

Research Article

Convergence of Per Capita CO₂ Emissions in EAGLE Economies: Evidence from the Fourier Quantile Unit Root Test

EAGLE Ekonomilerinde Kişi Başına CO₂ Emisyonlarının Yakınsaması: Fourier Kantil Birim Kök Testinden Bulgular

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Abstract

The aim of this research is to examine whether per capita CO₂ emissions among emerging economies stochastic converge in the context of EAGLE, namely Brazil, China, Egypt, India, Indonesia, Mexico, Russia, South Korea and Türkiye. In order to overcome the limitations of traditional unit root tests, the Fourier Quantile Unit Root Test, which takes into account structural breaks and nonlinearities, is used. This method allows a more detailed evaluation of the convergence behavior by examining the stationarity properties of the series at different quantiles. The originality of this research is that it makes an innovative contribution to the convergence analysis of per capita carbon emissions with its quantile-based and structural break-inclusive Fourier approach. Thus, it shows that environmental policies may have different effects depending on the country and distribution level, and guides policy makers in developing flexible and target-oriented strategies. The findings reveal a heterogeneous and quantile-dependent pattern of country-specific stochastic convergence. Stationarity is detected across all examined quantiles for China and South Korea. For the remaining economies, stationarity is observed only at particular quantiles: $\tau = 0.10, 0.30, 0.80$, and 0.90 for Brazil; $\tau = 0.30-0.90$ for Egypt; $\tau = 0.20-0.50$ for India; $\tau = 0.30, 0.40, 0.60, 0.70$, and 0.90 for Indonesia; $\tau = 0.30, 0.50, 0.80$, and 0.90 for Mexico; and $\tau = 0.10, 0.30-0.70$, and 0.90 for Türkiye. Russia exhibits limited evidence of stationarity, which is detected only at $\tau = 0.20$ and 0.80 . In addition, the Fourier Quantile Kolmogorov–Smirnov test provides distribution-wide evidence of stochastic convergence for China, Indonesia, and Türkiye. These results indicate country-specific mean reversion rather than direct convergence of emission levels across EAGLE economies.

Keywords: CO₂ Emissions, Convergence, Fourier Quantile Unit Root Test, EAGLE Economies

Öz

Bu araştırmanın amacı, yükselen ekonomiler arasında kişi başına düşen CO₂ salınımlarının stokastik yakınsama gösterip göstermediğini Brezilya, Çin, Mısır, Hindistan, Endonezya, Meksika, Rusya, Güney Kore ve Türkiye gibi EAGLE ülkeleri kapsamında incelemektir. Geleneksel birim kök testlerinin sınırlılıklarını aşmak amacıyla yapısal kırılmalar ve doğrusal olmayan durumları dikkate alan Fourier Kantil Birim Kök Testi kullanılmıştır. Bu yöntem, serilerin farklı kantillerdeki durağanlık özelliklerini inceleyerek, yakınsama davranışını daha ayrıntılı bir şekilde değerlendirmeye olanak tanımaktadır. Bu araştırmanın özgün yönü, kişi başına karbon emisyonlarına ilişkin

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yakınsama analizine kantil-temelli ve yapısal kırılmaları içeren Fourier yaklaşımıyla yenilikçi bir katkı sunmasıdır. Böylece çevre politikalarının ülkeye ve dağılım düzeyine göre farklı etkiler doğurabileceğini göstererek, politika yapıcılara esnek ve hedef odaklı stratejiler geliştirme konusunda yol göstermektedir. Bulgular, ülkeye özgü stokastik yakınsamanın heterojen ve kantile bağlı bir yapı gösterdiğini ortaya koymaktadır. Çin ve Güney Kore’de incelenen tüm kantillerde durağanlık tespit edilmiştir. Diğer ekonomilerde ise durağanlık yalnızca belirli kantillerde gözlemlenmiştir: Brezilya için $\tau = 0,10, 0,30, 0,80$ ve $0,90$; Mısır için $\tau = 0,30-0,90$; Hindistan için $\tau = 0,20-0,50$; Endonezya için $\tau = 0,30, 0,40, 0,60, 0,70$ ve $0,90$; Meksika için $\tau = 0,30, 0,50, 0,80$ ve $0,90$; Türkiye için ise $\tau = 0,10, 0,30-0,70$ ve $0,90$ kantillerinde durağanlık bulgusuna ulaşılmıştır. Rusya’da durağanlık yalnızca $\tau = 0,20$ ve $0,80$ kantillerinde tespit edilmiş olup, stokastik yakınsama kanıtı sınırlı düzeydedir. Ayrıca Fourier Kantil Kolmogorov–Smirnov testi Çin, Endonezya ve Türkiye için dağılımın geneline ilişkin stokastik yakınsama kanıtı sunmaktadır. Bu sonuçlar, EAGLE ekonomilerinin emisyon düzeylerinin birbirine doğrudan yakınsamasını değil, ülkeye özgü uzun dönem patikalarına dönüş eğilimini ifade etmektedir.

Anahtar Kelimeler: CO₂ Emisyonu, Yakınsama, Fourier Kantil Birim Kök Testi, EAGLE Ekonomileri

1. Introduction

Climate change and global warming are among the most significant environmental challenges currently faced by humanity. The increase in carbon dioxide (CO₂) emissions discharged into the atmosphere is one of the primary causes of these issues. The global environmental equilibrium is being disrupted by the accumulation of greenhouse gases in the atmosphere, which is caused by accelerated urbanization, increasing industrialization, and the use of fossil fuels. In this context, how the per capita CO₂ emissions of countries have evolved over time and whether these emissions show a convergence trend have become important research topics in the environmental economics literature.

Convergence analysis is a method initially developed to examine whether income disparities decrease over time in the literature on economic development (Barro and Sala-i-Martin, 1992). Nevertheless, in recent years, this analysis has been adapted to environmental indicators to understand the dynamics of inequality in per capita CO₂ emissions. Such analyses are critically important for evaluating the effectiveness of environmental policies and measuring the success of global emissions reduction strategies. In particular, the convergence of per capita CO₂ emissions provides important insights into the extent to which countries are achieving their sustainable development goals.

The convergence hypothesis essentially posits that global emission levels reach a common equilibrium or that countries with less pollution converge over time toward countries with high emissions. Testing this hypothesis is important for evaluating the success of international environmental policies, such as the Kyoto Protocol and the Paris Climate Agreement. If per capita CO₂ emissions convergence occurs over time, this could indicate that environmental disparities between nations are subsiding and that progress is being made toward shared sustainable development objectives. However, the differences between countries in terms of technological development, energy consumption habits, renewable energy investments, and environmental policies suggest that the convergence process may be heterogeneous.

Whether CO₂ emissions are stationary, meaning whether an external shock has temporary or permanent effects on emissions, is critically important in determining climate change and environmental policy. If the emissions are stationary, each country's series returns to its own long-term defining path. In the opposite case, the long-term effects of shocks come into play (Cai and Wu, 2019). In other words, if it is not stationary, the effects of shocks and policy interventions may be permanent. Conversely, if the data is stationary, any external intervention only creates a temporary effect and is not sufficient for long-term change. The trajectory of environmental policymaking is significantly influenced by this situation (Romero-Ávila and Omay, 2022).

