The Fourier KPSS Stationarity Test (Becker et al., 2006)

Becker et al. (2006) extended the stationarity test originally developed by Kwiatkowski et al. (1992) by incorporating Fourier functions into the testing framework. The primary motivation behind this approach is that Fourier approximations are capable of flexibly capturing unknown smooth structural changes in time series data. The inclusion of trigonometric terms allows the model to approximate nonlinear deterministic components without requiring prior information about the number, timing, or form of structural breaks (Becker et al., 2004, s. 899-993; Becker et al., 2006, s. 397-402; Gallant, 1981, s. 212-216).

The data-generating process considered by Becker et al. (2006) can be expressed as follows:

$$\begin{aligned} y_t &= X_t'\beta + Z_t'\gamma + s_t + e_t \\ s_t &= s_{t-1} + u_t \end{aligned} \tag{2}$$

where e_t denotes a stationary error term and $u_t$represents an independently and identically distributed error term with variance σ_u^2. The vector Z_t contains the trigonometric components:

$$Z_t = [\sin(2\pi kt/T), \cos(2\pi kt/T)]' \tag{3}$$

In this specification, t represents the time trend, T is the sample size, and k denotes the frequency parameter. To test level stationarity, $X_t = [1]$, whereas for trend stationarity, $X_t = [1, t]'$.

The null hypothesis of stationarity is defined as:

$$H_0: \sigma_u^2 = 0 \tag{4}$$

To compute the test statistic, one of the following regression models is estimated and residuals are obtained.

For level stationarity:

$$y_t = \alpha_0 + \gamma_1 \sin(2\pi kt/T) + \gamma_2 \cos(2\pi kt/T) + \varepsilon_t \quad (5)$$

For trend stationarity:

$$y_t = \alpha_0 + \beta t + \gamma_1 \sin(2\pi kt/T) + \gamma_2 \cos(2\pi kt/T) + \varepsilon_t \quad (6)$$

The test statistic is calculated as:

$$\tau_\mu(k) \text{ or } \tau_\tau(k) = \frac{1}{T^2}\sum_{t=1}^{T} \tilde{S}_t^2(k)/\tilde{\sigma}^2 \quad (7)$$

where $\tilde{S}_t(k) = \sum_{j=1}^{t} \tilde{\varepsilon}_j$, and $\tilde{\varepsilon}_j$ represents the residuals obtained from equations (5) and (6). The long-run variance estimator is computed non-parametrically as:

$$\tilde{\sigma}^2 = \tilde{\alpha}_0 + 2\sum_{j=1}^{l} w_j \tilde{\alpha}_j \quad (8)$$

Here, $\tilde{\alpha}_j$ denotes the sample autocovariance of the residuals at lag j, w_j is a weighting function, and l is the truncation lag parameter. The optimal frequency parameter k is selected as the value that minimizes the sum of squared residuals (SSR). To evaluate whether the trigonometric terms significantly improve the model, Becker et al. (2006) propose the following F-statistic:

$$F_i(k) = \frac{(SSR_0 - SSR_1(k))/2}{SSR_1(k)/(T-q)} \; i = \mu, \tau \quad (9)$$

where $SSR_1(k)$ refers to the residual sum of squares from the model including Fourier terms, SSR_0 denotes the residual sum of squares under the null hypothesis of no nonlinear trend, and q represents the number of regressors. If the F-statistic indicates that the trigonometric terms are not statistically significant, the standard KPSS test is preferred. The critical values required for the FKPSS test are provided by Becker et al. (2006). Rejection of the null hypothesis implies that the series contains a unit root. Non-stationary variables can be transformed into stationary form through differencing. If a series becomes stationary after being differenced d times, it is said to be integrated of order d, denoted as I(d).

In the present study, the stationarity properties of $\ln CO_2$, lnGDP, and IND are examined using both the ADF test and the Fourier KPSS test. The results of these tests determine the order of integration of the variables prior to the cointegration analysis.

