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Drivers of Green Economic Growth: Comparative Evidence from Turkey and Romania

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Abstract

In developing countries, sustainable development strategies are increasingly shifting toward a green economy that integrates economic, social, and environmental dimensions. Despite the growing importance of green economic growth, comparative empirical studies examining its determinants in Turkey and Romania remain limited. This study investigates the dynamic relationships between environmentally sustainable growth, carbon emissions, life expectancy, renewable energy consumption, education, and technological innovation in Turkey and Romania over the period 1980–2023. Using annual time series data, the analysis applies the Augmented Dickey–Fuller and Zivot–Andrews unit root tests to examine stationarity and potential structural breaks. The empirical framework is based on the Autoregressive Distributed Lag (ARDL) bounds testing approach, which allows the estimation of both long-run equilibrium relationships and short-run dynamics. The results provide partial evidence of long-run relationships among the variables. Although the ARDL bounds test results fall within the inconclusive region, the negative and statistically significant error correction terms indicate that deviations from long-run equilibrium are corrected over time. The findings also reveal heterogeneous short-run causal interactions across the two countries, suggesting that the drivers of environmentally sustainable growth differ between Turkey and Romania. Overall, the results highlight the importance of country-specific policy frameworks, institutional structures, and energy transition pathways in promoting green economic growth.

Keywords: sustainable development; environmental sustainability; renewable energy transition; human capital; technological innovation; ARDL model

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1. Introduction

Since the 1970s, environmental disasters in the global economy have led countries to reconsider their development strategies and adopt new policies that include environmental factors. The concept of sustainable development, which emerged during this process, has taken shape as a model aimed at balancing economic growth with environmental protection. This approach, based on the principle of meeting present needs without compromising the ability of future generations to meet their own needs, gained significant global attention, particularly in the last quarter of the 20th century. International agreements signed in the 1990s transformed sustainable development from a mere idea into a concrete strategy supported by policies and implementations, making it a globally adopted approach. However, the implementation of sustainable development varies from country to country, depending on each society's economic, social, and environmental dynamics. Therefore, sustainable development is considered a multidimensional approach that includes not only environmental policies but also elements such as social justice and economic well-being [1].

Sustainable development is addressed through three interconnected dimensions: economic, environmental, and social. Economic sustainability requires a system to continuously produce goods and services, maintain public finances at manageable levels, and regulate sectoral imbalances in a way that does not harm economic structures. In this context, the long-term stability of agricultural and industrial production must be ensured while preventing excessive borrowing and financial crises. Environmental sustainability, on the other hand, is based on the balanced use of natural resources; overconsumption of renewable resources should be avoided, and non-renewable resources should only be utilized when sufficient substitutes are available [2,3]. This approach aims to preserve biodiversity, maintain atmospheric stability, and ensure the functionality of ecosystems. Social sustainability emphasizes protecting fundamental human rights, increasing access to healthcare and education, ensuring gender equality, and strengthening democratic governance. Individuals should be encouraged to actively participate in society, and inequalities should be eliminated to provide a fair standard of living for all. When these three dimensions of sustainable development are considered together, it becomes evident that a holistic approach is necessary—one that not only prioritizes economic growth but also safeguards ecological balance and social well-being [4]. In this context, achieving comprehensive sustainable development requires a green economy. The determinants of the green economy are illustrated in Figure 1.

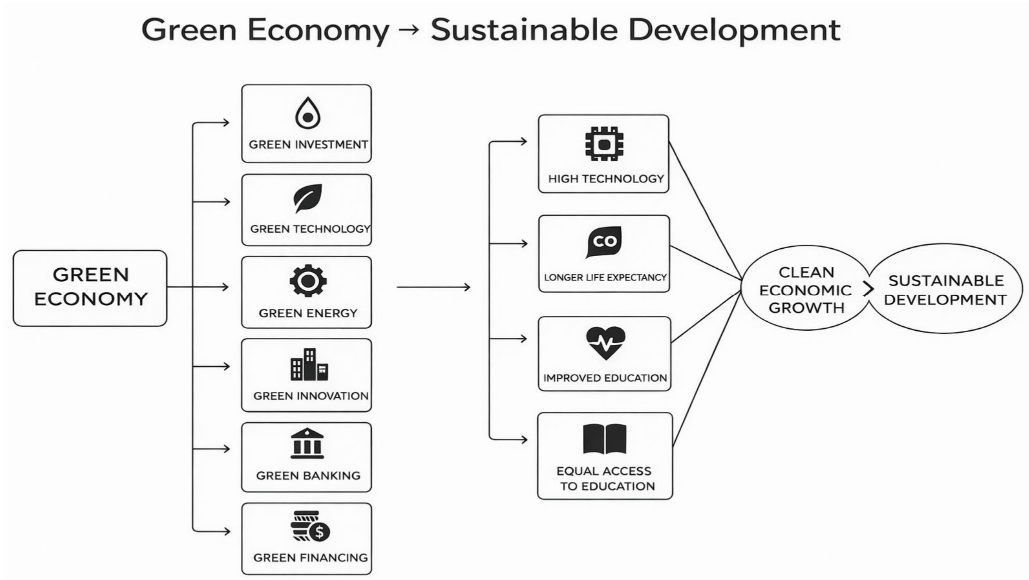

Figure 1. Determinants of the Green Economy. Source: [5].