The level of economic development, energy consumption patterns, and industrial structures of countries all contribute to significant variations in per capita carbon emissions. Developed countries have historically high emission levels, whereas emissions in developing countries are rapidly increasing (Peters et al., 2011). However, there has been an increase in academic interest in whether per capita CO₂ emissions are converging among countries. The convergence hypothesis means that the emission levels of different countries approach each other over time, and this process is critically important in terms of the effectiveness of climate policies (Aldy, 2006).

This approach is becoming increasingly important, especially because developing countries are increasing their emissions during industrialization. For instance, the per capita emissions of economies such as China and India have increased rapidly in recent years, while the European Union has implemented policies to achieve emission reduction objectives. However, the existence of a global convergence process is debatable. Aldy (2006) demonstrated that the per capita emissions of OECD countries exhibit mild β -convergence; however, this trend is not observed in developing countries.

The purpose of this study is to examine the country-specific stochastic convergence characteristics of per capita CO₂ emissions in the nine EAGLE economies (Brazil, China, Egypt, India, Indonesia, Mexico, Russia, South Korea, and Türkiye) for the period 1970-2023. The country-specific stochastic convergence behavior of per capita CO₂ emissions in EAGLE economies, which have high growth potential, has been addressed only to a relatively limited extent. Although the EAGLE countries share common characteristics in terms of rising energy demand and their importance in global production, they are markedly heterogeneous in terms of per capita emission levels, dependence on fossil fuels, industrial structures, technological capacities, and low-carbon transition processes. Therefore, this group of countries provides a suitable research area for examining how the persistence of emission shocks varies across developing economies and under different emission regimes.

The main research question of this study is whether shocks to each country's per capita CO₂ emissions series are temporary or permanent, and whether this behavior varies across different quantiles of the distribution. In this study, convergence is not used to mean a reduction in emissions differences among countries or a convergence of countries toward a common emissions level. Convergence is defined here as the tendency for each country's emissions series to return to its own long-run deterministic path following a shock.

This study contributes to the literature in four ways. First, while previous studies have generally focused on the OECD, G7, BRICS, or broad country panels, this study specifically examines the EAGLE economies, which possess high growth potential, increasing energy demand, and heterogeneous environmental policy structures. The countries in question were included in the analysis because of their increasing energy consumption and economic growth potential, as well as their share in global emission production. This choice is significant in terms of the study's contribution to the global sustainability discussions. Second, the study goes beyond conventional linear unit root and convergence tests by employing the Fourier Quantile Unit Root Test, which simultaneously accounts for smooth structural breaks, nonlinear dynamics, and distributional heterogeneity. This method has been preferred because it can model the complex dynamics present in time series more successfully than classical unit root tests. Third, by revealing convergence patterns that differ at the country and quintile levels, it offers more detailed policy implications than classical approaches. Fourth, the study distinguishes between findings related to the return to the stochastic mean and the direct effectiveness of environmental policies, and provides a more cautious framework for interpreting unit root results from a policy perspective.

2. Literature Review

The literature on CO₂ emissions convergence varies in terms of country groupings used, methodological approaches, and findings obtained. Therefore, to evaluate the existing literature in a more systematic manner, studies can be considered under several main groups. The first group consists of studies that examine the convergence of CO₂ emissions in OECD and other developed country groups. In OECD studies involving different numbers of countries, it has been concluded that per capita CO₂ emissions converge (Strazicich and List, 2003; Romero-Ávila, 2008; Presno et al., 2018; Ayazoğlu, 2022). In convergence-based studies covering different periods for OECD countries, different findings have been obtained (Pettersson et al., 2014; Cai and Wu, 2019; Lee et al., 2021; Solarin et al., 2022). Li et al. (2020) and Bhattacharya et al. (2020) have reached similar results by analyzing income groups and production-consumption-based emissions. A study conducted on G18 countries also found evidence of convergence (Lin et al., 2018).

The second group includes studies encompassing various country groups such as developing countries, emerging market economies, and developed countries. In studies examining different numbers of countries, results have also been obtained that confirm convergence. A study conducted on 39 African countries also found evidence of convergence (Solarin, 2014). A study conducted by Berk et al. (2022)

aimed to ascertain if per capita carbon dioxide emissions exhibited convergence among 65 nations between the years 1970 and 2014. The analysis results have shown that CO₂ emissions exhibit a convergence trend. Runar et al. (2017) concluded there is a convergence in CO₂ emissions influenced by economic growth and institutional quality. In studies involving Asian countries, convergence in CO₂ emissions has also been observed (De Oliveira and de Vargas, 2015; Tiwari and Mishra, 2017). Romero-Ávila and Omay (2022) analyzed long-term CO₂ emission data. According to the analysis results, when nonlinear tests capable of capturing soft and asymmetric behaviors were used, and with hybrid test approaches, the unit root hypothesis was rejected. Rodríguez-Benavides et al. (2024) used the Phillips and Sul methodology to analyze the convergence of carbon dioxide emissions from fossil fuels and cement production in 139 countries during the period from 1960 to 2017. The analysis results showed a convergence in CO₂ emissions among the countries.

In the third group of studies, it was concluded that there is no convergence in CO₂ emissions or that the evidence for convergence is weak. McKibbin and Stegman (2005) found no indication of a convergence between countries. Aldy (2007) concludes that there has been no convergence in CO₂ emissions from consumption for the U.S. Camarero et al. (2011) conducted an analysis of 22 OECD countries from 1950 to 2006. The investigation did not reveal any convergence in CO₂ emissions among OECD countries. The convergence hypothesis of greenhouse gas emissions for G7 was investigated by El-Montasser et al. (2015). Upon the application of the criteria, it was determined that the countries did not exhibit absolute convergence during the period 1990–2011. Zerbo and Darné (2019) investigated the convergence of per capita CO₂ emissions in 29 OECD countries and excluding Russia from the BRICS group during the 1960-2014 period. The analysis results exhibited that all countries were in a random walk process. This implies that the series is permanently impacted by the disturbances. Nazlioglu et al. (2021) examined whether per capita CO₂ emissions in OPEC and other oil-producing countries show convergence. According to the results of the tests applied, less evidence was found compared to some other major country groups. In other words, there is no strong evidence that relative CO₂ emissions have statistically converged among countries. Lee et al. (2023) have shown that per capita CO₂ emissions in OECD countries do not converge over time.

The studies in the fourth group are based on the finding that convergence differs across different countries or country groups. In studies involving different income groups, it is observed that the convergence results vary by period and country (Ahmed et al., 2017; Deniz, 2022; Borowiec and Papież, 2024; Anavatan and Ispir, 2025). In studies on the convergence of carbon emissions in the USA (Apergis et al., 2017), emerging market economies (Churchill, Inekwe, and Ivanovski, 2020), and countries with the highest CO₂ emissions (Sohail et al., 2022), different findings have also been observed. Another group of studies, on the other hand, is based on methods that employ panel data approaches. Studies based on panel data and panel unit root analyses also show that the results vary according to the country group and the type of test. In some of these studies, convergence was found to be valid (Aslan, 2009; Payne and Apergis, 2021; Yilanci et al., 2022), while in others, convergence was found not to be valid (Romuald, 2011; Magazzino, 2019).

