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SUSTAINABILITY IN E7 ECONOMIES: TESTING THE EKC HYPOTHESIS WITHIN THE FRAMEWORK OF ECONOMIC GROWTH AND ECOLOGICAL FOOTPRINT DYNAMICS

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Abstract: Rapidly changing economic and environmental conditions have brought the concept of sustainability to the forefront. Rapid industrialization, urbanization and technological developments have expanded the boundaries of economic growth while simultaneously placing significant pressure on natural resources. The E7 countries (Brazil, China, India, Indonesia, Mexico, Russia and Türkiye) have been gaining an increasingly significant role in global production and energy consumption through their rapid growth and industrialization processes. As these countries account for a substantial share of global economic growth and energy use, their rapid industrialization and urbanization have made them vulnerable in terms of environmental sustainability. This situation necessitates an examination of the relationship between economic growth and environmental degradation in the sample of these countries. In this context, this study examines the determinants of the ecological footprint (EFP) in E7 countries using panel data methods. The analysis employs variables such as real GDP per capita, renewable and non-renewable energy consumption, trade openness rate, gross fixed capital formation and labor force participation rate. Our study aims to reveal the dynamic relationships between variables using panel data econometric methods. The findings confirm the Environmental Kuznets Curve (EKC) hypothesis between economic growth and EFP. Non-renewable energy consumption increases environmental pressure, whereas renewable energy has a mitigating effect. In addition, gross fixed capital formation and labor force participation rate have increased the EFP, while trade openness rate was found to be statistically insignificant. The inclusion of labor market dynamics and capital formation, in addition to economic growth and energy consumption, ensures a novel contribution to the current literature on E7 countries by shifting the focus from a purely production-oriented approach to one centered on structural transformation.

Keywords: Ecological Foot Print, E7 Countries, Enviromental Kuznets Curve, Energy Consumption, Sustainable Development

JEL Kodu: F64, O13, O44, Q56

E7 EKONOMİLERİNDE SÜRDÜRÜLEBİLİRLİK: EKONOMİK BÜYÜME VE EKOLOJİK AYAK İZİ DİNAMİKLERİ KAPSAMINDA EKC HİPOTEZİNİN TESTİ

Özet: Hızla değişen ekonomik ve çevresel koşullar, sürdürülebilirlik kavramının daha fazla ön plana çıkmasına sebebiyet vermektedir. Hızlı sanayileşme, kentleşme ve teknolojik gelişmeler, ekonomik kalkınmanın sınırlarını genişletirken aynı zamanda doğal kaynaklar üzerinde ciddi baskılar oluşturmaktadır. E7 ülkelerinin (Brezilya, Çin, Hindistan, Endonezya, Meksika, Rusya ve Türkiye), hızlı büyüme ve sanayileşme süreçleriyle küresel üretim ve enerji tüketiminde ağırlıkları giderek artmaktadır. Küresel ekonomik büyümenin ve enerji tüketiminin büyük bir kısmını kullanan E7 ülkeleri, hızlı sanayileşme ve kentleşme süreçleri nedeniyle çevresel sürdürülebilirlik açısından kırılgan bir konuma gelmiştir. Bu durum, iktisadi büyüme ile çevresel bozulma arasındaki ilişkinin bu ülkeler nezdinde incelenmesini gerektirmektedir. Bu bağlamda çalışma, E7 ülkelerinde ekolojik ayak izinin (EFP) belirleyicilerini panel veri yöntemleriyle incelemektedir. Analizde kişi başına reel GSYH artışı, yenilenebilir ve yenilenemeyen enerji tüketimi, ticari açıklık, sabit sermaye oluşumu ve işgücüne katılım oranı değişkenleri kullanılmıştır. Çalışmamız, panel veri ekonometrisi yöntemlerini kullanarak, değişkenler arasındaki dinamik ilişkileri ortaya koymayı amaçlamaktadır. Elde edilen bulgular, iktisadi büyüme ile EFP arasında Çevresel Kuznets Eğrisi (EKC) hipotezini doğrulamaktadır. Yenilenemeyen enerji tüketimi çevresel baskıyı artırırken, yenilenebilir enerji azaltıcı bir etki göstermektedir. Ayrıca sabit sermaye oluşumu ve işgücüne katılım oranı EFP'yi artırmış, ticari açıklık oranı ise istatistiki olarak anlamlı bulunmamıştır. Çalışmada ekonomik büyüme ve enerji tüketimi ile birlikte işgücü piyasası dinamikleri ve sermaye oluşumu gibi değişkenlerin modele dahil edilmesi, E7 ekonomileri için sadece üretim odaklı değil, aynı zamanda yapısal dönüşüm odaklı güncel literatüre özgü bir katkı sağlanmıştır

Anahtar Kelimeler: Ekolojik Ayak İzi, E7 Ülkeleri, Çevresel Kuznets Eğrisi, Enerji Tüketimi, Sürdürülebilir Kalkınma

JEL Kodu: F64, O13, O44, Q56

Introduction

The rapid increase in the world's population, technological changes and the transformation of socioeconomic structures have significantly increased natural resources use, consequently leading to severe environmental problems. These environmental issues have established the necessity for two key concepts environmental sustainability and sustainable development to become global objectives for all nations. Although these concepts have been examined across various disciplines, the relationship between the economy and the environment holds particular significance within the field of economics. The necessity of utilizing limited natural resources efficiently and effectively positions economics at the center of debates on sustainable development and environmental sustainability.

Environmental sustainability aims to achieve the balanced and efficient use of finite natural resources, thereby ensuring their sustainability for future generations. Sustainable development, on the other hand, represents a holistic approach that integrates economic growth and social welfare with environmental considerations. Tennakoon, Janadari and Wattuhewa (2024) define environmental sustainability as a concept that encompasses policies, action plans and strategies applicable across multiple sectors from industry to transportation aimed at conserving resources, minimizing environmental impacts and promoting sustainable development. This definition underscores that achieving environmental sustainability requires a multidimensional and long-term programmatic framework. Ruggerio (2021) outlines the conceptual framework of sustainable development, viewing it as a multidimensional concept with economic, social, political and ecological dimensions. By emphasizing the inherent contradictions noted by different schools of thought, Ruggerio asserts that sustaining perpetual economic growth on a finite planet is impossible. This argument highlights the challenges of practical implementation, despite the theoretical appeal of the concept of sustainable development.

Environmental sustainability and sustainable development are not only subjects of environmental and economic policy but also possess theoretical foundations that attract attention from multiple disciplines. These concepts were first introduced in the Brundtland Report, which established a framework centered on safeguarding the needs of future generations. The relationship between environmental degradation and economic growth is analyzed within the framework of the Environmental Kuznets Curve (EKC) Hypothesis. In this context, the necessity of environmentally oriented economic activities has become one of the most significant areas of discussion in contemporary economic literature.

This study examines the determinants of the ecological footprint in E7 countries using panel data econometric methods, focusing not only on energy-related variables but also on structural macroeconomic factors. The variables employed in the analysis were tested for cross-sectional dependence and heterogeneity, after which the analysis was conducted using the CS-ARDL (Cross-Sectionally Augmented ARDL) and CS-DL (Cross-Sectionally Augmented Distributed Lag) estimators, which explicitly control for cross-sectional dependence.

Theoretical and Conceptual Framework

Developing economies are among the regions where environmental problems are most pronounced. The E7 countries have attracted significant attention in recent years due to their rapid economic growth rate, population increase and industrialization. The economic and demographic transformations in these countries, along with energy use that is closely tied to production structures, have intensified pressures on the environment. Therefore, accurately analyzing the determinants of the ecological footprint is of critical importance for ensuring environmental sustainability (Wackernagel & Rees, 1997a).

Wiedmann and Barrett (2010) define the ecological footprint (EFP) as a measure of the land and water area required to absorb the waste generated by an individual or collective activity. According to this definition, production based on existing technologies and resource management necessitates the reproduction of all consumed resources. In this sense, the EFP serves as both an indicator of sustainability and a measure of the environmental impact arising from human consumption. Liu, Wang and Zhao (2024) state that the ecological footprint is expressed in global hectares and present sectoral distinctions in its calculation. They employ differentiated methodologies for sectors such as transportation, fossil energy, paper and agricultural production. Another concept related to the ecological footprint is ecological overshoot. Wees (2023) defines ecological overshoot as resource consumption at a rate exceeding the regenerative capacity of ecosystems, driven by factors such as technological development, rapid population growth and fossil fuel use. Carbon emissions resulting from fossil fuel consumption are identified as the primary cause of overshoot.