Figure 1 illustrates the components of the green economy and how it contributes to clean economic growth, leading to sustainable development. The upper section presents various subcomponents under the green economy framework: green investment, green technology, green industry, green energy, green urbanization, green innovation, green banking, and green finance. These are key factors that support environmentally sustainable economic growth. The middle section demonstrates how these components, through a transformation process, lead to positive outcomes such as low carbon emissions, high

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renewable energy usage, advanced technology, longer life expectancy, and better education. This highlights how the green economy enhances human well-being by providing economic and social benefits. The lower section emphasizes that the ultimate result of this transformation is clean economic growth, which, in turn, leads to sustainable development. In other words, the green economy enables the adoption of environmentally friendly policies while simultaneously promoting economic growth and social progress. Figure 1 clearly visualizes the transition from the green economy to green economic growth and how this process contributes to sustainable development. While the green economy focuses on reshaping economic activities with an eco-friendly approach by prioritizing environmental sustainability and social welfare, green economic growth represents a dynamic transformation process that includes policies and strategies promoting economic development based on these principles.

According to the OECD, the process of increasing economic growth and development while ensuring the sustainable use of natural resources and ecosystem services for human well-being is referred to as "green economic growth" [6]. This concept emphasizes aligning economic activities with environmental sustainability principles. Green economic growth aims to foster economic development while minimizing excessive resource consumption and negative environmental impacts. By implementing eco-friendly policies and technologies, economic growth can be achieved while preserving natural ecosystems and maintaining biodiversity. In recent years, Turkey and Romania have experienced rapid economic growth while undergoing significant transformations in terms of environmental sustainability. Industrialization, energy consumption, and urbanization processes have supported economic growth, but increased fossil fuel usage and carbon emissions have introduced environmental risks. However, investments in renewable energy and sustainable development policies have enabled both Turkey and Romania to make progress in reducing carbon emissions and transitioning to green energy. In Turkey, investments in solar and wind energy, in particular, play a critical role in preventing environmental degradation. Considering the environmental impacts of economic growth, adopting a low-carbon development model will help Turkey and Romania achieve their long-term sustainability goals.

Based on this, the study proposes the following hypotheses:

H1: *There exists a long-run relationship between environmentally sustainable growth and its determinants in Turkey and Romania.*

H2: *Carbon emissions are associated with environmentally sustainable growth in both countries.*

H3: *Education is associated with environmentally sustainable growth, although the magnitude and direction of this relationship may vary across countries.*

H4: *Renewable energy consumption and technological innovation contribute to environmentally sustainable growth, with country-specific differences in their effects.*

H5: *The causal interactions among environmentally sustainable growth and its determinants differ between Turkey and Romania.*

In light of these hypotheses, green economic growth is conceptualized as a strategic development pathway that simultaneously delivers long-term economic performance and environmental sustainability. Despite the growing body of literature on green growth, comparative empirical evidence examining Turkey's green economic growth potential relative to Romania—a European Union member state that has achieved notable progress in environmental regulation, renewable energy deployment, and institutional alignment—remains limited. Addressing this gap, the present study analyzes the long-run relationships between green economic growth, carbon emissions, life expectancy, renewable energy consumption, education, and technological innovation in Turkey and Romania. By capturing the economic, social, and environmental dimensions of sustainable development, the study provides a comprehensive comparative assessment of the two countries.

Although a growing body of research has examined the relationship between economic growth and environmental sustainability, several important gaps remain. First, many existing studies focus either on single-country analyses or large panel datasets, which may overlook country-specific structural dynamics. Second, previous research often examines environmental indicators separately without jointly considering renewable energy, human capital, and technological innovation within a unified empirical framework. Third, structural breaks and transformation issues in sustainability indicators are frequently ignored in empirical analyses, which may lead to biased estimates. To address these gaps, this study provides a comparative time-series analysis of Turkey and Romania by incorporating renewable energy consumption, education, technological innovation, and life expectancy within an ARDL–ECM framework. In addition, the analysis accounts for structural breaks and applies an alternative transformation of the sustainability indicator, thereby offering a more robust examination of the determinants of environmentally sustainable growth.

Accordingly, this study contributes to the literature in three main ways. First, it provides a comparative time-series analysis of Turkey and Romania, two countries with distinct institutional and economic trajectories. Second, it integrates renewable energy consumption, education, technological innovation, and life expectancy within a unified empirical framework to explain environmentally sustainable growth. Third, the study accounts for structural breaks and transformation issues in sustainability indicators, thereby enhancing the robustness of the empirical analysis.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature. Section 3 presents the data and methodology. Section 4 reports the empirical results. Section 5 discusses the findings and policy implications, and Section 6 concludes the study.

2. Literature Review

In recent years, the concepts of green economic growth and sustainable development have gained significant importance within policy frameworks aimed at balancing economic growth with environmental and social impacts to ensure long-term prosperity. Traditional growth models often overlook environmental sustainability while increasing natural resource consumption, whereas the green growth approach seeks to align economic development with ecological balance. The literature on green economic growth examines its effects on economic, social, and environmental indicators, emphasizing that transitioning to a low-carbon economy is crucial for achieving sustainable development goals. For developing economies such as Turkey and Romania, variables such as renewable energy usage, environmental regulations, and social development policies are key factors in the green growth process. In this context, existing literature presents various theoretical and empirical models explaining the relationship between economic growth and environmental sustainability while increasingly analyzing the effects of renewable energy investments, ecological innovations, and sustainable development strategies on economic performance. Comparative analyses of Turkey and Romania provide a valuable framework for understanding how countries at different stages of development shape their green growth policies and how these policies impact sustainable development indicators.