The majority of early-stage research relies on linear unit root tests, panel unit root approaches, or methods that examine changes in cross-country variation over time. While these approaches provide useful insights into whether emission shocks are, on average, temporary or permanent, they may not adequately capture the structural changes and nonlinear adjustment processes that can be observed in long-term environmental time series. These limitations have reinforced the shift toward Fourier- and quantile-based methods in recent literature.

Recently, it has been observed that Fourier-based and quantile-based approaches have been increasingly used in the CO₂ emissions convergence literature. Lin et al. (2018) analyzed whether CO₂ emissions in G18 converged or diverged during the period 1950-2013. Ye et al. (2020) examined whether CO₂ emissions of the G7 economies and the world's largest CO₂ emission producers like China converged during the period 1950-2013. The emissions of Germany, Italy, and the UK generally exhibited convergence across a broad spectrum of quantiles, as indicated by the Fourier Quantile test results. For the other countries, convergence has emerged in some quantiles. Saliminezhad and Bahramian (2020) investigated whether CO₂ emissions converged for four countries during 1960-2017. Overall, the classical test results showed that there were permanent shocks in CO₂ emissions. The results of the unit

root tests indicate that, although there are signs of convergence in certain periods in some countries (especially Canada, Russia, and partially Iraq), the emissions in Saudi Arabia do not stabilize in all quantiles. Bayraktar et al. (2023) examined whether the ecological footprint (EF) of the countries comprising BRICS-T converged to the average of the BRICS-T group during the period 1992-2017. The Fourier test indicated convergence signals in China and Russia, while the Fractional Fourier Frequency test revealed convergence in Brazil and China.

The literature on the convergence of per capita CO₂ emissions has not reached a consensus. While some studies have found that emission series are stationary, particularly for developed countries and OECD samples, other studies show that shocks are persistent and that the convergence hypothesis is not supported. Another group of studies, however, demonstrates that convergence holds true only for specific countries, periods, or subgroups. These differences stem not only from countries' levels of economic development, energy mixes, and environmental policies but also from the period under study, the emission metric, the definition of convergence, and the econometric methods employed. Consequently, the findings in the literature indicate that convergence is not a homogeneous process applicable to all countries and periods but rather a phenomenon that is sensitive to both the country and the methodology used.

Overall, the literature points to three main gaps. First, findings vary across country groups and methods; therefore, it is not possible to speak of a homogeneous convergence outcome for developing economies. Second, traditional and mean-based tests are limited in their ability to simultaneously account for gradual structural changes and the persistence of shocks across different regions of the distribution. Third, the EAGLE economies, which stand out for their high growth and energy demand, have not been sufficiently examined as a distinct group in the existing literature on emissions convergence. In response to these gaps, this study examines country-specific stochastic convergence in per capita CO₂ emissions for the EAGLE economies using the Fourier Quantile Unit Root Test and investigates whether the persistence of shocks varies across countries and across different regions of the emissions distribution.

3. Data

In this study, a convergence analysis of per capita CO₂ emissions has been conducted. In this context, the emerging economies known as EAGLE, consisting of Brazil, China, Egypt, India, Indonesia, Mexico, Russia, South Korea, and Türkiye, have been analyzed for the period from 1970 to 2023. Taiwan, on the other hand, was not included in the analysis due to lack of data. Two different representations are used in the data presentation. Descriptive statistics are based on raw data, while the graph showing the trend in countries' emission levels over time is based on logarithmic per capita CO₂ emission values. In addition, the natural logarithms of the per capita CO₂ emissions time series were used in the econometric analyses to reduce the effect of heteroskedasticity, limit the impact of outliers, and ensure a more appropriate assessment of the proportional changes in the series.

In this context, convergence is addressed not as direct convergence between countries, but rather as the tendency of per capita CO₂ emissions series to return to their own long-term average path over time, that is, within the framework of stochastic convergence. These countries hold a significant place in the formulation of environmental sustainability policies not only because of their high growth potential but also because they produce a substantial portion of global carbon emissions. EAGLE countries, with their increasing levels of industrialization and rapidly growing energy demand, have a greater impact on the environment, necessitating the analysis of the structural characteristics of emissions. In terms of these characteristics, it is assumed that both the increase in emission levels and their responses to environmental policies may be heterogeneous across countries. In this context, analyzing the convergence behavior of per-capita CO₂ emissions over time in these countries is also important for formulating sustainable policies for developing countries.

Table 1: Descriptive Statistics of Raw Per Capita CO₂ Emissions

Series	Mean	Standard dev.	Minimum	Maximum	Skewness	Kurtosis
Brazil	1.484	0.665	0.368	2.788	-0.017	1.946
China	2.890	2.514	0.145	8.367	0.904	2.384
Egypt	1.354	0.690	0.408	2.514	0.249	1.615
India	0.764	0.551	0.176	2.129	0.919	2.634
Indonesia	0.981	0.723	0.134	2.643	0.615	2.150
Mexico	3.159	1.085	1.106	4.424	-0.678	1.841
Russian	11.163	3.195	4.014	17.024	-0.283	2.709
South Korea	5.809	4.622	0.111	12.977	0.221	1.454
Türkiye	2.509	1.557	0.451	5.222	0.276	1.709

The data has been obtained from the site "ourworldindata.org". Table 1 presents the descriptive statistics of CO₂ emissions per capita for the countries. The average values of per capita CO₂ emissions of the countries range from 0.764 to 11.163. According to the standard deviation values, South Korea has the highest variability, while India has the lowest variability. According to the skewness values, it was found that the per capita CO₂ emission series of Brazil, Mexico, and Russia showed a left-skewed distribution. The series for China, Egypt, India, Indonesia, South Korea, and Türkiye, on the other hand, show a right-skewed distribution. The natural logarithms of the data were taken. Figure 1 shows the change in per capita CO₂ emissions of countries during the period from 1970 to 2023. Figure 1 shows the time interval on the X axis and per capita CO₂ emissions values on the Y axis.

Figure 1: Logarithm of Per capita CO₂ emissions by country

Source: ourworldindata.org, <https://ourworldindata.org/co2-and-greenhouse-gas-emissions>

4. Methodology

In this study, the Fourier Quantile Unit Root Test approach was used to analyze the convergence of per capita CO₂ emissions. In time series, especially in long-term data, the trend component can change over time, but not in sharp jumps; rather, there can be more gradual (smooth) breaks. Traditional tests cannot

properly capture such structural changes, so using Fourier functions offers better modeling opportunities (Goswami and Saha, 2024).

The quantile unit root test, unlike traditional tests, shows whether there are different dynamics in certain sections of the time series (Cai et al., 2018). The quantile unit root test evaluates the series not by a single average but by conducting separate tests in different quantile regions of the series (for example, lower, middle, and upper quantiles). The Fourier quantile unit root test is an advanced method used to test the stationarity (or convergence) properties of time series, particularly considering complex situations such as structural breaks and non-linearity. The main purpose of this test is to reveal the convergence properties of the series at different distribution quantiles in a more flexible manner in situations where traditional linear unit root tests fall short (Lee et al., 2019).