2.3. 2. Fourier-Shin Cointegration Test (Tsong et al., 2016)

The concept of cointegration was initially introduced by Engle and Granger (1987), who developed a residual-based approach grounded in the augmented Dickey-Fuller (ADF) framework to test long-run relationships between non-stationary variables integrated of order one, I(1). In most conventional cointegration tests, the null hypothesis assumes the absence of

cointegration, whereas only a limited number of approaches directly test the null of cointegration (Shin, 1994, s. 93-97).

Shin (1994) proposed a residual-based test derived from the KPSS unit root framework, in which the null hypothesis assumes the existence of cointegration among the variables. However, this methodology does not account for structural breaks in the deterministic components of the model. Later, Arai and Kurozumi (2007) extended this approach by introducing a cointegration test in which the null hypothesis explicitly assumes cointegration while allowing for structural breaks. Nevertheless, the timing and number of such breaks must be specified exogenously.

To overcome these limitations, Tsong et al. (2016) developed the Fourier-Shin cointegration test by incorporating Fourier functions into the Shin (1994) framework. By adding trigonometric terms, this approach captures smooth structural shifts without requiring prior knowledge regarding the number or timing of structural changes. Thus, the Fourier-Shin method provides a flexible specification capable of approximating unknown nonlinear deterministic components.

The baseline regression model considered by Tsong et al. (2016) is expressed as:

$$y_t = d_t + x_t'\beta + \eta_t \tag{10}$$

where $\eta_t = \gamma y_{t-1} + v_t$, $\gamma_0 = 0$, and $x_t = x_{t-1} + v_{2t}$. The error term v_t is assumed to be independently and identically distributed with zero mean and finite variance. Accordingly, both x_t and y_t are integrated of order one, I(1) (Tsong et al., 2016, s. 1086-1090).

The deterministic component d_t can be written as:

$$d_t = \sum_{i=0}^{m} \delta_i \, t^i + f_t \tag{11}$$

where $m = 0$ implies a model with only an intercept, while $m = 1$ includes both intercept and trend terms (Tsong et al., 2016, s. 1086-1090). The Fourier function f_t is defined as:

$$f_t = \alpha_k \sin\left(\frac{2\pi kt}{T}\right) + \beta_k \cos\left(\frac{2\pi kt}{T}\right) \tag{12}$$

In this specification, T denotes the sample size and k represents the frequency parameter. In determining the optimal frequency (k), alternative frequency values were estimated, and the model minimizing the sum of squared residuals (SSR) was selected in line with Becker et al. (2006) and Tsong et al. (2016). Other candidate frequencies yielded higher SSR values and were therefore not retained. This selection procedure ensures that the Fourier approximation most effectively captures smooth deterministic components in the data.

Substituting equation (11) into equation (10), the cointegration regression augmented with Fourier terms is obtained as:

$$y_t = \sum_{i=0}^{m} \delta_i t^i + \alpha_k \sin\left(\frac{2\pi kt}{T}\right) + \beta_k \cos\left(\frac{2\pi kt}{T}\right) + x_t'\beta + v_t \quad (13)$$

Based on equation (12), the KPSS-type cointegration test statistic is calculated as:

$$CI_f^m = T^{-2}\hat{\omega}^{-2}\sum_{t=1}^{T} S_t^2 \quad (14)$$

where $S_t = \sum_{i=1}^{t} \hat{v}_i$ represents the partial sum of residuals obtained from equation (12), and $\hat{\omega}^2$ denotes a consistent estimator of the long-run variance of the residuals (Tsong et al., 2016). The test statistic is compared with the asymptotic critical values provided by Tsong et al. (2016).

In the Fourier-Shin framework, the null hypothesis states that cointegration exists among the variables. If the computed test statistic is smaller than the relevant critical value, the null hypothesis cannot be rejected, indicating the presence of a long-run equilibrium relationship that accounts for potential smooth structural shifts.

From an economic perspective, the inclusion of Fourier terms allows the model to capture gradual structural transformations in Türkiye's economy over the sample period. Rather than assuming abrupt regime shifts, the Fourier approximation reflects smooth changes associated with trade liberalization, energy market reforms, industrial restructuring, and macroeconomic adjustments. Thus, the methodology provides a flexible representation of long-term economic evolution without imposing exogenous break dates.