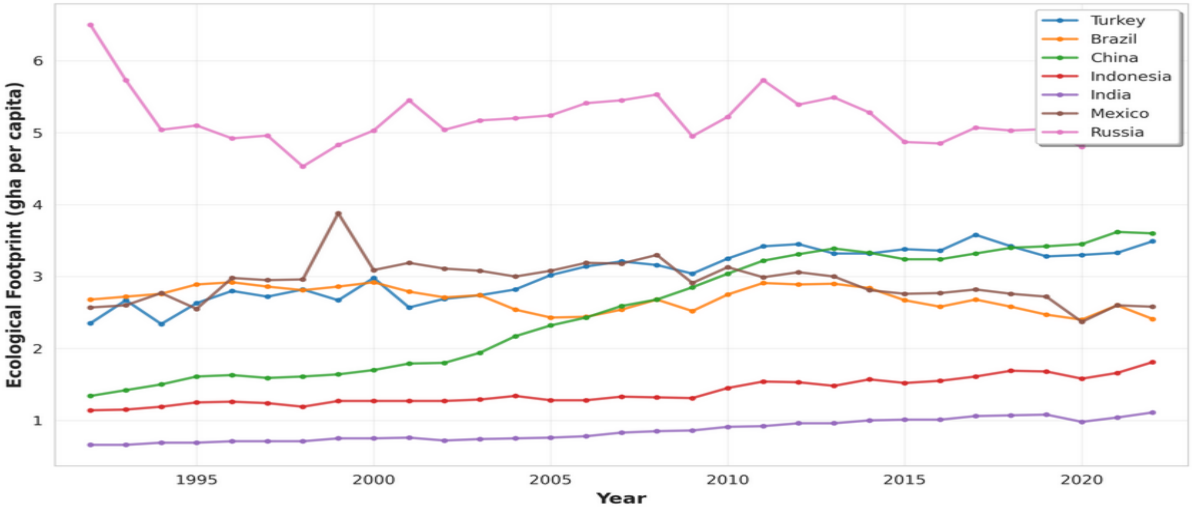

Figure 1. Ecological Footprint Trends in E7 Countries (1992-2022)

Note: This figure illustrates the temporal evolution of ecological footprint (measured in global hectares per capita) across E7 countries over the period 1992-2022. Data source: Global Footprint Network.

The figure 1 illustrates the trends in the ecological footprint of E7 countries over the period 1992–2022. As observed in the graph, China’s ecological footprint exhibits a pronounced upward trajectory throughout the analysis period, reaching approximately 3.7 global hectares per capita in 2022. Although Russia had the highest ecological footprint at the beginning of the period, it has displayed a declining trend since the early 2000s. The ecological footprints of Turkey, Brazil and Mexico exhibit a relatively stable trend, whereas those of India and Indonesia persist at comparatively low levels. These disparities indicate substantial heterogeneity among E7 countries and suggest that environmental pressure is shaped by country-specific dynamics.

The theoretical foundation of this study is based on the Environmental Kuznets Curve (EKC) Hypothesis. Bo (2011) explains the emergence and historical evolution of the EKC hypothesis, noting that while Grossman and Krueger (1991) were the first to identify a relationship between environmental quality and income, Shafik and Bandyopadhyay (1992) found supporting evidence. Panayotou (1993) reached similar conclusions and coined the term Environmental Kuznets Curve to describe this relationship. Thus, the EKC hypothesis entered the literature through multiple studies yielding comparable results, drawing from the original hypothesis developed by Simon Kuznets. Kaika and Zervas (2013) and Stern (2017) assert that the EKC illustrates the relationship between environmental degradation and income in the form of an inverted U-shaped curve. Kijima, Nishide and Ohyama (2010) describe the functioning of the EKC as follows: in the early stages of economic growth, the desire for expansion leads to increased production at the expense of the environment, accelerating degradation. However, once income surpasses a certain threshold, environmental degradation begins to decline due to institutional and regulatory interventions. Per capita income, which is closely linked to the EKC, represents the economic dimension of the environment-economy relationship. Beyond being a simple mathematical ratio obtained by dividing total output by population, per capita income also reflects broader economic and social outcomes. Cordova-Lepe (2019) defines per capita income as a key component of poverty reduction, economic progress and overall welfare.

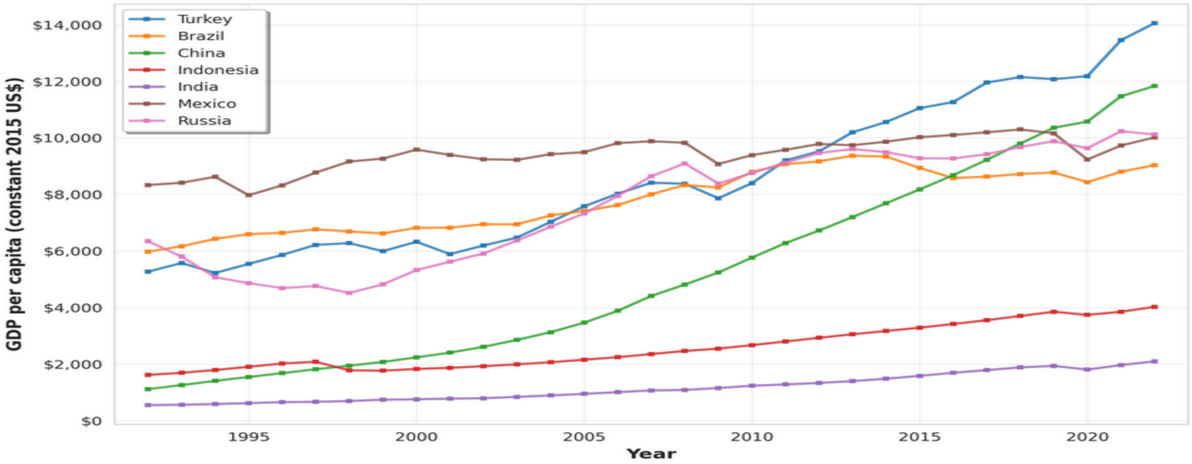

Figure 2. GDP per capita Trends in E7 Countries (1992-2022)

Note: This figure depicts the evolution of real GDP per capita (constant 2015 US$) in E7 countries from 1992 to 2022. Data source: World Bank, World Development Indicators.

Figure 2 illustrates the evolution of GDP per capita in E7 countries over the period 1992–2022. Within the sample, Russia records the highest income level, reaching approximately USD 12,000 per capita. China, on the other hand, exhibits the most rapid economic growth performance throughout the analysis period with GDP per capita increasing markedly from around USD 700 in 1992 to nearly USD 12,000 in 2022. The per capita income levels of Turkey, Brazil and Mexico converge within a similar range, fluctuating between USD 8,000 and USD 10,000, indicating comparable stages of economic development. In contrast, India and Indonesia remain at the lower GDP per capita levels ranging between USD 2,000 and USD 5,000, making them the lowest-income countries within the E7 group. These trends reveal significant income heterogeneity across E7 economies and reflect divergent growth trajectories driven by differences in industrialization, productivity and structural transformation. This variation in income levels provides an important basis for analyzing the relationship between economic growth and environmental pressure within the framework of the Environmental Kuznets Curve hypothesis.

Significant indicators influencing environmental degradation include the intensity of renewable and non-renewable energy use, which together defines the structure of energy consumption. Non-renewable energy sources such as coal, natural gas and oil are among the primary contributors to carbon emissions and environmental pollution. In contrast, renewable energy sources such as wind, solar and hydropower are sustainable, non-polluting and characterized by near-zero emissions (Panwar, Kaushik & Kothari, 2011). Given this dual energy structure, a transition toward renewable sources and the reduction of non-renewable energy use are expected to contribute positively to mitigating environmental degradation. Increasing the share of renewables in total energy consumption has emerged as a strategic objective for both energy security and environmental sustainability. However, the transition to renewable energy remains a critical challenge within the broader energy transformation process. Integration into existing energy systems, high initial investment costs, institutional and political barriers (Saraji & Streimikiene, 2023) have collectively delayed this transition. Consequently, the implementation of measures required to reduce environmental degradation has been significantly slowed.

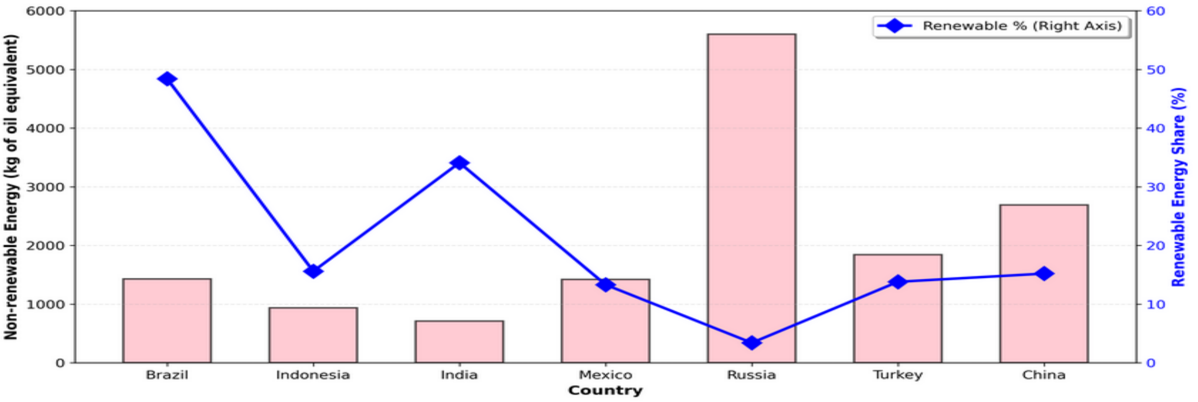

Figure 3. Energy Consumption Patterns in E7 Countries (2022)

Note: This figure illustrates the dual structure of energy consumption in E7 countries for 2022. The bars represent non-renewable energy consumption (kg of oil equivalent per capita, left axis), while the line indicates the share of renewable energy in total energy consumption (%, right axis). Data source: World Bank, World Development Indicators.