Fourier Quantile Unit Root Test, unlike traditional unit root tests, examines the stationarity property of the series not only around the conditional mean but also at different quantile levels of the distribution. In this respect, the method allows for the analysis of whether the responses of the series to shocks differ across low, medium, and high emission levels. The basic principle of the test is to integrate a quantile regression-based unit root approach with Fourier functions, thereby incorporating both nonlinear dynamics and gradual, smooth structural breaks into the model. In this test, the null hypothesis asserts that the series contains a unit root at the relevant quantile level, that is, it does not exhibit convergence. The alternative hypothesis, on the other hand, indicates that the series is stationary at the relevant quantile level and tends to revert to its long-term trend following shocks.

The Fourier Quantile Unit Root approach is implemented by combining the Quantile Regression-Based Unit Root Test developed by Koenker and Xiao (2004) with the Fourier approach proposed by Enders and Lee. This approach aims to achieve stronger results by using Fourier transformations to model structural changes in the series while examining unit root behavior at different quantile levels. Bahmani-Oskooee et al. (2017, 2018) proposed a new approach by adding Fourier terms within the quantile regression framework of Koenker and Xiao (2004).

$$y_t = \lambda_1 + \lambda_2 t + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + v_t \quad (1)$$

In Equation (1), γ_1 and γ_2 are the coefficients of the Fourier terms. λ_1 is the constant term; λ_2 is the trend coefficient, t is deterministic trend and v_t is the error term. In this approach, the value of k that minimizes the sum of the squares of the error terms is obtained, as in the approach of Becker et al. (2006). These error terms are obtained using the Ordinary Least Squares (OLS) method from equation (1). For each value of k , the models are estimated separately using the OLS method. The sum of the squared errors obtained from each estimate is recorded, and the optimal frequency is selected. Koenker and Xiao (2004) define $e_t = \hat{v}_t$, and the τ_{th} conditional quantile is shown in equation (3) (Bahmani-Oskooee et al., 2018):

$$Q_{e_t}(\tau|\xi_{t-1}) = \alpha_0(\tau) + \rho_1(\tau) \epsilon_{t-1} + \sum_{k=1}^{k=I} \rho_{1+k}(\tau) \Delta \epsilon_{t-k} + v_t \quad (2)$$

In Equation (2), $Q_{e_t}(\tau|\xi_{t-1})$ is the τ -th quantile dependent on the past value of ξ_t . Here, the estimated values reveal the magnitudes of the shocks in each quantile. The persistence of a shock in each quantile can be measured with $\rho_1(\tau)$ (Bahmani-Oskooee et al., 2018).

QKS statistics are generated in the range $\tau_i \in [0.1, 0.9]$. Thus, it is possible to examine in detail whether the convergence behavior differs across the lower, middle, and upper regions of the distribution. The Fourier frequency value was determined by selecting the value among the candidate frequency values that minimizes the sum of squared errors. This approach ensures that the Fourier functions represent the structural change in the series in the most appropriate manner. Since the distribution of QKS test statistics is non-standard, critical values are generated using the steps outlined by Koenker and Xiao (2004), as detailed by Bahmani-Oskooee et al. (2017). To evaluate the finite sample properties of the test, equation (3) is first constructed to obtain the finite sample critical values of the Fourier Quantile Kolmogorov-Smirnov (FQKS) test statistics.

$$y_t = Z_t \lambda + \gamma_1 \sin\left(\frac{2\pi k^* t}{T}\right) + \gamma_2 \cos\left(\frac{2\pi k^* t}{T}\right) + w_t \quad (3)$$

$$w_t = w_{t-1} + \vartheta_t \quad t = 1, 2, \dots, T$$

Since the distribution of quantile unit root tests differs from standard normality, simulations are used instead of analytical results to determine critical values (Goswami and Saha, 2024). To measure the statistical significance of the test, the FQKS statistic obtained with 5000 iterations (Bootstrap) and the critical values calculated at different significance levels based on this are used to make decisions on the test results (Doğanlar et al., 2021). For the FQKS test, the null hypothesis states that there is a unit root in the quantile range under examination; the alternative hypothesis states that there is stationarity in at least a systematic portion of the distribution.

To investigate the finite sample power of the FQKS test from the unit root test, equation (4) is ultimately formed:

$$y_t = Z_t \lambda + \gamma_1 \sin\left(\frac{2\pi k^* t}{T}\right) + \gamma_2 \cos\left(\frac{2\pi k^* t}{T}\right) + w_t \quad (4)$$

$$w_t = \rho w_{t-1} + u_t \quad t = 1, 2, \dots, T$$

In Equation (4), $k^* = 1, 2, 3, 4, 5$ are the values that the parameters and frequencies can take. As part of this study, the FQKS statistic was calculated, and a bootstrap process with 5,000 repetitions, as well as critical values of 1%, 5%, and 10%, were obtained using the R.

5. Findings

The descriptive statistics reported in Table 1 are based on raw per capita CO₂ emission values, whereas the natural logarithm of the series was used in the econometric analyses. Before applying the Fourier Quantile Unit Root Test, conventional unit root and stationarity tests were used to preliminarily assess the stationarity properties of the series. In this context, the natural logarithms of the per capita CO₂ emission series for each country were subjected to Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests. These tests were carried out considering both the model with a constant and the model with a constant and trend. In the ADF test, the appropriate lag length was determined according to the Schwarz Information Criterion. For the PP and KPSS tests, the Bartlett kernel and the Newey-West automatic bandwidth method were used for long-run variance estimation. The decision criteria differ according to the hypothesis structures of the tests. In the ADF and PP tests, the null hypothesis posits that the series contains a unit root; therefore, rejection of the null hypothesis indicates that the series is stationary. In contrast, in the KPSS test, the null hypothesis states that the series is stationary; thus, rejection of the null hypothesis indicates that the series is not stationary. Test results were evaluated at the 1%, 5%, and 10% significance levels.

Table 2: Results of ADF, PP ve KPSS Tests

Series	Constant			Constant + Trend		
	ADF	PP	KPSS	ADF	PP	KPSS
Brazil	-3.232** (0.022)	-3.001** (0.039)	1.074***	-1.683 (0.749)	-1.784 (0.702)	0.229***
China	-1.679 (0.438)	-2.302 (0.174)	1.139***	-4.206*** (0.007)	-3.694** (0.029)	0.097
Egypt	-1.002 (0.749)	-0.979 (0.756)	1.125***	-2.644 (0.263)	-2.809 (0.199)	0.116
India	0.333 (0.979)	0.373 (0.981)	1.158***	-2.169 (0.499)	-2.268 (0.446)	0.155**
Indonesia	-1.114 (0.706)	-1.114 (0.706)	1.158***	-2.591 (0.286)	-2.649 (0.261)	0.119*
Mexico	-3.363** (0.016)	-3.071** (0.033)	0.927***	-0.692 (0.969)	-0.692 (0.969)	0.281***
Russia	-2.898* (0.051)	-3.473** (0.008)	0.488**	-2.511 (0.011)	-2.508 (0.011)	0.251***

	(0.051)	(0.012)		(0.322)	(0.323)	
South Korea	-7.999*** (0.000)	-8.701*** (0.000)	1.086***	-1.763 (0.712)	-1.807 (0.691)	0.293***
Türkiye	-2.207 (0.206)	-2.430 (0.137)	1.128***	-0.809 (0.959)	-0.598 (0.976)	0.267***

Note: ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively. The values in parentheses are p-values for ADF and PP tests. The tests are conducted using the natural logarithms of the per capita CO₂ emission series.