In the present study, the Fourier-Shin cointegration test is employed to examine the long-run relationship among $\ln CO_2$, lnGDP, and IND in Türkiye. By incorporating Fourier terms, the analysis allows for smooth structural variations in the deterministic components of the model, thereby providing more reliable inference in the presence of gradual macroeconomic transformations.

3. Empirical Analysis

This section presents the empirical findings of the study. The analysis begins with unit root test results to determine the order of integration of the variables. Subsequently, the existence of a long-run equilibrium relationship is examined using the Fourier-Shin cointegration test. Finally, long-run coefficient estimates are reported and interpreted to evaluate the impact of industrial value added and economic growth on carbon emissions in Türkiye.

3.1. Unit Root Test Results

The stationarity properties of the variables are examined using both the conventional Augmented Dickey-Fuller (ADF) test and the Fourier KPSS (FKPSS) test. Employing both approaches allows for more robust inference, as the ADF test evaluates the null hypothesis of

a unit root, whereas the FKPSS test assumes stationarity under the null hypothesis while accounting for potential smooth structural shifts.

Table 2. ADF Unit Root Test Results

	Intercept		Intercept and Trend		
Variables	Test Statistic	5% Critical Value	Test Statistic	5% Critical Value	
$lnCO2$	-2.359 (0)	-2.916	-2.737 (0)	-3.495	
IND	-2.305 (1)	-2.917	-2.081 (1)	-3.453	
$lnGDP$	0.931 (0)	-2.916	-1.486 (0)	-3.495	
$\Delta lnCO2$	-6.785 (0)	-2.917	-6.436 (1)	-3.498	
ΔIND	-6.111 (0)	-2.917	-6.172 (0)	-3.496	
$\Delta lnGDP$	-7.008 (0)	-2.917	-7.149 (0)	-3.496	

Note: ** indicates significance at the 5% level. Values in parentheses denote the optimal lag length selected according to the Schwarz Information Criterion (SIC).*

The ADF test results, reported in Table 2, indicate that $lnCO_2$, IND, and lnGDP are non-stationary in levels under both intercept and intercept-with-trend specifications. However, when first differences are considered, all variables become statistically significant at the 5% level. Therefore, the null hypothesis of a unit root is rejected for the first differences, suggesting that all variables are integrated of order one, I(1).

Table 3. Fourier KPSS (FKPSS) Unit Root Test Results

Variables	Frequency (k)	Min SSR	FKPSS	F-statistic
$lnCO2$	1	0.20932	0.07548	24.75591
IND	1	236.2002	0.05618	31.15284
$lnGDP$	1	0.09765	0.06617	60.93841

Note: *For the FKPSS test, the critical values at the 10%, 5%, and 1% significance levels are 0.0471, 0.0546, and 0.0716, respectively. The F-statistic is used to test the significance of the trigonometric (Fourier) terms, with corresponding critical values of 4.162, 4.972, and 6.873 at the 10%, 5%, and 1% levels. The bandwidth parameter is selected using the Newey–West method. Min SSR denotes the minimum sum of squared residuals.*

The FKPSS results presented in Table 3 further support these findings. For $lnCO_2$, the FKPSS statistic exceeds the corresponding critical value even at the 1% significance level, indicating strong evidence against stationarity in levels. Similarly, for IND and lnGDP, the FKPSS statistics exceed the 5% critical value, leading to the rejection of the null hypothesis of stationarity. Thus, all variables are found to be non-stationary in levels according to the Fourier-based approach.

Moreover, the reported F-statistics are statistically significant at the 1% level for all variables, confirming the relevance of the Fourier terms in the model specification. This result suggests the presence of smooth structural shifts in the deterministic components of the series and justifies the use of Fourier-based econometric techniques.

Overall, the evidence from both ADF and FKPSS tests consistently indicates that $lnCO_2$, IND, and lnGDP are integrated of order one, I(1). Since the variables share the same order of

integration, it is appropriate to proceed with cointegration analysis to examine the existence of a long-run equilibrium relationship among them.