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2.1. Renewable Energy and Environmental Sustainability

Renewable energy consumption and environmental sustainability have become central themes in the green growth literature.

Mensah et al. (2018) [7] conducted a study on 28 OECD countries using FMOLS analysis with annual data from 1990 to 2014, finding that renewable energy consumption, economic growth, and innovation negatively impact CO_2 emissions.

Rahman & Velayutham (2020) [8] examined the effect of renewable energy on economic growth in South Asian countries, using Panel FMOLS and Panel DOLS tests on annual data from 1990 to 2014, concluding that a 1% increase in renewable energy consumption raises per capita real GDP by approximately 66%. Razmi et al. (2020) [9], employing the ARDL approach for Iran during the 1990–2014 period, found that renewable energy consumption positively affects GDP in both the short and long run. These studies generally suggest that renewable energy plays an important role in shaping both environmental quality and economic performance, although the direction and magnitude of the relationship may vary across countries and methodological approaches. Koyuncu and Karabulut (2021) [10] analyzed Turkey's 1961–2015 period using a Threshold Autoregressive (TAR) model, determining that ecological footprint positively influences economic growth in both regime periods, while renewable energy-derived electricity generation negatively impacts growth in the first regime but positively in the second.

Qoyash & Eren (2022) [11] studied Turkey's 1990–2019 period using a dynamic ARDL simulation method, finding that non-renewable energy consumption and technological innovation positively impact CO_2 emissions, while renewable energy consumption has a negative but statistically insignificant effect.

Liu et al. (2024) [12] investigate the relationship between economic development and environmental sustainability in OECD countries over the period 1990–2022, with a particular focus on renewable energy consumption and environmental technologies. Using empirical panel data analysis, the study finds that renewable energy adoption and environmental technological innovation significantly reduce CO_2 emissions. The results further reveal that while economic growth, urbanization, industrialization, and trade initially increase emissions, their impact becomes negative as economies mature and integrate cleaner technologies. These findings highlight the dynamic and non-linear relationship between economic development and environmental sustainability in OECD economies.

Alvi et al. (2025) [13] investigate the combined effects of energy transition, green finance, digitalization, and technological innovation on greenhouse gas emissions in 31 OECD countries over the period 2000–2020. Using multiple econometric techniques, including FMOLS, FGLS, MMQR, and panel causality tests, the study finds that digitalization, renewable energy, environmental patents, and green finance significantly reduce greenhouse gas emissions, thereby enhancing environmental sustainability. In contrast, economic growth, urbanization, and trade liberalization are shown to increase emissions. The findings highlight the importance of integrated policy frameworks aligned with SDG 7 and SDG 13 for achieving net-zero targets in OECD economies.

Asif et al. (2026) [14] assess the impact of climate policy uncertainty and renewable energy consumption on greenhouse gas emissions in G7 countries between 2000 and 2024. Employing the Method of Moments Quantile Regression framework, the study reveals that climate policy uncertainty reduces emissions in low-emission countries, while institutional quality mitigates its adverse effects by stimulating green investments. The findings also highlight the mediating role of technological innovation in strengthening the emissions-reducing effects of renewable energy, underscoring the importance of institutional and technological capacity in achieving environmental sustainability.

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These studies highlight the crucial role of renewable energy in reducing environmental degradation and supporting sustainable economic growth.

2.2. Human Capital, Education, and Technological Innovation

Melnyk et al. (2021) [15] investigate the role of digitalization, structural change, and social factors in promoting sustainable development in OECD countries over the period 2007–2018. Using random-effects GLS estimation, the study finds that digital transformation positively affects GDP per capita through lower transaction costs and the expansion of the service sector, while its direct environmental impact remains statistically insignificant. The results further suggest that urbanization and income distribution play important roles in shaping both economic performance and environmental outcomes in OECD economies.

Khan et al. (2023) [16] examined the impact of energy efficiency, green innovation, and foreign direct investment on sustainable economic growth in OECD countries (2000–2019), employing Cross-Sectional Autoregressive Distributed Lag (CS-ARDL) and Augmented Mean Group (AMG) tests, concluding that these factors significantly and positively influence green economic development. Tekbaş & Yıldırım (2023) [17] analyzed 13 developing countries (2000–2019) using panel econometric tests, revealing that innovation reduces CO_2 emissions in Armenia and North Macedonia but increases them in Brazil, Bulgaria, China, Colombia, and Turkey, while economic growth and renewable energy consumption are crucial in reducing emissions. Overall, these studies emphasize the growing importance of human capital development, technological innovation, and digital transformation as key drivers of sustainable economic development.

In recent years, the role of digitalization and technological transformation has attracted increasing attention in the green growth literature. Lei et al. (2024) [18] examine the relationship between digitalization development and sustainable development with a particular focus on advanced economies, many of which are members of the OECD. Using an entropy-based composite index to measure digitalization and panel data covering 36 developed countries over the period 2010–2020, the study estimates Green Total Factor Productivity (GTFP) growth as an indicator of sustainable development. Employing fixed effects, mediation effect, and threshold regression models, the authors find a significant positive association between digitalization development and GTFP growth. The results further suggest that digitalization indirectly enhances green productivity through technological innovation, human capital accumulation, and industrial structure upgrading. Importantly, the study identifies a non-linear relationship, indicating that the environmental benefits of digitalization vary across countries depending on their levels of innovation capacity, human capital development, and financial development—an insight particularly relevant for OECD countries characterized by heterogeneous institutional and economic structures.