Table 2 presents the ADF, PP, and KPSS test results for the natural logarithm of per capita CO₂ emissions under two different deterministic structures: a model containing only a constant term and a model containing a constant term and a linear deterministic trend. According to the ADF test with constant, results show that the series for Brazil, Mexico, Russia, and South Korea reject the presence of a unit root at the level. This means that these series are stationary. According to the PP test with constant results, the unit root presence of the series for Brazil, Mexico, Russia, and South Korea was rejected, therefore these series were obtained as level-stationary. According to the KPSS test results based on the constant, it is observed that all series reject the null hypothesis of stationarity.

According to the ADF and PP tests with constant and trend, results have not rejected the unit root status of all series outside of China. Accordingly, while the China series was obtained as stationary, the other series have a unit root. According to the KPSS test, which included the equation with the trend, results have shown that the China and Egypt series could not reject the null hypothesis of stationarity. The results have shown the China and Egypt series are stationary, while the other series have a unit root.

Table 3: Results of Fourier Quantile Unit Root Test

Series	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Brazil	0.923** * (0.000)	0.971 (0.104)	0.853** (0.049)	0.912 (0.258)	0.953 (0.561)	0.932 (0.339)	0.982 (0.813)	0.946** * (0.001)	0.948** * (0.005)
China	0.898** * (0.000)	1.034** * (0.000)	0.736** * (0.000)	0.792** * (0.000)	0.770** * (0.000)	0.787** * (0.000)	0.781** * (0.000)	0.948** * (0.000)	0.936** * (0.000)
Egypt	0.972 (0.534)	1.015 (0.624)	0.761** (0.012)	0.742** (0.015)	0.769** (0.017)	0.662** * (0.001)	0.645** * (0.001)	0.965* (0.079)	0.959* (0.057)
India	1.004 (0.817)	0.966** * (0.000)	0.797** (0.027)	0.822* (0.053)	0.823* (0.056)	0.915 (0.189)	0.873 (0.116)	1.009 (0.231)	1.008 (0.436)
Indonesia	0.975 (0.204)	1.014 (0.408)	0.827** (0.044)	0.799** (0.029)	0.864 (0.132)	0.775** (0.019)	0.736** (0.011)	0.979 (0.264)	0.952** (0.032)
Mexico	0.953 (0.269)	0.997 (0.891)	0.796** * (0.009)	0.884 (0.105)	0.868* (0.068)	0.888 (0.153)	0.945 (0.534)	0.966* (0.094)	0.935** * (0.000)
Russia	0.977 (0.227)	0.922** * (0.000)	0.987 (0.695)	0.997 (0.916)	0.975 (0.360)	0.969 (0.244)	0.970 (0.250)	0.918** (0.011)	0.964 (0.165)
South Korea	0.926** * (0.000)	0.940** * (0.000)	0.647** * (0.001)	0.684** * (0.002)	0.719** * (0.008)	0.878* (0.052)	0.854* (0.058)	0.975* (0.053)	0.942** * (0.000)
Türkiye	0.899** * (0.000)	0.989 (0.439)	0.688** (0.015)	0.771* (0.062)	0.680** * (0.008)	0.766** (0.030)	0.790* (0.099)	0.987 (0.341)	0.958** * (0.004)

Note: ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively. The values in parentheses are p-values. The tests are conducted using the natural logarithms of the per capita CO₂ emission series.

Traditional unit root tests do not take into account structural breaks or asymmetric behaviors in the series. In this context, after the traditional unit root tests, the Fourier Quantile Unit Root Test was also applied in the study to analyze whether the countries' emissions converge or diverge. In this study, the test was applied for nine quantile levels from $\tau = 0.10$ to $\tau = 0.90$. The Fourier frequency was determined based on the value that minimizes the sum of squared errors among the candidate frequency values. In addition, to assess evidence of convergence at the general distribution level, the Fourier Quantile Kolmogorov-Smirnov (FQKS) test statistic is calculated; since the critical values do not rely on the standard distribution, they are obtained using the bootstrap method with 5000 replications.

In Table 3, the results of the Fourier Quantile Unit Root Test for per capita CO₂ emission series at different quantile levels ($\tau = 0.1-0.9$) are presented. According to the results of the Fourier Quantile Unit Root Test, while stationarity (convergence) is observed at certain quantiles in some countries, the presence of stationarity is noted across all quantile ranges in China and South Korea. The fact that stationarity is observed in all quantiles studied in China and South Korea suggests that shocks to per capita CO₂ emissions may be temporary in different regions and that the series tend to revert to their country-specific long-term. However, this finding does not prove that the environmental policies implemented in these countries are directly successful or effective. The observed behavior of returning to the mean may reflect the combined effect of numerous factors, such as energy mix, production structure, technological change, economic fluctuations, environmental regulations, and institutional capacity. Therefore, the results should be interpreted not as causal evidence of policy effectiveness, but as country-specific empirical indicators that must be evaluated in conjunction with more comprehensive country analyses.

Table 3 showed that the series is stationary for Brazil at the 0.1, 0.3, 0.8, and 0.9 quantiles. For Egypt, it was concluded that the series is stationary in the middle and upper quantiles, specifically in the range of 0.3 - 0.9. For Türkiye, it has been observed that the series is stationary at all quantiles except for 0.2 and 0.8. In the results obtained for Brazil, India, Indonesia, and Mexico, stationarity was observed at certain quantiles. In the results for Brazil, significance was obtained at the 0.1, 0.3, 0.8, and 0.9 quantiles. For Mexico, significant findings have been obtained indicating stability at the middle and upper quantiles of 0.3, 0.5, 0.8, and 0.9. For India, results indicating stability were obtained at the middle quantiles of 0.2, 0.3, 0.4, and 0.5. For Indonesia, significant results were found at the mid quantiles of 0.3, 0.4, 0.6, 0.7, and 0.9. The fact that stationarity is observed only in certain quantiles in Brazil, Egypt, India, Indonesia, Mexico, and Türkiye indicates that the persistence of shocks is not homogeneous across the emission distribution. This finding provides an indirect empirical indication that different adjustment mechanisms may be at work at low, medium, and high emission levels. However, quantile-specific stationarity or unit root findings do not, on their own, provide conclusive evidence regarding the effectiveness of specific environmental policies. These patterns must be evaluated in conjunction with factors such as policy changes, energy demand, industrialization, foreign trade, economic crises, energy prices, and technological transformation.