Figure 3 presents the energy consumption structure of E7 countries in 2022. As shown in the figure, there is a clear inverse relationship between fossil fuel dependence and the share of renewable energy. Russia exhibits the highest level of fossil fuel consumption, amounting to approximately 5,600 kilograms of oil equivalent per capita, while its renewable energy share remains extremely limited at only 3.4%. In contrast, Brazil stands out with a remarkably high renewable energy share of 48.4%, despite its relatively low level of fossil fuel consumption, indicating a more advanced stage of energy consumption. India (34.1%) and Indonesia (15.6%) also display comparatively lower fossil fuel consumption levels, accompanied by higher renewable energy shares than several other E7 economies, suggesting a partial shift toward cleaner energy sources. China (15.2%), Turkey (13.8%), and Mexico (13.3%) are characterized by moderate fossil fuel consumption levels combined with relatively low renewable energy shares, reflecting a continued reliance on conventional energy sources. This pattern implies that these countries remain structurally dependent on fossil fuels, despite ongoing energy transition efforts. The pronounced cross-country variation in energy consumption patterns highlights that E7 economies are positioned at markedly different stages of the energy transition process, shaped by disparities in resource endowments, energy policies, and institutional frameworks.

The empirical analysis in our study also incorporates economic and structural factors, including gross fixed capital formation of GDP (GFCF), trade openness rate and the labor force participation rate. Trade openness rate is measured as the ratio of total trade volume to GDP, calculated by dividing the sum of exports and imports by GDP (Musila & Yiheyis, 2015). With globalization, trade volumes have expanded rapidly, raising economic performance on the one hand while increasing emissions due to higher energy demand on the other (Shahbaz, Nasreen, Ahmed & Hammoudeh, 2017). This effect is particularly evident in the use of fossil fuels in transportation. Gross fixed capital formation (GFCF), a key component of domestic investment, plays a vital role in economic growth and employment (Sinha, 2024). It reflects the acquisition of fixed assets used for the production of goods and services over periods longer than one year.

While fixed capital investments are essential indicators of industrial output and growth, they often entail increased resource use, thereby exacerbating environmental pressures (Pata, 2018). The environmental impact of investments depends largely on technological efficiency and production processes; therefore, investment decisions should be designed to minimize ecological harm. The acquisition of assets compatible with renewable energy systems can mitigate the environmental burden of GFCF during the energy transition process (Qamruzzaman, 2024).

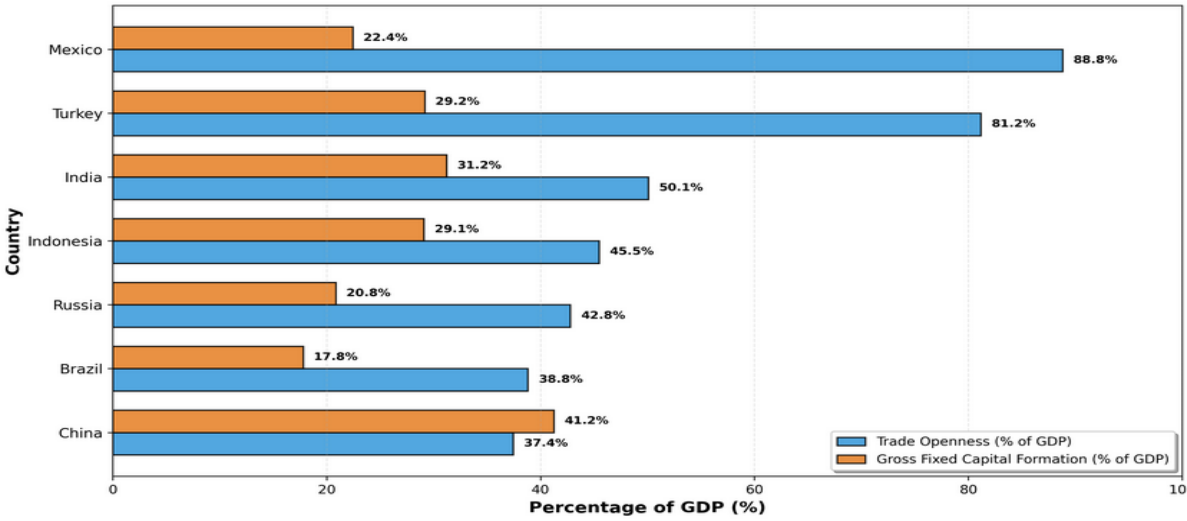

Figure 4. Trade Openness Rate and Gross Fixed Capital Formation in E7 Countries (2022): Comparative Analysis

Data source: World Bank, World Development Indicators

Figure 4 illustrates that there is no clear linear relationship between trade openness rate and gross fixed capital formation across E7 countries. Mexico (88.8%) and Turkey (81.2%) exhibit high levels of trade openness rate, yet their gross fixed capital formation ratios remain at moderate levels, amounting to 22.4% and 29.2%, respectively. This indicates that greater integration into international trade does not automatically translate into higher domestic investment levels. In contrast, China records the highest level of gross fixed capital formation rate (41.2%) despite having a relatively low trade openness rate (37.4%), suggesting that domestic investment dynamics and state-led development strategies play a more decisive role than external trade integration. Brazil, on the other hand, displays the lowest values in both trade openness rate (38.8%) and gross fixed capital formation rate (17.8%), reflecting a comparatively weaker linkage between external trade and investment-driven growth. The divergence observed in Figure 4 highlights the heterogeneity among E7 countries in terms of development strategies, where some economies rely more heavily on domestic investment-led growth, while others are characterized by trade-driven but investment-moderate structures. These patterns imply that the impact of trade openness rate on capital accumulation is highly country-specific and mediated by structural and institutional factors.

The labor force participation rate represents the proportion of the working-age population engaged in or seeking employment. An increase in labor participation rate is expected to raise income levels, stimulate aggregate demand and consequently support higher production levels. However, when production relies heavily on non-renewable energy sources, such increases can lead to further environmental degradation. While shifting employment toward green jobs may offset environmental losses in polluting sectors, sectoral skill mismatches and geographical disparities often hinder this transition (Graham & Knittel, 2023).

Literature Review

Conceptually, the ecological footprint (EFP) defined as the environmental pressure generated by human activities was developed by Wackernagel and Rees (1998). Wackernagel and Rees (1998) describe the ecological footprint as the amount of land and water area required to produce the resources consumed by economic agents and to absorb all the waste generated during production using existing technologies. In simpler terms, the ecological footprint reflects the environmental pressure created by the production of goods and services necessary to sustain modern lifestyles. In recent studies, the ecological footprint has been widely employed as an indicator of environmental degradation in the works of Bagliani et al. (2008), Caviglia-Harris et al. (2009), Wang et al. (2013), Al-Mulali et al. (2015), Aşıcı and Acar (2016), Charfeddine and Mrabet (2017), Mrabet and Alsamara (2017) (Danish et al., 2019; Sharif et al., 2020).

While most studies investigating the nexus between the environment and economic growth identify a relationship between the ecological footprint and GDP, empirical evidence testing the validity of the Environmental Kuznets Curve (EKC) hypothesis using ecological footprint measures remains mixed. Hassan et al. (2019), Mrabet and Alsamara (2017), Özbek and Naimoğlu (2025), Wang et al. (2022), Bölük and Karaman (2024) and Saboori and Tarazkar (2024) found that economic growth initially increases the ecological footprint but subsequently improves environmental quality, thereby validating the EKC hypothesis. Conversely, Villanthenkodath et al. (2024) found an N-shaped EKC relationship between ecological footprint and economic growth. Addai et al. (2022) and Eweade et al. (2024) reported a unidirectional long-run causality running from economic growth to ecological footprint, while Wang and Dong (2019), Neifar et al. (2024) and Makhdum et al. (2022) identified a bidirectional causal relationship between the two variables. Similarly, Sharif et al. (2020), Alola et al. (2019) and Li et al. (2022) pointed to bidirectional causality between economic growth and ecological footprint, emphasizing that in both the short and long run, economic growth positively affects the ecological footprint.