Wang et al. (2024) [19] provide empirical evidence on the effects of green energy, green finance, green innovation, and eco-digitalization on environmental sustainability in BRICS countries from 1995 to 2019. Applying the STIRPAT framework with second-generation estimators, the study finds that green energy adoption, financial development, innovation, and digitalization significantly reduce CO_2 emissions, ecological footprint, and air pollution. The results highlight the importance of coordinated green policies and technological advancement in improving environmental quality.

Elfaki et al. (2024) [20] examine the role of digital technology adoption and globalization in promoting green sustainable economic growth across selected Asia-Pacific countries. Employing panel data techniques and a random effects model, the study demonstrates that digitalization and digitization significantly enhance economic growth and green total factor productivity (GTFP). The results suggest that digital technology adoption facilitates innovation, knowledge diffusion, and technology transfer, thereby supporting sustainable development and the achievement of Sustainable Development Goals through improved productivity and environmental integration.

Manta et al. (2025) [21] examine the interplay between digitalization, banking performance, and renewable energy consumption in European Union countries. Applying FMOLS, VAR, and Granger causality techniques, the study demonstrates that higher levels of digitalization and stronger financial performance in the banking sector are associated with increased investments in renewable energy. The results emphasize the importance of digital financial infrastructure and regulatory frameworks in facilitating the transition toward a green economy, while also revealing heterogeneity across EU member states depending on national policies and digital readiness.

Shi & Nisar (2025) [22] analyze the joint effects of circular economy practices, green finance, and information and communication technologies on ecological sustainability in 27 OECD countries from 2000 to 2022. Using the CS-ARDL approach, the study finds that circular economy initiatives and ICT development exhibit short-term adjustment costs but generate significant long-term benefits in terms of resource productivity and ecological sustainability. The findings further indicate that green finance plays a crucial role in directing investments toward environmentally efficient technologies, particularly under stringent environmental policy regimes.

More recent studies increasingly focus on the role of digital finance, technological innovation, and institutional factors in promoting environmentally sustainable growth. Cihangir (2025) [23] analyzes the impact of financial innovation on environmental quality in OECD economies using panel data from 18 countries over the period 2009–2021. Applying advanced econometric techniques that account for cross-sectional dependence and long-run relationships, the study finds that financial innovation significantly reduces carbon emissions by promoting green technological innovation and expanding renewable energy production. The results further reveal bidirectional causality between financial innovation and green technology, emphasizing the importance of coordinated sustainable finance and energy transition policies.

Ahmad et al. (2025) [24] explore the role of the digital economy in fostering green growth across 104 global economies over the period 2000–2022. Using Method of Moments Quantile Regression and system GMM approaches, the study reports a significant and positive impact of digital economy development on green growth across all income groups and quantiles. The findings indicate that digitalization plays a critical role in achieving sustainable development goals by enhancing innovation, supporting environmentally sustainable practices, and complementing fiscal and trade policies aimed at green growth.

Okere et al. (2025) [25] examine the non-linear relationship between digitalization, resource dependence, and green growth using an extended STIRPAT framework over the period 1990–2023. Employing Hansen's threshold regression approach, the study identifies a digitalization threshold beyond which information and communication technologies mitigate the environmental costs of natural resource exploitation. The findings suggest that while green growth remains in a transitional phase, deeper ICT integration and technological innovation are essential for achieving long-term ecological resilience.

Chen and Wang (2025) [26] examine the effects of digital economy development, economic growth, and financial expansion on CO_2 emissions across major carbon-emitting countries using quantile-based econometric techniques. The results show that while digitalization may directly increase emissions at higher emission levels, its interaction with economic growth mitigates environmental degradation. Financial expansion is found to consistently reduce emissions across all quantiles. These findings underscore the dual and context-dependent role of digitalization in environmental sustainability.

Overall, these studies emphasize the importance of human capital development and technological innovation in facilitating environmentally sustainable economic transitions.

2.3. Economic Growth, Emissions, and Green Growth Dynamics

Hasan et al. (2023) [5], using the ARDL method for Bangladesh (1990–2019), found a positive and significant relationship between CO_2 emissions and GDP, with a 3.66% GDP increase corresponding to rising emissions. They also reported that a 1% increase in life expectancy raises GDP by approximately 4.2%, while the relationship between technological innovation, education, and GDP is insignificant.

Küçük & Dural (2024) [27] assessed Turkey's green economy performance within the European Green Deal framework using a Green Economy Measurement Framework (GEP) index, finding that Turkey is advancing toward a green economy but falls short of meeting the European Green Deal criteria.

Wani et al. (2024) [28] analyzed the role of green energy, green technology, foreign direct investment, and globalization in green economic growth for G7 countries (1995–2020) using the CS-ARDL method, finding that green energy and FDI contribute positively to both the short and the long term, while green technology also enhances green economic growth.

Ciot et al. (2025) [29] investigated energy policies in Black Sea states—Romania, Bulgaria, Turkey—and the structural changes caused by the war in Ukraine through quantitative and qualitative analyses, concluding that the conflict has led to energy policy restructuring, including resource diversification, alternative supply routes, and increased investment in renewable energy.