In the results obtained for Russia, limited levels of stationarity were observed at the 0.2 and 0.8 quantiles. The observation of stationarity in certain regions of Russia provides limited empirical evidence that the shocks to per capita CO₂ emissions may be persistent across a large portion of the distribution. However, this finding does not directly indicate that Russia's environmental policies are failing or ineffective. The persistence of these shocks may stem from various factors, such as a fossil-fuel-based production structure, energy exports, industrial composition, economic and geopolitical developments, the pace of technological transformation, and institutional regulations. Unraveling these mechanisms requires additional econometric analyses that incorporate policy and structural variables.

Table 4: Results of Fourier Quantile Kolmogorov-Smirnov Test

Series	FQKS statistics	%1	%5	%10	F statistics
Brazil	5.883	14.418	11.85	10.734	658.266***
China	8.073*	13.616	10.104	8.052	35.275***
Egypt	3.891	13.572	11.081	9.892	747.186***
India	3.961	45.706	33.565	26.174	9.33***
Indonesia	16.437***	11.929	7.893	6.328	11.481***

Mexico	7.214	23.71	18.111	15.453	0.716
Russia	7.585	13.174	11.124	10.162	14.925***
South Korea	6.477	12.985	8.793	7.217	26.993***
Türkiye	12.493*	20.964	14.997	12.241	20.702***

Note: ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively. The table shows critical values based on significance levels. The tests are conducted using the natural logarithms of per capita CO₂ emission series.

Table 4 presents the Fourier Quantile Unit Root test results for the entire quantile, showing the Fourier QKS (FQKS) test statistic and the critical values at different significance levels. In this test, the critical values were generated through a bootstrap technique with 5000 replications. The results of the FQKS test statistic indicate that it is statistically significant for China, Indonesia, and Türkiye. The lack of an overall convergence trend among EAGLE countries may be attributed to differences in their energy policies, levels of transition to renewable energy, industrial structures, and variations in institutional capacity. This situation, as emphasized by Runar et al. (2017), indicates that not only economic growth but also institutional quality and policy impact shape the convergence process. In this context, environmental policies need to be differentiated by taking into account the characteristics of each country.

When interpreting Table 3 and Table 4 together, the distinction between quantile-based and general test results should be taken into account. The results of the Fourier Quantile Unit Root Test in Table 3 provide evidence of stationarity at each quantile level, while the FQKS test in Table 4 is a general test that evaluates the entire quantile distribution collectively. Therefore, it is not a contradiction if the FQKS test is not found significant, even though significant results are obtained at certain quantiles in some countries. This indicates that the convergence tendency emerges only in specific regions of the distribution, but there is no strong and comprehensive convergence process extending across the entire emission distribution. In contrast, the significance of the FQKS test in China, Indonesia, and Türkiye demonstrates that the stationarity findings at the quantile level in these countries have translated into stronger overall evidence of convergence across the distribution.

In conclusion, this study indicates the presence of a quantile-specific, fragmented convergence pattern in carbon emissions among emerging economies. This finding emphasizes that environmental policies should be designed and implemented in a country-specific manner in line with sustainable development goals. This situation indicates that general and uniform policy recommendations may be ineffective (Bhattacharya et al., 2020; Anavatan and Ispir, 2025).

6. Conclusion

In this study, the convergence behavior of per capita CO₂ emissions in emerging economies consisting of Brazil, China, Egypt, India, Indonesia, Mexico, Russia, South Korea, and Türkiye has been analyzed. In this context, the Fourier Quantile Unit Root Test, which takes into account structural breaks and nonlinear dynamics, has been applied. Thanks to the methodological flexibility offered by the test, not only the average behaviors of the countries but also the stationarity structure of the emission distribution at the lower, middle, and upper quantile levels have been evaluated. The study also reveals the limitations of classical unit root tests. It shows ignoring structural breaks and distribution differences in these tests can lead to misleading results. Therefore, the preference for advanced and flexible methods such as the Fourier Quantile Unit Root Test is important for a more accurate understanding of the complex structure of emission data. With the Fourier Quantile Unit Root approach, it is possible to analyze whether the series converge in different quantile ranges. Thus, it allows for healthier inferences to be made, especially in cases where environmental data are prone to structural breaks and nonlinear fluctuations.

The findings should be interpreted within the country-specific stochastic convergence framework adopted in this study. The analysis does not demonstrate that per capita CO₂ emission levels in EAGLE economies are converging, that cross-country emission differences are decreasing, or that countries are moving toward a common equilibrium emission level. Rather, it assesses whether shocks in each country's emission series are temporary and whether the series return to their own long-run deterministic paths. The results obtained from the Fourier Quantile Root Test indicate that a single, homogeneous

answer cannot be provided to this research question. The persistence of shocks varies both across countries and among low, medium, and high emission levels within the same country. Therefore, it is not possible to speak of a common stochastic convergence pattern applicable to all EAGLE economies.

Country-level findings show that China and South Korea exhibit stationarity across all quantiles examined; this indicates that shocks in different segments of the emission distributions of both countries are temporary. In other countries, stochastic convergence behavior depends on the quantile: in Brazil, at 0.10, 0.30, 0.80, and 0.90; in Egypt, in the quantiles between 0.30 and 0.90; in India, at 0.20, 0.30, 0.40, and 0.50; in Indonesia, at 0.30, 0.40, 0.60, 0.70, and 0.90; In Mexico, stability was observed at the 0.30, 0.50, 0.80, and 0.90 quantiles; and in Türkiye, at the 0.10, 0.30, 0.40, 0.50, 0.60, 0.70, and 0.90 quantiles. These findings indicate that emission shocks in these countries are temporary only in certain regions of the distribution and that the persistence of shocks varies depending on the emission level. In Russia, stationarity was identified only at the 0.20 and 0.80 quantiles. Therefore, evidence of country-specific stochastic convergence is limited for Russia, and it appears that shocks may be persistent across a large portion of the distribution.

The FQKS test provides statistically significant evidence of stochastic convergence regarding the overall distribution for China, Indonesia, and Türkiye. Although stationarity was observed at specific quantiles, the fact that the FQKS test was not significant in other countries does not constitute a contradiction. This indicates that the mean-reversion behavior in these countries emerges only in specific regions of the distribution and does not exhibit a robust structure that extends across the entire quantile distribution.

Overall, the findings reveal that the stochastic properties of per capita CO₂ emissions in EAGLE economies are heterogeneous across countries and quantiles. The concept of convergence used in this study does not refer to a reduction in emission differences among countries or a convergence of countries toward a common equilibrium level, but rather to each country's emission series returning to its own long-run deterministic path. Therefore, the results should not be interpreted as evidence of direct convergence across countries. The findings provide preliminary empirical insights into which countries and at which emission levels emission shocks may be more persistent.

The main limitation of this study is that the convergence analysis was conducted solely on per capita CO₂ emissions series. Indicators such as energy consumption, renewable energy use, industrial structure, energy intensity, technological development, and environmental policy were not directly included in the model. Therefore, the findings provide evidence regarding the stochastic convergence behavior of CO₂ emissions; however, they do not directly explain the economic, technological, or policy mechanisms underlying this convergence. For this reason, the findings should be interpreted not as direct or causal evidence of the success of specific policies, but as empirical indicators of the country- and quantile-specific persistence of emission shocks. Future studies may analyze emission convergence in EAGLE economies more comprehensively using multivariate models that include these variables.