A number of studies including Danish et al. (2019), Nathaniel et al. (2021), Ahmed et al. (2022), Hussain et al. (2021), Shayanmehr et al. (2023), Zhu et al. (2024), Akpanke et al. (2024), Magazzino (2024), Riaz et al. (2024), Quan et al. (2024), Uzar (2024), Güler et al. (2025) and Kartal et al. (2025) demonstrated that increases in GDP adversely affect the ecological footprint, thereby intensifying environmental degradation. Çakmak and Acar (2022) showed that economic growth exerts a significant influence on the ecological footprint, confirming the Pollution Haven Hypothesis. They further argued that economic growth is a major determinant of ecological footprint levels, particularly in oil-producing countries. Udemba (2020) identified a positive and unidirectional causal link from economic growth to ecological footprint, implying that both variables increase concurrently. Usman et al. (2021a) found a bidirectional causal relationship and concluded that economic growth negatively affects environmental quality. Hacıimamoğlu and Sungur (2024) demonstrated a cointegrated relationship between economic growth and the ecological footprint pressure index, indicating that economic growth contributes to environmental degradation.

The increase in population, the Industrial Revolution and advances in technology have led to a growing demand for energy. Globally, the heavy dependence on non-renewable energy sources has exacerbated issues like climate change and pollution. Therefore, the use and development of renewable, sustainable and low-carbon energy sources, which exert less environmental pressure, have become critically important. In recent years, research exploring the relationship between energy consumption and the environment has proliferated (Hacıimamoğlu & Sungur, 2024; Öncel et al., 2023). For example Saqib et al. (2024), Shayanmehr et al. (2023), Alola et al. (2019), Udemba (2020), Nathaniel et al. (2021), Ritu and

Kaur (2024), Riaz et al. (2024) and Kartal et al. (2025) emphasized that economic growth driven by intensive use of fossil fuels deteriorates environmental quality and adversely affects the ecological footprint. Murshed et al. (2021) found that non-renewable energy consumption increases the ecological footprint, whereas renewable energy consumption decreases it. Similarly, Riaz et al. (2024) and Saboori and Tarazkar (2024) reported a positive impact of fossil fuel energy consumption on the ecological footprint. Kongkuah (2024) found a significant negative relationship between renewable energy consumption and ecological footprint and a significant positive relationship between non-renewable energy use and ecological impact.

Conversely, contrary evidence is also present in the literature. Daştan and Eygü (2024) and Çakmak and Acar (2022) found that renewable energy has no significant environmental impact. However, Joof et al. (2024), Eweade et al. (2024), Ashraf et al. (2024), Danish et al. (2020), Nathaniel et al. (2021), Damak (2024), Musa et al. (2024), Azimi and Rahman (2024), Mahmood (2024), Akpanke et al. (2024), Alola et al. (2019), Qing et al. (2024), Gao et al. (2024) and Şimşek et al. (2025) concluded that the use of renewable energy sources reduces the ecological footprint. Jie et al. (2023) argued that renewable energy consumption supports environmental sustainability in both the short and long term, while Wang et al. (2022) found that renewable energy consumption has a long-run improving effect on global environmental quality. Zhu et al. (2024) provided evidence supporting the feedback hypothesis, suggesting a bidirectional causal relationship between renewable energy consumption and the ecological footprint. Similarly, Usman et al. (2021b), Sahoo et al. (2024) and Quan et al. (2024) found that renewable energy consumption exerts a significant negative effect on the ecological footprint.

Economic activities with increasing environmental costs have gained considerable importance in recent years. The interaction between trade and the environment is complex and multidimensional. Differences in countries' levels of development, industrialization and technological changes serve as major determinants of environmental outcomes, preventing consensus in the literature regarding the relationship between the ecological footprint and trade openness rate. Ritu and Kaur (2023), Dada et al. (2022), Eweade et al. (2023) and Kartal et al. (2025) observed an inverse relationship between trade openness rate and ecological footprint. Nathaniel (2021) found that trade openness rate worsens the ecological footprint in the long run and produces heterogeneous environmental effects. Conversely, Abdullahi et al. (2024), Okelele et al. (2022) and Liu et al. (2022) reported a significant positive relationship between trade openness rate and the ecological footprint. Güler et al. (2025) concluded in their study that trade openness has positive effects on environmental sustainability.

Gross fixed capital formation (GFCF) also shows a strong association with environmental outcomes. The existing literature suggests that higher GFCF promotes economic growth, but the subsequent rise in energy use leads to environmental degradation (Rahman & Ahmad, 2019). Li et al. (2023) found that GFCF increases the ecological footprint and stressed the importance of effective resource management to ensure environmental sustainability in the long run. Similarly, Kang (2025) reported that GFCF make worse the ecological footprint, thereby contributing to environmental degradation.

Finally, the relationship between labor dynamics and environmental quality also deserves attention when investigating the determinants of environmental degradation. To understand the environmental consequences of economic growth, it is essential to analyze the dynamics of the labor market, which is one of its key driving forces. Damrah et al. (2022) and Ahmad and Satrovic (2024) found that increases in the labor force participation rate lead to higher energy consumption, thereby worsening environmental conditions and increasing the ecological footprint.

Empirical Analysis

In this section, the relationships between the ecological footprint, economic growth, energy consumption, and other macroeconomic variables in E7 countries (Brazil, China, India, Indonesia, Mexico, Russia, and Turkey) are examined empirically. The study uses balanced panel data analysis using annual data covering the period from 1992 to 2022.

Data and Variables

Data Sources and Sample Structure

The empirical analysis of the study is conducted using annual data spanning the period 1992–2022. The E7 country group consists of seven emerging economies (Brazil, China, India, Indonesia, Mexico, Russia, and Turkey) that hold a significant share among emerging markets. These countries are of critical importance for environmental sustainability, as they account for approximately 35% of global GDP in purchasing power parity (PPP) terms, are home to more than half of the world's population, and face rapidly increasing energy demand.

The variables used in the study are selected based on the Environmental Kuznets Curve (EKC) hypothesis and the existing literature on the energy–environment–economy nexus. The ecological footprint (EFP) is used as the dependent variable, while GDP per capita and its square, non-renewable and renewable energy consumption, gross fixed capital formation, trade openness, and the labor force participation rate are included as independent variables. Detailed descriptions of the variables are presented in Table 1.

Table 1. Variable Definitions and Data Sources

Variable	Abbreviation	Definition	Unit of Measurement	Source
Ecological Footprint	efp	Biologically productive land required to support individuals' consumption and absorb generated waste	Global hectares per capita (gha per capita)	Global Footprint Network
GDP per capita	lngdpc	Real gross domestic product per capita (constant 2015 prices)	Constant 2015 US dollars (logarithmic form)	World Bank-WDI
GDP squared	lngdpc_sq	Squared real GDP per capita (included to test the Environmental Kuznets Curve hypothesis)	Constant 2015 US dollars, squared (logarithmic squared term)	World Bank-WDI
Non-renewable energy	lnnrec	Fossil fuel energy consumption per capita	Kilograms of oil equivalent per capita (logarithmic form)	World Bank-WDI
Renewable energy	lnrec	Share of renewable energy in total energy consumption	% (logarithmic form)	World Bank-WDI
Capital formation	lngfc	Gross fixed capital formation	% of GDP (logarithmic form)	World Bank-WDI
Trade openness	lnto	Ratio of total exports and imports to GDP	Percentage of GDP (logarithmic form)	World Bank-WDI
Labour force participation	lnlpr	Labor force participation rate of the population aged 15 and above	% (logarithmic form)	ILO ILOSTAT

All variables were transformed into their natural logarithmic forms, including those already expressed in percentage terms (trade openness, gross capital formation, and labor force participation rate). The log–log specification offers several advantages. First, it facilitates elasticity interpretation. Specifically, a 1% increase in a given explanatory variable indicates the percentage change in the ecological footprint. This allows variables measured in different units to become directly comparable. Second, the logarithmic transformation helps mitigate heteroskedasticity. The E7 countries exhibit substantial variation in trade openness (18.5%–66.8%) and capital formation (17.2%–48.2%). Logarithmic transformation moderates this variability by stabilizing the variance and enhancing methodological consistency. By reducing variance instability in the error term, this approach contributes to the efficiency of the estimators.Third, the use of log–log models is consistent with the Environmental Kuznets Curve (EKC) literature (Grossman and Krueger, 1995; Shahbaz et al., 2016).

Environmental sustainability has become a major global issue within the framework of economic development objectives. The ecological footprint, developed by Wackernagel and Rees (1997b) to measure the pressure exerted by human activities on nature, is widely used in the literature as a leading indicator of environmental degradation. The ecological footprint (EFP) quantifies the amount of land and water area required to produce the resources consumed by economic actors and to absorb the waste generated as a result, thereby concretely reflecting the actual environmental impact of prevailing patterns of production and consumption (Wackernagel and Rees, 1997b: 3).