Nica et al. (2026) [30] investigate energy transition heterogeneity across European economies by applying an integrated fuzzy clustering and machine learning framework. Analyzing multiple indicators related to renewable energy, digitalization, emissions, and economic development, the study identifies distinct structural typologies among countries and highlights persistent divergence in energy transition paths. The findings underscore the importance of accounting for country-specific structural characteristics when designing energy and digitalization policies to support sustainable development.

Together, these studies demonstrate that the relationship between economic growth and environmental sustainability is complex and shaped by multiple structural and institutional factors. Despite the growing literature on green growth and sustainability, empirical studies focusing on OECD countries using comprehensive green growth proxies remain limited. Existing research primarily concentrates either on single-country analyses or global panel datasets, often overlooking cross-country institutional differences within a comparative country framework. Therefore, this study contributes to the literature by providing a comparative time-series analysis of Turkey and Romania, thereby offering additional comparative evidence on the determinants of green economic growth. Recent studies also emphasize the importance of green growth, sustainable development, and environmental policies in shaping long-term economic and environmental outcomes across different economies [31–38].

Theoretical Framework

This study is grounded in the theoretical perspectives of sustainable development and endogenous growth theory. Within this framework, green economic growth is conceptualized as an outcome of the interaction between environmental quality, human capital accumulation, technological innovation, and energy transition. Endogenous growth theory emphasizes the role of knowledge, education, and innovation in sustaining long-term economic growth, while sustainable development theory highlights the necessity of preserving natural capital alongside economic expansion. Renewable energy adoption contributes to green economic growth by reducing dependence on fossil fuels and mitigating environmental degradation, thereby improving long-run productivity and sustainability. Technological innovation enhances resource efficiency and supports the diffusion of cleaner production processes, while education strengthens human capital and environmental awareness, indirectly fostering green innovation and sustainable growth. Life expectancy is incorporated as a proxy for human development and social welfare, reflecting the feedback mechanisms between environmental quality, health outcomes, and economic performance. By integrating these dimensions, the study develops a coherent conceptual framework that links economic, social, and environmental factors to green economic growth, providing a theoretical foundation for the empirical analysis of Turkey and Romania. This study contributes to the existing literature by offering a comparative ARDL-based analysis that explicitly accounts for structural breaks, long-run equilibrium relationships, and short-run adjustment dynamics. By jointly examining carbon emissions, life expectancy, renewable energy, education, and technological innovation, the study provides new insights into the heterogeneous pathways through which green economic growth can be achieved in different economic contexts.

3. Research Methodology

In this study, which examines the long-term relationship between green economic growth and carbon emissions, life expectancy, renewable energy, education, and technological development in Turkey and Romania from 1980 to 2023, the established model was analyzed using time series modeling. A time series consists of data measured at specific intervals and aims to understand the structural characteristics and trends of the data. To protect the series from potential variable variance and autocorrelation, logarithmic transformations of non-negative variables should be obtained, and the model should be constructed accordingly [39]. Time series analysis requires certain prerequisites. In regression analyses conducted with time series, it is expected that the time periods of the data are consistent and regular. One of the fundamental assumptions of these analyses is that the series used must be stationary, meaning they are integrated. Stationarity implies that the mean and variance of a time series do not change over time; a non-stationary time series is not suitable for analysis as it contains structural changes and trends. Additionally, the movement of a non-integrated time series can only be evaluated within the examined period. If a regression analysis is performed with a non-integrated time series, the R^2 value may be inflated, leading to the issue of spurious regression [40] (p. 320). Therefore, in this study, the stationarity of the series was first tested using the Augmented Dickey–Fuller (ADF) unit root test.

3.1. ADF Unit Root Test

In the literature, one of the most commonly used methods to test whether a series contains a unit root is the ADF unit root test. Accordingly, this study also employs ADF tests to determine whether the variables contain unit roots.

The Dickey–Fuller unit root test is based on the following first-order autoregressive model:

$$Yt = \varnothing Yt - 1 + \varepsilon t \quad (1)$$

where εt represents an error term series with a mean of zero and constant variance, and $Yt - 1$ denotes the lagged values of the dependent variable. Subtracting $Yt - 1$ from both sides of the equation gives:

$$Yt - Yt - 1 = \varnothing Yt - 1 - Yt - 1 + \varepsilon t \quad (2)$$

Which simplifies to:

$$\Delta Yt = (\varnothing - 1)Yt - 1 + \varepsilon t \quad (3)$$

Defining $\delta = \varnothing - 1$, the model can be rewritten as:

$$\Delta Yt = \delta Yt - 1 + \varepsilon t \quad (4)$$

The null and alternative hypotheses of the Dickey–Fuller unit root test are as follows:

H_0: $\delta = 0$ (The series contains a unit root)

H_1: $\delta < 0$ (The series does not contain a unit root)

In interpreting the analysis results, if the probability value (*p*-value) is greater than 0.05 ($p > 0.05$), it is concluded that the series contains a unit root. If the *p*-value is less than 0.05 ($p < 0.05$), the series is considered stationary. In the ADF framework, the null hypothesis states that the series contains a unit root, whereas the alternative hypothesis implies stationarity. Therefore, rejecting the null hypothesis indicates that the series is stationary, while failure to reject the null suggests non-stationarity. Given the long sample period, potential structural breaks are examined using the Zivot–Andrews (1992) [41] unit root test. Lag lengths are selected based on the Akaike and Schwarz information criteria to ensure model stability. The ADF tests were estimated with an intercept and without a deterministic trend, and the optimal lag lengths were selected using the Akaike Information Criterion.