Accordingly, throughout this study, the term “convergence” refers solely to the country-specific stochastic mean return. Any assessment of whether EAGLE economies are converging toward one another would require a different empirical design based on relative emission series, cross-country dispersion measures, panel convergence tests, or club convergence approaches.

The findings provide preliminary empirical insights into which countries and at what emission levels emission shocks may be more persistent. However, the unit root and stationarity results do not causally identify the effects of specific environmental policies. Policy implications must be evaluated in conjunction with factors such as energy mix, fossil fuel dependence, industrial structure, technological capacity, economic fluctuations, and institutional arrangements. Future studies could examine the underlying mechanisms of emission shocks using multivariate or causal models that directly incorporate these variables and specific policy implementations.

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Araştırma Makalesi

Convergence of Per Capita CO₂ Emissions in EAGLE Economies: Evidence from the Fourier Quantile Unit Root Test

EAGLE Ekonomilerinde Kişi Başına CO₂ Emisyonlarının Yakınsaması: Fourier Kantil Birim Kök Testinden Bulgular

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Bu çalışma yükselen ekonomiler arasında kişi başına karbondioksit (CO₂) salınımlarının zaman içinde yakınsama gösterip göstermediğini analiz etmeyi amaçlamaktadır. Analiz kapsamında Brezilya, Çin, Mısır, Hindistan, Endonezya, Meksika, Rusya, Güney Kore ve Türkiye'den oluşan EAGLE ülkeleri ele alınmıştır. Bu ülkeler hem hızlı ekonomik büyüme potansiyelleri hem de küresel karbon salınımları içindeki payları nedeniyle çevresel sürdürülebilirlik çalışmalarında önemli bir konuma sahiptir.

Küresel iklim değişikliği ve çevresel bozulma özellikle artan CO₂ salınımları nedeniyle günümüzün en önemli sorunlarından biri haline gelmiştir. Sanayileşme, kentleşme ve fosil yakıt kullanımının artmasıyla birlikte sera gazı yoğunluğu yükselmekte ve bu durum küresel hızlanmayı artırmaktadır. Bu bağlamda, ülkelerin kişi başına düşen CO₂ salınımlarının zaman içindeki dinamiklerini anlamak ve bu emisyonların birbirine yakınsayıp yakınsamadığını belirlemek, hem akademik literatür hem de politika yapıcılar açısından büyük önem taşımaktadır.

Yakınsama kavramı ilk olarak ekonomik büyüme literatüründe gelir farklılıklarının zaman içinde azalmasını açıklamak amacıyla geliştirilmiştir. Ancak son yıllarda bu yaklaşım çevresel göstergelere de uygulanmaya başlanmıştır. CO₂ salınımlarının yakınsaması, ülkeler arasındaki çevresel eşitsizliklerin azalması ve sürdürülebilir kalkınma hedeflerine ulaşılması açısından kritik bir gösterge olarak kabul edilmektedir. Eğer emisyonlar zaman içinde yakınsıyorsa, bu durum uluslararası çevre politikalarının (örneğin Kyoto Protokolü ve Paris İklim Anlaşması) etkinliğine dair olumlu bir işaret olarak yorumlanabilir. Ancak ülkeler arasındaki ekonomik yapı, enerji tüketim alışkanlıkları, teknolojik gelişmişlik ve çevre politikalarındaki farklılıklar, bu sürecin homojen olmayabileceğini göstermektedir. CO₂ salınımlarının durağan olup olmadığı, yani dış bir şokun emisyonlar üzerinde geçici veya kalıcı etkileri olup olmadığı, iklim değişikliği ve çevre politikalarının belirlenmesinde kritik öneme sahiptir. Emisyonlar durağan ise, sapmalar zaman içinde ortalamaya döner. Bunun tersi durumda ise, şokların uzun vadeli etkileri devreye girer (Cai & Wu, 2019). Başka bir deyişle, eğer durağan değilse, şokların ve politika müdahalelerinin etkileri kalıcı olabilir. Durağalık söz konusu ise, herhangi bir dış müdahale yalnızca geçici bir etki yaratır ve uzun vadeli bir değişiklik için yeterli değildir (Romero-Ávila & Omay, 2022).

Literatürde yapılan bazı çalışmalarda, farklı ülkeler için Fourier yaklaşımları kullanılmıştır. Lin vd. (2018), 1950-2013 döneminde G18 ülkelerindeki CO₂ emisyonlarının yakınsadığını mı yoksa uzaklaştığını mı analiz etmiştir. Ye vd. (2020), 1950-2013 döneminde G7 ekonomilerinin ve Çin gibi dünyanın en büyük CO₂ emisyon üreticilerinin CO₂ emisyonlarının yakınsadığını incelemiştir. Fourier

Kantil testi sonuçlarına göre, Almanya, İtalya ve İngiltere'nin emisyonları genel olarak geniş bir kantil yelpazesinde yakınsama göstermiştir. Diğer ülkeler için ise yakınsama bazı çeyrek dilimlerde ortaya çıkmıştır. Saliminezhad ve Bahramian (2020), 1960-2017 döneminde dört ülke için CO₂ emisyonlarının yakınsadığını araştırmıştır. Genel olarak, klasik test sonuçları CO₂ emisyonlarında kalıcı şoklar olduğunu göstermiştir. Birim kök testlerinin sonuçları, bazı ülkelerde (özellikle Kanada, Rusya ve kısmen Irak'ta) belirli dönemlerde yakınsama belirtileri olmasına rağmen, Suudi Arabistan'daki emisyonların tüm kantillerde istikrar kazanmadığını göstermektedir. Bayraktar vd. (2023), BRICS-T ülkelerinin ekolojik ayak izlerinin 1992-2017 döneminde BRICS-T grubunun ortalamasına yakınsadığını incelemiştir. Fourier testi Çin ve Rusya'da yakınsama sinyalleri gösterirken, Kesirli Fourier Frekans testi Brezilya ve Çin'de yakınsamayı ortaya koymuştur.