3.2. Fourier-Shin Cointegration Test Results

Following the confirmation that all variables are integrated of order one, the next step is to investigate whether a long-run equilibrium relationship exists among lnCO₂, IND, and lnGDP. For this purpose, the Fourier-Shin cointegration test is employed. The results are reported in Table 4.

Table 4. Fourier-Shin Cointegration Test Results

Frequency (k)	Min SSR	CI_f^0	$F^m(k)$
3	0.03188	0.04345	13.29641

Notes: *The 10%, 5%, and 1% critical values for the Fourier-Shin cointegration test under the trend specification (m = 1) with two regressors (p = 2) and frequency k = 3 are 0.075, 0.094, and 0.143, respectively (Tsong et al., 2016, s. 1092). The corresponding critical values for the F-test of the Fourier terms are 3.306, 4.019, and 5.860. The null hypothesis of the Fourier-Shin test assumes the existence of cointegration. The bandwidth parameter is selected using the Newey–West procedure.*

The Fourier-Shin cointegration test results are presented in Table 4. The test is conducted under the trend specification (m = 1) with two explanatory variables, and the optimal frequency is selected as k = 3 based on the minimum sum of squared residuals criterion.

The calculated CI_f^0 statistic (0.04345) is lower than the corresponding critical values at the 10%, 5%, and 1% significance levels. Therefore, the null hypothesis of cointegration cannot be rejected. This finding indicates the existence of a long-run equilibrium relationship among carbon emissions, industrial value added, and economic growth in Türkiye. Furthermore, the F-statistic (13.29641) exceeds the critical value at the 1% significance level, confirming the statistical significance of the Fourier terms. This suggests the presence of smooth structural shifts in the deterministic component of the model and validates the use of the Fourier-based approach.

While the empirical findings are clearly reported, the manuscript would benefit from a more explicit comparison of the cointegration and long-run coefficient results with the existing Türkiye-focused literature. In particular, the confirmation of a long-run equilibrium relationship and the positive, income-elastic effect of GDP on CO_2 emissions should be discussed in relation to prior ARDL and nonlinear cointegration studies (e.g., Bayramoğlu and Koç-Yurtkur, 2016; Karaca and Çımat, 2023; Pata, 2018). Clarifying whether the magnitude and direction of the estimated coefficients are consistent with or diverge from earlier findings would strengthen the interpretative depth of the study and better position its contribution within the broader empirical debate.

Overall, the results provide strong evidence of a stable long-run relationship among the variables within a framework that accounts for gradual structural changes. Given the presence of cointegration, the next step is to estimate the long-run coefficients using the Dynamic Ordinary Least Squares (DOLS) estimator.

3.3. Long-Run Coefficient Estimates

The long-run coefficient estimates obtained from the Dynamic Ordinary Least Squares (DOLS) estimator are reported in Table 5. The results indicate that both industrial value added and economic growth have statistically significant effects on carbon emissions in Türkiye.

Table 5. Long-Run Coefficient Estimates (DOLS Results)

Variables	Coefficient	t-Statistic	Probability
IND	0.023927	2.061560	0.0453
lnGDP	1.383917	15.78430	0.0000
Constant	-7.571429	-10.20567	0.0000

Note: Long-run coefficients are estimated using the Dynamic Ordinary Least Squares (DOLS) estimator. Standard errors are Newey–West corrected.

The coefficient of industrial value added (IND) is positive and statistically significant at the 5% level. Specifically, a one percentage-point increase in industrial value added (as a share of GDP) increases carbon emissions by approximately 0.0239 units in logarithmic terms. This finding suggests that industrial expansion contributes to environmental degradation in the long run.

Although the numerical magnitude of the IND coefficient appears smaller than that of income elasticity, its economic significance should not be underestimated. Since the dependent variable is in logarithmic form, a one-percentage-point increase in the industrial share of GDP leads to approximately a 2.39% increase in carbon emissions in the long run. Given that fluctuations in industrial share can be substantial over extended periods, this structural effect remains economically meaningful.