3.2. Zivot–Andrews Structural Break Unit Root Test

To determine the stationarity properties of the variables while accounting for potential structural breaks, the Zivot–Andrews (1992) [41] unit root test is employed. Conventional unit root tests may yield misleading results in the presence of structural changes. The Zivot–Andrews test addresses this issue by endogenously identifying a single structural break in each time series.

The test equation allowing for a break in both the intercept and trend (Model C) is specified as follows:

$$\Delta \log X_t = \mu + \theta\ DU_t\ \beta\ t + \gamma\ DT_t + \alpha \log X_{t-1} + \Sigma_{i=1}{}^{k}\ c_i\ \Delta \log X_{t-1} + \varepsilon_t \quad (5)$$

where logX represents GE_asinh, $\log CO_2$, logLE, logRE, logSE, or logTI. DU_t is a dummy variable capturing a shift in the intercept, DT_t represents a change in the trend slope, and k denotes the optimal lag length. The break date is selected based on the minimum t-statistic associated with the coefficient α.

Rejection of the null hypothesis implies that the series is stationary in the presence of a structural break. These findings ensure the correct identification of the integration order of the variables and support the applicability of the ARDL bounds testing approach.

3.3. ARDL Bounds Testing Approach

This study examines the long-run and short-run relationships between environmentally sustainable growth and its economic, social, energy, and technological determinants using the Autoregressive Distributed Lag (ARDL) bounds testing approach developed by Pesaran et al. (2001) [42]. The ARDL framework is well suited for this analysis because it allows variables to be integrated of order zero I(0) or order one I(1), provides reliable estimates in relatively small samples, and enables the simultaneous estimation of long-run equilibrium relationships and short-run adjustment dynamics, provided that none of the variables is integrated of order two I(2).

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In the model, $LOGCO_2$ denotes carbon dioxide emissions, GE_asinh represents green economic growth, LOGLE refers to life expectancy, LOGRE captures renewable energy consumption, LOGSE indicates school enrollment, and LOGTI reflects technological innovation. Most variables are transformed into natural logarithms in order to reduce potential heteroskedasticity and to interpret the estimated coefficients as elasticities. However, the dependent variable is transformed using the inverse hyperbolic sine function to accommodate possible zero or negative values.

For the ARDL specification, the optimal lag length was selected using the Akaike Information Criterion (AIC), while the Schwarz Information Criterion (SIC) was used as a robustness check to ensure model stability.

The unrestricted error correction model (UECM) forming the basis of the ARDL bounds testing procedure is specified as follows:

$$\begin{aligned}\Delta GE\_asinh &= \alpha_0 + \Sigma_{i=1}{}^{P}\, \alpha_i\, \Delta\, GE\_asinh_{\,t-i} + \Sigma_{j=0}{}^{p1}\, \beta_j\, \Delta LOG\, CO_{2t-j} + \Sigma_{k=0}{}^{p2}\, \gamma_k\, \Delta LOGLE_{t-k} \\ &+ \Sigma_{l=0}{}^{p3}\, \delta_1\, \Delta LOGRE_{t-1} + \Sigma_{m=0}{}^{p4}\, \theta_m\, \Delta LOGSE_{t-m} + \Sigma_{n=0}{}^{p5}\, \psi_n\, \Delta LOGTI_{t-n} + \lambda_1\, LOGCO_{2t-1} + \\ &\lambda_2\, GE\_asinh_{\,t-1} + \lambda_3\, LOGLE_{t-1} + \lambda_4\, LOGRE_{t-1} + \lambda_5\, LOGSE_{t-1} + \lambda_6\, LOGTI_{t-1} + \varepsilon_t\end{aligned} \quad (6)$$

where Δ denotes the first difference operator, p represents the optimal lag length selected using standard information criteria, and ε_t is a white-noise error term.

The existence of a long-run cointegration relationship among the variables is tested using the following hypotheses:

H_0: $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = \lambda_6 = 0$ (no cointegration)
H_1: At least one $\lambda_i \neq 0$ (cointegration exists)

The calculated F-statistic is compared with the lower and upper bound critical values provided by Pesaran et al. (2001) [42]. If the F-statistic exceeds the upper bound, the null hypothesis of no cointegration is rejected, suggesting the presence of a long-run equilibrium relationship among the variables.

Upon establishing cointegration, long-run coefficients are estimated, and the short-run dynamics are analyzed through the error correction model (ECM), which is specified as:

$$\begin{aligned}\Delta GE\_asinh_{\,t} &= \beta_0 + \Sigma_{i=1}{}^{P}\, \beta_i\, \Delta\, GE\_asinh_{\,t-i} + \Sigma_{j=0}{}^{p1}\, \delta_j\, \Delta LOGCO_{2t-j} + \Sigma_{k=0}{}^{p2}\, \varphi_k\, \Delta LOGLE_{t-k} \\ &+ \Sigma_{l=0}{}^{p3}\, \omega_1\, \Delta LOGRE_{t-1} + \Sigma_{m=0}{}^{p4}\, \eta_m\, \Delta LOGSE_{t-m} + \Sigma_{n=0}{}^{p5}\, \kappa_n\, \Delta LOGTI_{t-n} + \rho\, ECM_{t-1} + \mu_t\end{aligned} \quad (7)$$

where ECM_{t-1} is the lagged error correction term derived from the long-run relationship. The coefficient ρ is expected to be negative and statistically significant, indicating that short-run deviations from equilibrium are corrected over time.