E7 countries (Brazil, China, India, Indonesia, Mexico, Russia, and Turkey), which account for a substantial share of global economic growth and energy consumption, have become environmentally vulnerable due to rapid industrialization and urbanization processes. This situation necessitates an examination of the relationship between economic growth and environmental degradation within the context of these countries. The high energy demand of these countries is largely met by non-renewable resources, which exacerbates problems such as climate change and environmental pollution. However, limiting the causes of environmental degradation solely to energy use leads to an incomplete assessment of the issue. Macroeconomic and structural factors such as trade openness, gross fixed capital formation, and labor also constitute important determinants of the ecological footprint. The literature presents conflicting findings regarding the effects of these factors on EFP. Therefore, the environmental implications of each of these dynamics need to be evaluated within a holistic framework.

In this context, the fundamental macroeconomic and structural factors determining the ecological footprint in E7 countries are examined empirically. This study aims to reveal the dynamic relationships among the variables by using panel data econometric methods.

Within the scope of the empirical analysis, the following panel regression model (1) is established to examine the macroeconomic and structural determinants of the ecological footprint in E7 countries.

$$efp_{it} = \alpha_i + \beta_1 lngdpc_{it} + \beta_2 lngdpc_{it}^2 + \beta_3 lnnrec_{it} + \beta_4 lnrec_{it} + \beta_5 lngfc_{it} + \beta_6 lnto_{it} + \beta_7 lpr_{it} + \varepsilon_{it} \qquad (1)$$

The ecological footprint (efp_{it}) is included in the model as the dependent variable. This indicator constitutes a more comprehensive measure of environmental pressure than CO₂ emissions, as it encompasses multiple components such as the carbon footprint, cropland, forest land, fishing grounds and built-up land (Wackernagel and Rees, 1997). Real GDP per capita ($lngdpc_{it}$) and its squared term ($lngdpc_{it}^2$) are incorporated into the model to test the validity of the Environmental Kuznets Curve (EKC) hypothesis. The EKC hypothesis posits that environmental degradation increases during the early stages of economic development but begins to decline once a certain income threshold is reached (Grossman and Krueger, 1995). This relationship is represented by an inverted U-shaped curve, whereby the coefficient of ($lngdpc_{it}$) is expected to be positive, while that of ($lngdpc_{it}^2$) is expected to be negative. Non-renewable energy consumption ($lnnrec_{it}$) measures per capita fossil fuel (oil, natural gas, and coal) consumption in kilograms of oil equivalent. Fossil fuel–based energy systems are expected to exert upward pressure on the ecological footprint. Renewable energy consumption $(lnrec_{it})$, by contrast, represents the share of clean energy sources—such as hydropower, solar, wind, geothermal, and biomass—in total energy consumption and is expected to contribute positively to environmental sustainability. Gross fixed capital formation $(lngfc_{it})$ serves as a proxy for domestic investment and is measured as a percentage of GDP. The effect of capital accumulation on the ecological footprint remains theoretically ambiguous.

Trade openness $(lnto_{it})$, is defined as the ratio of total exports and imports to GDP and reflects a country's degree of integration into the global economy. The environmental impact of trade openness is commonly discussed within the frameworks of the Pollution Haven Hypothesis and the Pollution Halo Hypothesis. While the Pollution Haven Hypothesis suggests that trade may lead to the relocation of polluting industries to countries with lax environmental regulations, the Pollution Halo Hypothesis argues that trade can facilitate the diffusion of cleaner technologies (Copeland and Taylor, 2004). The labor force participation rate $(lnlpr_{it})$ indicates the proportion of the population aged 15 and above that is active in the labor market and is used as a proxy for the level of economic activity. Increases in labor force participation rate may intensify environmental pressure through higher levels of production and consumption.

Descriptive Statistics

Table 2 presents the results of the Jarque-Bera Test, which examines normality based on Skewness and Kurtosis, alongside the distribution characteristics of the variables used in the analysis, such as mean, median, and standard deviation.

Table 2. Descriptive Statistics and Normality Tests

Variables	Average	Median	Standard	Skewness	Kurtosis	Jarque-Bera
efp	2.6677	2.72	1.36	0.57	2.8	0.0064
lngdpc	8.4437	8.7755	0.83	-0.89	2.6	0.0000
lngdpc_sq	71.9886	77.0088	13.48	-0.77	2.32	0.0000
lnnrec	7.1491	7.2078	0.71	0.37	2.6	0.0394
lnrec	2.9158	3.0301	0.87	-0.65	2.34	0.0001
lnto	45.7283	46.7871	15.61	-0.58	3.08	0.0056
lngfc	3.2151	3.1666	0.27	0.3	2.28	0.0025
lnlpr	61.8037	61.922	6.87	-0.14	2.77	0.5762

According to Table 2, only the variable *lnlpr* follows a normal distribution, while the assumption of normality is rejected for all other variables. The results of the Variance Inflation Factor (VIF) test, which is used to examine the presence of multicollinearity, are presented in Table 3. The VIF test measures the degree of correlation among the independent variables and allows for the assessment of multicollinearity within the model.

Table 3. VIF Test Results

Variables	VIF	1/VIF
lnnrec	8.52	0.425
lnrec	7.07	0.184
lngdpc	4.62	0.216
lngdpc_sq	2.34	0.42
lnlpr	1.64	0.607
lnto	1.92	0.52
lngfc	1.30	0.77
Mean VIF	2.68	

According to Table 3, although the variables *lnnrec* and *lnrec* have relatively high VIF values, these values remain below the generally accepted threshold of 10. Therefore, it can be stated that there is no multicollinearity problem in the model.

Method

Econometric Strategy and Method Selection

In panel data analysis, the selection of the appropriate econometric method is of critical importance for the validity and reliability of estimation results. In this study, new-generation panel data methods that account for cross-sectional dependence (CSD) and heterogeneity—issues frequently encountered in country groups that are highly integrated into the global economy, such as the E7 countries—are used.

In this study, the Cross-Sectionally Augmented ARDL (CS-ARDL) and Cross-Sectionally Augmented Distributed Lag (CS-DL) methods, which systematically control for CSD, are utilized. The CS-ARDL approach, developed by Chudik et al. (2016), controls for common factors by incorporating cross-sectional averages of both dependent and independent variables into the model. This method is capable of estimating both short-run and long-run relationships and is robust to endogeneity issues. The CS-ARDL model is expressed as follows.

$$\Delta efp_{(it)} = \phi_i\left(efp_{(i,t-1)} - \theta_i' X_{(i,t-1)}\right) + \sum_{j=1}^{p-1} \lambda_{(ij)} \Delta efp_{(i,t-j)} + \sum_{j=0}^{q-1} \delta_{(ij)}' \Delta X_{(i,t-j)} + \sum_{j=0}^{p} \pi_{(ij)} \overline{efp}_{t-j} + \sum_{j=0}^{q} \gamma_{(ij)}' \overline{X}_{t-j} + u_{(it)} \qquad (2)$$

Here, Δ denotes the first-difference operator; ϕ_i represents the error correction coefficient; θ_i denotes the long-run coefficients; X_{it} is the vector of independent variables; and $\overline{efp}_t$ve $\overline{X}_t$ represent the cross-sectional averages of the dependent and independent variables, respectively. The inclusion of cross-sectional averages in the model controls for the effects of common shocks and unobserved factors, thereby addressing the issue of cross-sectional dependence (CSD) (Chudik and Pesaran, 2015; Chudik et al., 2016). The CS-DL model, developed by Chudik and Pesaran (2015), is the version of the Dynamic OLS (DOLS) approach that accounts for CSD.

$$efp_{it} = \alpha_i + \theta_i' X_{it} + \Sigma_{j=-q}^{q} \delta_{ij}' \Delta X_{i,t-j} + \Sigma_{j=0}^{p} \overline{\pi_{ij}'} (efp)_{t-j} + \Sigma_{j=0}^{p} \overline{\gamma_{ij}'} (X)_{t-j} + u_{it} \qquad (3)$$

Here, α_i denotes the unit-specific fixed effects; θ_i', represents the long-run coefficients. The CS-DL approach estimates long-run relationships directly by incorporating both lead and lag values of the explanatory variables into the model, thereby controlling for endogeneity (Chudik et al., 2016). According to Chudik et al. (2016), the use of the CS-ARDL and CS-DL methods provides the following advantages: (i) systematic control of cross-sectional dependence (CSD); (ii) efficient estimation in heterogeneous panels; (iii) validity in the presence of a mixture of I(0) and I(1) variables; (iv) strong small-sample performance; and (v) robustness to endogeneity.