Economic growth (lnGDP) also exhibits a strong positive and highly significant impact on carbon emissions. Since both $lnCO_2$ and lnGDP are expressed in natural logarithms, the estimated coefficient (1.3839) can be interpreted as an elasticity. Accordingly, a 1% increase in GDP per capita leads to approximately a 1.38% increase in carbon emissions in the long run. This elasticity greater than one indicates that carbon emissions increase more than proportionally with economic growth.

The estimated income elasticity greater than one suggests that carbon emissions increase more than proportionally with economic growth. This finding indicates that Türkiye's growth trajectory has remained carbon-intensive over the long run. Such an elasticity may reflect persistent fossil fuel dependency, energy inefficiency in industrial production, and incomplete structural decarbonization. Compared to previous ARDL-based studies for Türkiye (e.g., Karaca and Çımat, 2023; Pata, 2018), the magnitude of the elasticity underscores that growth has not yet been effectively decoupled from carbon emissions.

CONCLUSION

This study examines the long-run relationship between carbon dioxide emissions, industrial value added, and economic growth in Türkiye over the period 1970–2024 using a Fourier-based time-series framework. After confirming that all variables are integrated of order one, the Fourier-Shin cointegration test provides strong evidence of a stable long-run

equilibrium relationship among the variables, even when smooth structural transformations are taken into account.

The empirical findings are broadly consistent with the existing Türkiye-focused literature documenting a positive relationship between economic growth, industrialization, and carbon emissions (Bayramoğlu and Koç-Yurtkur, 2016; Karaca and Çımat, 2023; Pata, 2018). However, by explicitly modeling gradual structural shifts, this study extends prior research that relies primarily on linear or discrete-break frameworks. The results suggest that Türkiye's growth trajectory has remained carbon-intensive despite structural transformations, reinforcing the scale effect hypothesis in the context of a fossil fuel–dependent energy structure.

From a methodological perspective, the use of the Fourier-Shin cointegration test constitutes an important contribution. Unlike conventional approaches that assume abrupt structural breaks, the Fourier framework captures smooth and continuous economic transformations, such as trade liberalization, energy market reforms, and industrial restructuring. This flexibility provides more reliable long-run inference in economies characterized by gradual structural change, such as Türkiye. The findings therefore demonstrate the practical relevance of Fourier-based econometric techniques for environmental macroeconomics.

The elasticity estimates offer important economic insights. The income elasticity of carbon emissions exceeding unity indicates that emissions increase more than proportionally with economic growth. This pattern suggests that economic expansion in Türkiye continues to rely heavily on energy-intensive production and fossil fuel consumption. In contrast, the positive coefficient of industrial value added confirms that structural shifts toward industry amplify environmental pressure. Although the numerical magnitude of the industrial share coefficient appears modest, its cumulative effect over time implies substantial increases in emissions, underscoring the environmental cost of industrial-led growth.

These findings highlight the urgency of a targeted green transformation strategy. Rather than treating growth and environmental sustainability as mutually exclusive goals, policy design should prioritize reducing the carbon intensity of production. Specific measures may include accelerating renewable energy deployment in industrial sectors, promoting energy efficiency through fiscal incentives and technological upgrading, and strengthening carbon pricing mechanisms to internalize environmental costs. In addition, the transition toward electric and hybrid vehicles represents a critical component of low-carbon transformation strategies, as the electrification of transportation can significantly reduce fossil fuel dependency and carbon emissions (Ak and Öz, 2025, s. 121-124). Supporting low-carbon transportation systems can therefore complement industrial decarbonization efforts and contribute to a broader sustainable growth framework.

Overall, the study contributes to the literature by providing robust evidence that Türkiye's long-term growth path remains closely linked to rising carbon emissions when gradual structural changes are taken into account. Future research may extend this framework by incorporating energy composition, technological innovation, and sectoral heterogeneity to

better understand the pathways through which economic growth can be decoupled from environmental degradation.

Ethical Principles and Publication Policy

No ethics committee approval is required for this article. A wet-signed consent form stating that no ethics committee decision is required is included in the article process files on the system.

Ethical Committee Approval

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Declaration of Authors' Contribution

This article has a single author, and therefore, the contribution rate of the author is 100%.

Declaration of Interest

There is no conflict of interest in this study with any institution, journal, or individual.

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