3.4. Block Granger Causality Test

The Granger causality test is widely used to examine predictive relationships between time series variables. Originally introduced by Granger (1969) [43], the test aims to determine whether past values of one variable contain information that helps predict another variable. Sims (1980) [44] later extended this framework within the Vector Autoregression (VAR) approach.

In this study, the block Granger causality test is employed to investigate short-run causal relationships among the variables. Within this framework, the null hypothesis states that the lagged values of an explanatory variable do not jointly influence the dependent variable. Rejection of the null hypothesis indicates the presence of short-run Granger causality. The causality analysis is interpreted together with the ARDL–ECM results in order to provide a more comprehensive understanding of the dynamic interactions among environmentally sustainable growth and its key determinants.

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It should be noted that causality in the Granger sense reflects predictive ability rather than true structural causation. In some cases, bidirectional causality may arise when two variables mutually influence each other over time, meaning that each variable may Granger-cause the other [45]. Therefore, the results of the block Granger causality test help determine whether the relationships between the variables are unidirectional or bidirectional and whether these predictive effects are statistically significant. The empirical results of the block Granger causality analysis are presented in Section 4.3.

3.5. Data Collection and Research Variables

This study adopts a quantitative research approach and uses annual time series data covering the period from 1980 to 2023 for Turkey and Romania. The definitions of the variables, together with their symbols and data sources, are reported in Table 1. Green economic growth is the dependent variable in this study and is proxied by adjusted net savings (ANS), an indicator widely used by the World Bank to measure sustainable economic performance by accounting for investments in human capital, natural resource depletion, and environmental damages. ANS reflects sustainable economic performance by incorporating investments in physical and human capital while accounting for the depletion of natural resources and environmental degradation. However, it should be noted that ANS captures broader sustainability dynamics rather than directly measuring green technological progress or environmental policy effectiveness. Unlike conventional GDP-based indicators, ANS provides a broader perspective on sustainability by capturing whether an economy is accumulating or depleting its productive base over time. Nevertheless, ANS is not a direct measure of welfare or green innovation and may not fully reflect short-term environmental policy impacts. In addition, the ANS series may take zero or negative values during periods of economic stress or intensive resource depletion, which makes the direct logarithmic transformation technically infeasible. To address this issue, the inverse hyperbolic sine (asinh) transformation is applied to the ANS variable. This transformation behaves similarly to the natural logarithm for large values while remaining defined for zero and negative observations. Accordingly, environmentally sustainable growth is represented by the transformed variable GE_asinh. Most explanatory variables are transformed into natural logarithms in order to reduce potential heteroskedasticity and facilitate elasticity-based interpretation of the estimated coefficients. Specifically, $LOGCO_2$ represents carbon emissions, LOGLE denotes life expectancy, LOGRE indicates renewable energy consumption, LOGSE captures education, and LOGTI represents technological innovation. To investigate the dynamic relationships among environmentally sustainable growth, carbon emissions, life expectancy, renewable energy consumption, education, and technological innovation in Turkey and Romania, the study first examines the stationarity properties of the variables using the Augmented Dickey–Fuller (ADF) unit root test. In order to account for possible structural changes in the series, the Zivot–Andrews unit root test is also employed. Variables that are found to be non-stationary at level are transformed by taking their first differences where necessary. The empirical analysis is conducted within the Autoregressive Distributed Lag (ARDL) bounds testing framework, which allows the estimation of both long-run equilibrium relationships and short-run dynamics regardless of whether the variables are integrated of order I(0) or I(1). The ARDL bounds test is used to examine the existence of a long-run cointegration relationship among the variables. Finally, short-run causal interactions among the variables are investigated using the block Granger causality test. The presence of country-specific structural breaks also justifies the inclusion of dummy variables representing the 2008 global financial crisis for Turkey and the 2007 EU accession for Romania in the ARDL specification. To account for major structural changes in the economies of the two countries, dummy variables are incorporated into the ARDL

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models. For Turkey, a dummy variable representing the 2008 global financial crisis is included, taking the value of 1 from 2008 onward and 0 otherwise. For Romania, a dummy variable representing the country's accession to the European Union in 2007 is included in a similar manner. These dummy variables help capture potential structural shifts in economic and environmental dynamics that may influence the relationship between the variables.

Table 1. Variables, Definitions and Data Sources.

Variable Name	Symbol	Definition	Source
Green economic growth	GE_asinh	Inverse hyperbolic sine transformation of adjusted net savings (ANS).	WDI
CO_2 Emission	$LOGCO_2$	(CO_2) emissions excluding LULUCF per capita (t CO_2e/capita)	WDI
Life expectancy	LOGLE	Life expectancy at birth, total (years)	WDI
Renewable energy	LOGRE	Renewable energy (% of primary energy supply)	WDI
School enrollment	LOGSE	School enrollment, secondary (gross), gender parity index (GPI)	WDI
Technology Innovation	LOGTI	Patent applications (resident + nonresident = total patents)	WDI

4. Findings

In this study, annual data from 1980 to 2023 were used to examine the relationships between green economic growth, carbon emissions, life expectancy, renewable energy, education, and technological development for Turkey and Romania. Table 2 presents the mean, median, maximum, minimum, and standard deviation values of the series for Turkey and Romania.