Preliminary Tests

Prior to the estimation of the econometric model, a series of preliminary tests were conducted in order to identify the characteristics of the panel dataset and to ensure the selection of an appropriate estimator. These tests include, respectively, the cross-sectional dependence test, the homogeneity test, the panel unit root test, and the panel cointegration tests.

Cross-Sectional Dependence Test

In order to correctly specify panel data models and ensure the validity of the results, the Pesaran CD test (2015, 2021), the CD* test developed by Pesaran and Xie (2021), and the CDw test proposed by Juodis and Reese (2021), along with its augmented version CDw+, were employed to examine cross-sectional dependence among units. The underlying rationale of these tests is based on the sum of pairwise correlation coefficients ($\hat{\rho}_{ij}$) obtained from the model residuals. The general representation underlying these tests is as follows:

$$CD = \sqrt{\left(2T/\left(N(N-1)\right)\right)}\left(\Sigma_{(i=1)}^{(N-1)}\Sigma_{(j=i+1)}^{N}\hat{\rho}_{ij}\right) \tag{4}$$

Here, ($\hat{\rho}_{ij}$) represents the residual correlation between units i and j, N denotes the number of cross-sectional units, and T refers to the time dimension. The CDw test proposed by Juodis and Reese (2021) aims to capture local dependence more precisely by incorporating cross-sectional weighting matrices into this structure. The CD* and CDw+ versions, on the other hand, include bias-correction procedures designed to eliminate potential biases, particularly those arising in cases of weak dependence and high-dimensional models. The main hypotheses tested are as follows:

$H_0: \rho_{ij} = 0$ (There is no cross-sectional dependence among units / dependence is weak.)
$H_1: \rho_{ij} \neq 0$ (There is statistically significant cross-sectional dependence among units.)

Rejection of the null hypothesis (H_0) indicates that a shock occurring in any unit within the panel affects other units as well.

Homogeneity Test

The homogeneity test examines whether the slope coefficients in the panel data model are identical across all countries. In heterogeneous panels, each country exhibits its own specific dynamics, and the coefficients differ across countries. Ignoring heterogeneity may lead to misleading estimates. The Delta (Δ) test developed by Pesaran and Yamagata (2008) is employed. This test evaluates the homogeneity of slope coefficients and provides the following test statistics:

$$\tilde{\Delta} = \sqrt{N}\left(\left(N^{-}1\tilde{S} - k\right)/\sqrt{2k}\right) \tag{5}$$

Here, $\tilde{S}$ denotes the Swamy test statistic, and k represents the number of explanatory variables. The hypotheses of the test are as follows:

$H_0: \beta_i = \beta$ (The slope coefficients are homogeneous; there is no variation across units.)
$H_1: \beta_i \neq \beta_j$ (The slope coefficients are heterogeneous; there is variation across units.)

If the calculated $\tilde{\Delta}$ statistic is statistically significant, the null hypothesis (H_0) is rejected, leading to the conclusion that the slope coefficients differ across units (heterogeneity).

Panel Unit Root Test

Panel unit root tests are used to determine the stationarity properties of variables. Conducting regression analysis with non-stationary series leads to the problem of spurious regression. In the presence of cross-sectional dependence (CSD), first-generation unit root tests (Levin–Lin–Chu, Im–Pesaran–Shin) lose their validity, making it necessary to apply second-generation tests. In this study, the CIPS (Cross-sectionally Augmented IPS) test developed by Pesaran (2007) is employed. The CIPS test controls for CSD by incorporating cross-sectional averages into the model:

$$CIPS = (1/N)\Sigma_{(i=1)}^{N} t_i(N,T) \tag{6}$$

Here, $t_i(N,T)$denotes the t-statistics obtained from the CADF regression calculated for each cross-sectional unit. The hypothesis structure of the test is as follows:

$H_0: \alpha_i = 0$ (The series is non-stationary for all units / a unit root exists.) $H_1: \alpha_i < 0$ (The series is stationary for at least one unit or for some units.)

The calculated CIPS statistic is compared with the critical values provided in Pesaran (2007) in order to determine the order of integration of the series.

Panel Cointegration Tests

Panel cointegration tests examine the existence of a long-run equilibrium relationship among non-stationary variables. A cointegration relationship emerges when a linear combination of I(1) series is I(0).In this study, three different cointegration tests are applied:

(i) Kao (1999) Test: This test is the panel data version of the Engle–Granger approach. It is a residual-based test and relies on the assumption of a homogeneous cointegration vector. The analysis primarily tests the stationarity of the residuals obtained from the long-run relationship between the dependent and independent variables. The Dickey–Fuller type regression equation and the corresponding test statistic underlying the test are as follows:

$$e\widehat{}_{i}t = \rho e\widehat{}_{i}t - 1 + \sum(j = 1)^{p}\vartheta_{j}\Delta e\widehat{}_{i}\,t - j + \upsilon_{i}t \tag{7}$$

$$ADF = \left(t_{\rho} + \sqrt{6N}\sigma\widehat{}_{\upsilon}/(2\sigma\widehat{}_{0\upsilon})\right) / \left(\sqrt{\sigma\widehat{}^{2}_{0\upsilon}/(2\sigma\widehat{}^{2}_{\upsilon}) + 3\sigma\widehat{}^{2}_{\upsilon}/(10\sigma\widehat{}^{2}_{0\upsilon})}\right) \tag{8}$$

(ii) Pedroni (2004) Test: Unlike the Kao test, this test allows for heterogeneity in the cointegration vector, meaning that the coefficients are permitted to vary across units, and it provides seven different test statistics. These statistics are classified into two categories: within-dimension (panel statistics) and between-dimension (group statistics). The test is based on the following regression:

$$y_{i}t = \alpha_{i} + \delta_{i}t + \beta_{1}ix_{1}it + \cdots + \beta_{m}ix_{m}it + e_{i}t \tag{9}$$

Panel statistics are computed under the assumption that all units share a common autoregressive coefficient, whereas group statistics are calculated under the assumption that each unit has its own autoregressive coefficient (heterogeneity).

(iii) Westerlund (2007) Test: This is an error correction model (ECM)-based test that produces robust results under cross-sectional dependence (CSD) and is capable of controlling for CSD through the bootstrap method. The underlying error correction equation is specified as follows:

$$\Delta y_{i}t = \delta_{i}'d_{t} + \alpha_{i}(y_{i}t - 1 - \beta_{i}'x_{i}t - 1) + \sum(j = 1)^{p}\, i\phi_{i}j\Delta y_{i}t - j + \sum(j = -qi)^{p}\, i\gamma_{i}j\Delta x_{i}t - j + e_{i}t \tag{10}$$

For all three tests, the null hypothesis (H_0) indicates the absence of a cointegration relationship, while the alternative hypothesis (H_1) implies the existence of a cointegration relationship.

COVID-19 Period Trend Analysis

Since the study period (1992–2022) encompasses the COVID-19 pandemic, a descriptive trend analysis was conducted to identify potential structural changes in the ecological footprint during the 2020–2022 period. For this purpose, ecological footprint values for each E7 country in the years 2020, 2021, and 2022 were compared, and annual growth rates were calculated.

$$RateofChange_{(t,t+1)} = \left(\left(EFP_{(t+1)} - EFP_t\right)/EFP_t\right) * 100 \tag{11}$$

This analysis was carried out to visualize the impact of the pandemic period on environmental pressure in the E7 countries.

Results

Table 4 reports the results of the cross-sectional dependence tests. The findings presented in Table 4 confirm the presence of cross-sectional dependence among the variables under investigation. While the CD, CDw, and CDw+ tests strongly detect cross-sectional dependence, the results of the CD* test indicate that part of this dependence stems from common factors. Overall, these findings reveal the existence of strong cross-sectional dependence among the E7 countries. This outcome underscores the necessity of employing econometric methods that explicitly account for cross-sectional dependence.

Table 4. Cross-Sectional Dependence Results

Variables	CD	CDw	CDw+	CD*
efp	3.87***(0,000)	4.39***(0,000)	52.05***0,000	-1.44(-151,000)
lngdpc	22.83***(0,000)	10.00***(0,000)	114.63***(0,000)	2.50**(-12,000)
lngdpc_sq	22.81***(0,000)	9.95***(0,000)	114.47***(0,000)	2.19**(-28,000)
lnnrec	14.02***(0,000)	6.67***(0,000)	84.05***(0,000)	1.50(-132,000)
lnrec	13.54***(0,000)	4.25***(0,000)	68.91***(0,000)	-0.56(-578,000)
lnto	1.95 (0,051)	-2.14**(0,032)	55.21***(0,000)	2.84**(0,0004)
lngfc	8.64***(0,000)	3.10***(-2,000)	46.26***(0,000)	-3.53***(0,000)
lpr	0.02(-986,000)	1.17(-243,000)	35.96***(0,000)	2.78***(-5,000)

Note: ***, *, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. CD refers to Pesaran (2015, 2021); CDw to Juodis and Reese (2021); CDw+ to the CDw test augmented using the bias-correction technique proposed by Fan et al. (2015); and CD to Pesaran and Xie (2021). Values reported in parentheses indicate p-values.