Bu çalışmanın metodolojik katkısı, geleneksel birim kök testlerinin sınırlılıklarını aşmak amacıyla Fourier Kantil Birim Kök Testi'nin kullanılmasıdır. Geleneksel testler genellikle doğrusal varsayımlara dayanmakta ve yapısal kırılmaları yeterince dikkate alamamaktadır. Oysa çevresel veriler çoğu zaman doğrusal olmayan yapılar içerebilmektedir. Kantil birim kök testi, geleneksel testlerden farklı olarak, zaman serisinin belirli bölümlerinde farklı dinamikler olup olmadığını gösterir (Cai vd., 2018). Fourier kantil birim kök testi, özellikle yapısal kırılmalar ve doğrusal olmayan durumlar gibi karmaşık durumları dikkate alarak, zaman serilerinin durağanlık özelliklerini test etmek için kullanılan gelişmiş bir yöntemdir. Bu testin temel amacı, geleneksel doğrusal birim kök testlerinin yetersiz kaldığı durumlarda, serinin farklı dağılım kantillerindeki yakınsama özelliklerini daha esnek bir şekilde ortaya çıkarmaktır (Lee vd., 2019). Fourier Kantil Birim Kök yaklaşımı, Koenker ve Xiao (2004) tarafından geliştirilen Kantil Regresyon Tabanlı Birim Kök Testi ile Enders ve Lee tarafından önerilen Fourier yaklaşımının birleştirilmesiyle uygulanır. Bu yaklaşım, farklı kantil seviyelerinde birim kök davranışını incelerken serideki yapısal değişiklikleri modellemek için Fourier dönüşümlerini kullanarak daha güçlü sonuçlar elde etmeyi amaçlamaktadır. Fourier yaklaşımı, bu tür yapısal değişimleri daha esnek bir şekilde modelleyebilmekte; kantil yaklaşımı ise serilerin yalnızca ortalama davranışlarını değil, dağılımın farklı bölgelerindeki dinamikleri de analiz etmeye olanak tanımaktadır. Bu sayede düşük, orta ve yüksek emisyon düzeylerine sahip ülkelerin farklı davranış kalıpları daha ayrıntılı şekilde incelenebilmektedir.

Çalışma 1970–2023 dönemi yıllık verilerini kapsamaktadır. Elde edilen bulgular, ülkeler arasında önemli farklılıklar olduğunu göstermektedir. Örneğin Rusya'nın ortalama salınım değeri oldukça yüksekken, Hindistan'ın salınım seviyesi görece düşüktür. Standart sapma değerleri ise Güney Kore'de yüksek oynaklığa, Hindistan'da ise daha istikrarlı bir yapıya işaret etmektedir. Analizin ilk aşamasında geleneksel birim kök testleri olan ADF, PP birim kök testleri ile KPSS durağanlık testi uygulanmıştır. Bu testlerden elde edilen sonuçlar ülkeler arasında farklılık göstermekte ve genel olarak serilerin durağanlığı konusunda tutarsız bulgular ortaya koymaktadır. Bu durum, geleneksel testlerin yapısal kırılmaları ve doğrusal olmayan dinamikleri yeterince yakalayamamasından kaynaklanmaktadır. Bu nedenle çalışmada ikinci aşamada Fourier Kantil Birim Kök Testi uygulanmıştır. Bu test, serilerin farklı kantillerdeki durağanlık özelliklerini inceleyerek yakınsama davranışını daha kapsamlı bir şekilde analiz etmektedir. Kişi başına CO₂ emisyon serisi için farklı kantil seviyelerinde ($\tau = 0,1-0,9$) Fourier Kantil Birim Kök Testinin sonuçları sunulmuştur. Bu testte, kritik değerler 5000 tekrarlı bir bootstrap tekniği ile oluşturulmuştur. Elde edilen bulgular, ülkeler arasında genel bir mutlak yakınsama eğiliminin bulunmadığını göstermektedir. Ancak bazı ülkelerde belirli kantillerde veya tüm kantillerde durağanlık (yakınsama) gözlemlenmiştir.

Özellikle Çin ve Güney Kore için tüm kantillerde durağanlık tespit edilmiştir. Bu durum, bu ülkelerde CO₂ salınımlarının hem düşük hem de yüksek seviyelerde şoklara karşı geçici tepkiler verdiğini ve uzun dönemde ortalamaya döndüğünü göstermektedir. Türkiye, Brezilya, Meksika, Hindistan ve Endonezya gibi ülkelerde ise çoğu kantilde yakınsama bulgularına rastlanmıştır. Ancak bu yakınsama tüm kantilleri kapsamamaktadır. Bu durum, söz konusu ülkelerde salınımların belirli düzeylerde istikrarlı bir yapı sergilediğini, ancak genel anlamda homojen bir yakınsama sürecinin bulunmadığını göstermektedir. Bu ülkelerde salınım dinamiklerinin yapısal kırılmalara, politika değişikliklerine ve dışsal şoklara karşı daha duyarlı olduğu ifade edilebilir. Rusya için elde edilen bulgular ise daha sınırlı bir yakınsama sürecine işaret etmektedir. Yalnızca iki kantilde durağanlık gözlemlenmiş olup, bu durum salınımların genel olarak kalıcı şoklara maruz kaldığını göstermektedir.

Çalışmada ayrıca Fourier Quantile Kolmogorov-Smirnov (FQKS) testi uygulanarak genel yakınsama eğilimi test edilmiştir. Bu testin sonuçları Çin, Endonezya ve Türkiye için istatistiksel olarak anlamlı bulunmuştur. Bu durum, bu ülkelerde salınım dinamiklerinin belirli bir yapısal istikrar gösterdiğini ve çevre politikalarının kısmen etkili olduğunu ortaya koymaktadır. Elde edilen bulgular, çevresel yakınsama sürecinin ülkeler arasında heterojen bir yapıya sahip olduğunu açıkça göstermektedir. Bu durum, tüm ülkeler için geçerli tek tip politika önerilerinin yetersiz kalabileceğini ortaya koymaktadır. Özellikle gelişmekte olan ülkelerde artan enerji talebi ve sanayileşme süreci, CO₂ salınımlarını hızla artırmakta ve çevresel eşitsizlikleri derinleştirmektedir. Bu nedenle, politika yapıcıların ülke bazlı ve esnek stratejiler geliştirmesi gerekmektedir.

Bu çalışmanın temel sınırlaması, yakınsama analizinin yalnızca kişi başına düşen CO₂ emisyon serileri üzerinde yapılmış olmasıdır. Enerji tüketimi, yenilenebilir enerji kullanımı, sanayi yapısı, enerji yoğunluğu, teknolojik gelişme ve çevre politikası gibi göstergeler modele doğrudan dahil edilmemiştir. Bu nedenle, bulgular CO₂ emisyonlarının stokastik yakınsama davranışına ilişkin kanıtlar sunmaktadır; ancak bu yakınsamanın altında yatan ekonomik, teknolojik veya politika mekanizmalarını doğrudan açıklamamaktadır. Gelecekteki çalışmalar, bu değişkenleri içeren çok değişkenli modeller kullanarak EAGLE ekonomilerindeki emisyon yakınsamasını daha kapsamlı bir şekilde analiz edebilir.

Sonuç olarak bu çalışma, EAGLE ülkelerinde kişi başına CO₂ salınımlarının yakınsama sürecinin karmaşık ve ülkeye özgü bir yapıya sahip olduğunu ortaya koymaktadır. Fourier Kantil Birim Kök Testi gibi ileri yöntemlerin kullanımı, bu karmaşık yapının daha doğru bir şekilde analiz edilmesine olanak sağlamaktadır. Çalışma, yalnızca ortalama değerlere odaklanan geleneksel yaklaşımların yetersiz olduğunu ve dağılımın farklı bölgelerindeki dinamiklerin de dikkate alınması gerektiğini göstermektedir. Bu bağlamda, çevresel sürdürülebilirlik hedeflerine ulaşabilmek için esnek, veri temelli ve ülke bazlı politika tasarımlarının geliştirilmesi büyük önem taşımaktadır.