The presence of cross-sectional dependence (CSD) among the E7 countries can be attributed to their high degree of integration into the global economy, trade linkages, financial market integration, and exposure to fluctuations in global energy markets. Consequently, an economic shock or policy change in one country can be transmitted to other countries through trade and financial channels.

Following the cross-sectional dependence tests, the Delta (Δ) homogeneity test developed by Pesaran and Yamagata (2008) is employed to examine whether slope coefficients are homogeneous across units in panel data analysis. Table 5 presents the results of the Pesaran and Yamagata Delta (Δ) and Adjusted Delta (Δadj) homogeneity tests.

Table 5. Homogenity Test

Test	Statistic Value	p-value
Delta (Δ)	8.106***	(0.000)
Adjusted Delta (Δ_{adj})	9.622***	(0.000)

The results of the Pesaran–Yamagata (2008) slope homogeneity test applied to the panel indicate that the coefficients are not homogeneous, implying that econometric approaches accounting for cross-sectional heterogeneity should be employed in the panel data analysis. In other words, due to the presence of structural differences across countries, heterogeneity must be explicitly considered in the model. This finding is expected, given the differences among E7 countries in terms of their economic structures, energy systems, environmental policies, and stages of development.

In empirical analysis, examining the stationarity properties of variables is essential for ensuring the validity of econometric models. Unlike conventional unit root tests, Table 6 reports the results of the Cross-Sectionally Augmented Im–Pesaran–Shin (CIPS) panel unit root test, which explicitly accounts for the problem of cross-sectional dependence in panel data. The null hypothesis (H_0) of this test assumes that all series contain a unit root (I(1)), whereas the alternative hypothesis (H_1) posits that at least some of the series are stationary (I(0)).

Table 6. CIPS Panel Unit Root Rest Results

Variables	t-bar	%10	%5	%1	Z[t-bar]	P-value	Stationarity
efp	-1.888	-2.730	-2.840	-3.060	1.360	0.913	I(1)
lngdpc	-2.096	-2.730	-2.840	-3.060	0.733	0.768	I(1)
lngdpc_sq	-2.159	-2.730	-2.840	-3.060	0.545	0.707	I(1)
lnnrec	-2.571	-2.730	-2.840	-3.060	-0.695	0.243	I(1)
lnrec	-1.759	-2.730	-2.840	-3.060	1.748	0.960	I(1)
lngfc	-2.660	-2.730	-2.840	-3.060	-0.963	0.168	I(1)
lnto	-3.106	-2.730	-2.840	-3.060	-2.825	0.011	I(0)
lnlpr	-2.136	-2.730	-2.840	-3.060	0.613	0.730	I(1)

According to Table 6, only the *lnto* variable is found to be stationary in levels (I(0)), while all other variables contain a unit root and become stationary after first differencing, that is, they are integrated of order one (I(1)). This finding indicates that the necessary conditions for applying panel cointegration tests are satisfied.

The ARDL bounds testing approach allows for the analysis of variables with mixed orders of integration. The CS-ARDL method employed in this study represents a cross-sectionally augmented version of the ARDL framework, explicitly accounting for cross-sectional dependence and permitting the joint analysis of both I(0) and I(1) variables.

The existence of long-run relationships among the variables is examined using the cointegration tests proposed by Kao (1999), Pedroni (2004), and Westerlund (2007), and Table 7 presents the results of the panel cointegration tests.

Table 7. Cointegration Test Results

Test Method	Statistic	p-value	Decision
Kao (1999)			
Modified DFt	-3.248***	0.001	Cointegration Exists
DFt	-2.879***	0.002	Cointegration Exists
ADFt	-3.515***	0.000	Cointegration Exists
Unadjusted DFt	-2.125**	0.017	Cointegration Exists
Unadjusted ADFt	-1.856*	0.031	Cointegration Exists
Pedroni (2004)			
Panel PP	-4.236***	0.000	Cointegration Exists
Panel ADF	-3.991***	0.000	Cointegration Exists
Group PP	-3.657***	0.000	Cointegration Exists
Group ADF	-3.425***	0.000	Cointegration Exists
Westerlund (2007)			
Variance Ratio (VR)	-1.415*	0.077	Cointegration Exists

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. For the Westerlund test, the p-value is based on the bootstrap distribution to account for cross-sectional dependence.

According to the results reported in Table 7, the Kao (1999) test indicates that four out of the five test statistics are significant at the 1% level, leading to the rejection of the null hypothesis of no cointegration (H_0). This finding provides strong evidence of a cointegration relationship among the variables. The Pedroni (2004) test, which allows for heterogeneity, shows that all panel within-dimension and between-dimension statistics are statistically significant at the 1% level, further confirming the presence of cointegration. The results of the Westerlund (2007) test, which is based on an error correction framework and explicitly accounts for cross-sectional dependence, indicate that the Variance Ratio (VR) statistic is significant at the 10% level based on bootstrap p-values. When the findings from these three different cointegration tests are jointly evaluated, it can be concluded that the variables included in the model are linked by a long-run cointegration relationship.

CS-ARDL Estimation

Table 8 presents the long-run coefficient estimates obtained using the Cross-Sectionally Augmented ARDL (CS-ARDL) approach for the E7 countries. The diagnostic test results indicate that cross-sectional dependence (CSD) has been effectively controlled for and that the model exhibits strong explanatory power.

Table 8. CS-ARDL Estimation Results

Variable	Coefficient	Std. Error	t-statistic	p-value
lngdpc	0.842***	0.187	4.502	0.000
lngdpc_sq	-0.038**	0.016	-2.375	0.019
lnnrec	0.564***	0.092	6.130	0.000
lnrec	-0.127**	0.051	-2.490	0.014
lngfc	-0.094*	0.054	-1.741	0.084
lnto	0,151	0.104	1.442	0.149
lnlpr	0.168*	0.089	1.888	0.061
Diagnostic Tests				
Pesaran CD	-1.27		p-value:	0.203
R-squared	0.876			
RMSE	0.342			

Note: *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. The CS-ARDL model controls for cross-sectional dependence (CSD). The Pesaran CD test confirms CSD is effectively controlled (p=0.203>0.10).

According to the results reported in Table 8, the positive coefficient of the income variable (lngdpc) and the negative coefficient of its squared term (lngdpc_sq) provide evidence that the Environmental Kuznets Curve (EKC) hypothesis holds for the E7 countries. This finding indicates that economic growth increases environmental pollution up to a certain threshold level, beyond which environmental quality begins to improve. Non-renewable energy consumption (lnnrec), with a coefficient of 0.564, emerges as the factor that most strongly increases the ecological footprint. In contrast, the coefficient of renewable energy consumption (lnrec) is negative and statistically significant, indicating that greater use of renewable energy significantly reduces environmental degradation. Gross fixed capital formation (lngfc) contributes to a reduction in environmental pressure, likely reflecting the impact of green investments, whereas labor force participation rate (lpr) increases the ecological footprint through higher levels of production and consumption. The effect of trade openness rate (to) is statistically insignificant, suggesting that trade integration does not exert a clear long-run impact on the ecological footprint.

The diagnostic tests support the validity of the model. The Pesaran CD test indicates that cross-sectional dependence in the model residuals has been effectively controlled. This result demonstrates that the CS-ARDL approach successfully mitigates cross-sectional dependence by incorporating cross-sectional averages into the model.

CS-DL Estimation (Robustness Check)

Table 9 presents the long-run coefficients estimated using the CS-DL approach. By incorporating both lead and lag values of the explanatory variables into the model, CS-DL controls for potential endogeneity and directly estimates long-run relationships. The CS-DL results are reported to assess the robustness of the findings obtained from the CS-ARDL framework.

Table 9. CS-DL Estimation Results

Variable	Coefficient	Std. Error	t-statistic	p-value
lngdpc	0.796***	0.192	4.146	0.000
lngdpc_sq	-0.035**	0.017	-2.059	0.041
lnnrec	0.521***	0.098	5.316	0.000
lnrec	-0.115**	0.053	-2.170	0.032
lngfc	-0.087	0.056	-1.554	0.122
lnto	0.100	0.100	1.000	0.316
lnlpr	0.152*	0.091	1.670	0.097
Diagnostic Tests				
Pesaran CD	-1.04		p-value:	0.299
R-squared	0.868			
RMSE	0.356			

Note: *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. CS-DL results are provided to check the robustness of the CS-ARDL findings. The Pesaran CD test indicates CSD is effectively controlled (p=0.299>0.10).

The CS-DL estimates reported in Table 9 support the CS-ARDL results in terms of coefficient magnitudes, signs, and levels of statistical significance. These findings demonstrate that the results are not sensitive to the choice of econometric methodology. The coefficients of the income variables (lngdpc positive and lngdpc_sq negative) confirm the validity of the EKC hypothesis for the E7 countries. The effect of non-renewable energy consumption in increasing the ecological footprint and the mitigating impact of renewable energy consumption remain statistically significant in this model as well. Moreover, the insignificance of the Pesaran CD test statistic confirms that the problem of cross-sectional dependence has been successfully addressed in the model.

The consistency between the CS-ARDL and CS-DL results indicates that the estimated findings are robust and not driven by the choice of estimator. This consistency enhances the reliability of the empirical results.

Findings from the COVID-19 Period Trend Analysis

Figure 5 illustrates the trajectory of the ecological footprint in the E7 countries over the period 2020–2022. The figure reveals notable cross-country differences during the pandemic period and the subsequent recovery phase.

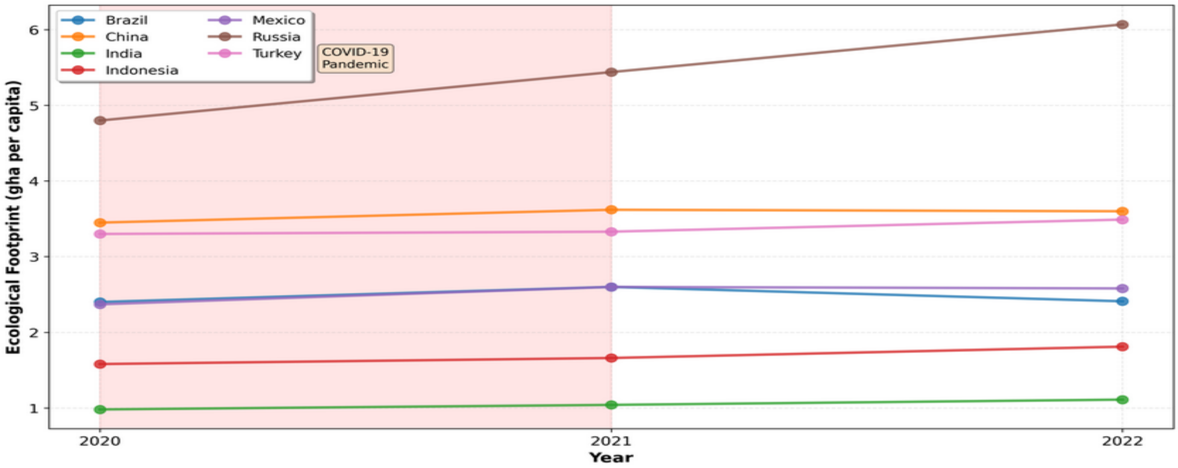

Figure 5. Ecological Footprint Trends in E7 Countries During the COVID-19 Period (2020–2022) Data Source: Global Footprint Network

The shaded area represents the pandemic period (2020–2021). Russia recorded the largest increase in ecological footprint (26.5%), whereas Brazil exhibited the smallest change (0.4%).

The pronounced increase in Russia can be associated with the rapid rebound in energy consumption in the post-pandemic period and the expansion of fossil fuel exports.

Mexico and China experienced moderate increases of 8.9% and 4.3%, respectively. Mexico's ecological footprint rose by 9.7% during the 2020–2021 period but declined slightly by 0.8% in the 2021–2022 period. China's ecological footprint increased from 3.45 gha in 2020 to 3.60 gha in 2022. China's relatively low growth rate may be attributed to restrictions on economic activity resulting from its COVID-19 containment policies. Turkey's increase in ecological footprint, at 5.8%, remained below the E7 average. While Turkey recorded a minimal increase of 0.9% during the 2020–2021 period, its ecological footprint rose by 4.8% in the 2021–2022 period. Brazil recorded the lowest overall increase, with a total change of only 0.4%. Specifically, Brazil's ecological footprint increased by 8.3% in the 2020–2021 period but declined by 7.3% in the 2021–2022 period, returning nearly to its initial level.

Overall, the average ecological footprint of the E7 countries increased from 2.70 gha in 2020 to 3.01 gha in 2022, corresponding to a total rise of 11.5%. This finding indicates that the COVID-19 pandemic temporarily alleviated environmental pressure; however, in the post-pandemic period, environmental pressures rebounded rapidly and, in some countries (Russia, Indonesia, and India), even exceeded pre-pandemic trends.

Conclusions, Discussion and Recommendations

The E7 countries (Brazil, China, India, Indonesia, Mexico, Russia, and Turkey) have been gaining an increasingly significant share in global economic output and energy consumption due to their rapid growth and industrialization processes. However, this development trajectory has generated vulnerabilities in terms of environmental sustainability as a result of intensive energy use, accelerated urbanization, and industry-based production structures. Therefore, investigating the effects of economic growth, energy use, and macroeconomic factors on the ecological footprint in E7 countries is of critical importance for both the academic literature and policymakers.

The findings of this study are largely consistent with the existing literature on the ecological footprint in E7 countries. The positive coefficient of per capita GDP and the negative coefficient of GDP squared support the Environmental Kuznets Curve (EKC) hypothesis. This result is in line with the findings of Nathaniel et al. (2021), Ahmed et al. (2022), and Danish et al. (2020) for E7 countries. The positive effect of non-renewable energy consumption on the ecological footprint is consistent with the findings of Li et al. (2022) and Qamruzzaman (2023). However, this study examines the effects of the energy structure in greater detail by modeling non-renewable and renewable energy as separate variables. The negative coefficient of the renewable energy share supports the findings of Shayanmehr et al. (2023) and Joof et al. (2022), which indicate that clean energy use enhances environmental sustainability.

The coefficient of capital formation is found to be negative. This finding suggests that a portion of capital accumulation in E7 countries has been directed toward green technologies. In particular, China's high investment rate (41.2%) includes projects aimed at expanding renewable energy capacity and disseminating energy efficiency technologies. The labor force participation rate has a positive and statistically significant coefficient. This result is consistent with studies indicating that increases in labor force participation rate raise energy demand and thereby intensify environmental pressures (Damrah et al., 2022; Ahmad and Satrović, 2024). In contrast, the trade openness rate variable is found to be statistically insignificant in the long run. This outcome supports the divergent views in the literature. While some studies argue that trade improves environmental quality (Ritu and Kaur, 2023; Dada et al., 2022), others suggest that it leads to environmental degradation (Nathaniel, 2021; Abdullahi et al., 2024). Our findings indicate that the impact of foreign trade on the ecological footprint is heterogeneous and that no clear long-run effect is observed for the sample group.

The analysis of COVID-19 trends results reveal differences among E7 countries in terms of environmental sustainability in the post-pandemic period. Russia's 26.5% increase reflects a rapid rebound in energy demand that had been suppressed during the pandemic, with environmental pressure rising above pre-pandemic levels following the removal of restrictions. Russia's status as a major oil and natural gas exporter further amplifies this increase. The generally rising trend observed in Asian countries (China, India, and Indonesia) can be associated with rapid industrialization and economic growth in the region. The decline observed in Brazil during the 2021–2022 period can be linked to economic stagnation and low investment rates.

The empirical findings of this study provide policy-relevant implications for ensuring environmental sustainability in E7 countries. First, renewable energy investments should be expanded, and policies aimed at improving energy efficiency should be promoted. The results indicate that non-renewable energy use increases the ecological footprint, whereas renewable energy significantly mitigates this effect. Consequently, focusing on energy transition would help these countries achieve sustainable economic growth while alleviating ecological pressures. Second, gross fixed capital formation and labor market policies should be integrated with environmental objectives. The finding that capital accumulation reduces environmental degradation implies that the adoption of environmentally friendly technologies in new investments should be encouraged. Similarly, since labor market dynamics increase energy demand, employment policies should be designed with mechanisms that promote environmental awareness. The analysis of COVID-19 trends findings indicate that, in future crises, economic stimulus packages should be directed toward renewable energy investments and sustainable infrastructure. Finally, foreign trade policies should be reshaped through regulations that account for environmental sensitivity. The uncertainty surrounding the long-run impact of foreign trade on the ecological footprint highlights the need for sustainability-oriented policy frameworks in this area.

Future research that examines the determinants of the ecological footprint at a more micro level by accounting for sectoral distinctions and regional differences is expected to contribute to the development of more targeted and actionable policy recommendations. Overall, the findings of this study indicate that E7 countries need to reduce their dependence on fossil fuels, rapidly expand renewable energy capacity, and align their economic growth objectives with environmental sustainability goals. Methodologically, this study contributes to the literature by applying new-generation econometric techniques.

Author Contribution

The overall preparation, design, and writing process of the manuscript were carried out with equally by Okan Güleç, Selen Utlu Koçdemir and Tuğba Özyıldız.

Ethics Approval

Ethical approval was not required for this study

Conflict of Interest Statement

There is no conflict of interest with any person/institution in this study.

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