Table 2. Summary of descriptive statistics.

	GE_asinh	$LOGCO_2$	LOGLE	LOGRE	LOGSE	LOGTI
Turkey						
Mean	1.194395	0.525885	1.853111	3.548643	−0.131071	3.307019
Median	1.233216	0.520967	1.857608	3.543062	−0.121950	3.284956
Maximum	1.561863	0.738336	1.894731	3.698886	−0.010523	3.932220
Minimum	0.646835	0.247931	1.795908	3.430986	−0.316548	2.708421
Std. Dev.	0.222506	0.145670	0.028067	0.306203	−0.090942	0.369375
Romania						
Mean	1.323205	0.74574	1.855038	3.295162	0.002334	3.247835
Median	1.449791	0.695304	1.852249	3.286116	0.002721	3.149676
Maximum	1.766110	0.972486	1.878564	3.345626	0.012441	3.782401
Minimum	−0.815314	0.569758	1.838880	3.261639	−0.012951	2.912222
Std. Dev.	0.489880	0.136500	0.013744	0.026970	0.005741	0.254128

Figure 2 shows the changes over time in key factors such as Turkey's green economic growth (GE_asinh), carbon emissions ($LOGCO_2$), life expectancy (LOGLE), renewable energy use (LOGRE), education (LOGSE), and technological development (LOGTI).

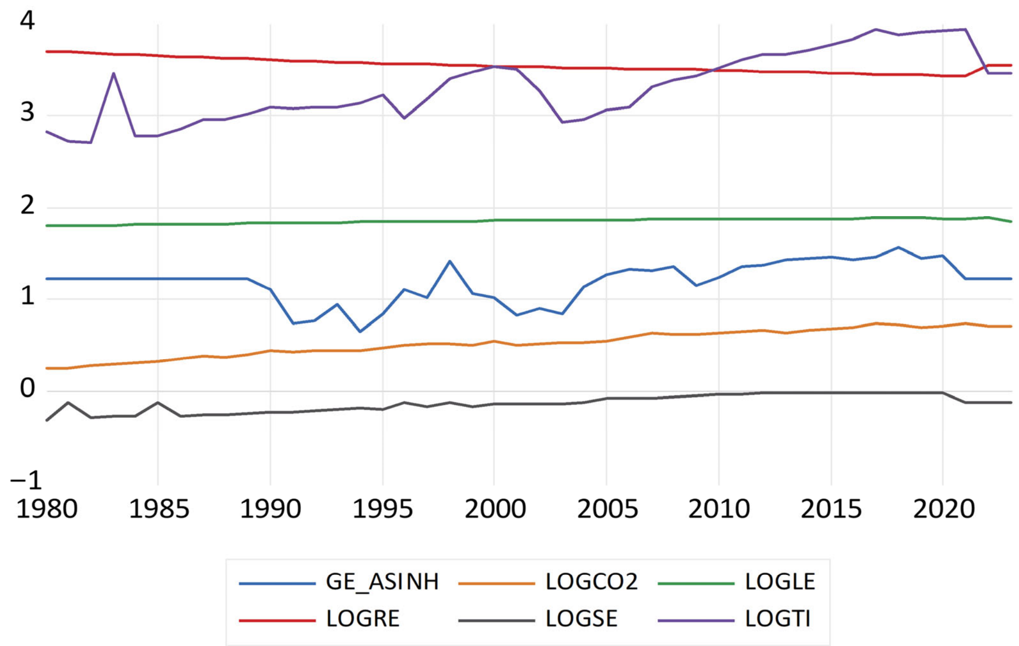

Figure 2. The course of data for Turkey over time.

GE_asinh (environmentally sustainable growth indicator) shows moderate fluctuations over time, reflecting changes in adjusted net savings dynamics, though with some fluctuations, while LOGCO$_2$ (Carbon Emissions) shows a more stable and slightly increasing trend, as clearly seen in Figure 2. This suggests that economic growth is continuing, but carbon emissions are also increasing in parallel. Renewable energy use (LOGRE) is one of the variables with the highest levels in the graph but has shown a decreasing trend over time. The figure indicates that renewable energy consumption exhibits a declining trend over part of the sample period. In Figure 2, life expectancy (LOGLE) appears to be quite stable, which could be due to the lack of significant changes in health and welfare. Education (LOGSE) shows a slight increasing trend over time, but without major fluctuations, as seen in Figure 2.

Figure 3 illustrates the changes over time in Romania's green economic growth (GE_asinh), carbon emissions (LOGCO$_2$), life expectancy (LOGLE), renewable energy use (LOGRE), education (LOGSE), and technological development (LOGTI).

In Figure 3, GE_asinh (Blue Line), the green economic growth variable experiences a sudden drop at a certain point before recovering. This reflects a temporary decline followed by a recovery in the environmentally sustainable growth indicator. LOGCO$_2$ (Orange Line), representing carbon emissions, remains relatively stable over time but exhibits minor fluctuations corresponding to declines in green economic growth. LOGLE (Green Line), representing life expectancy, appears quite stable with no significant changes, indicating that it is a long-term variable. LOGRE (Red Line), representing renewable energy use, remains nearly constant, with no significant increases or decreases observed. LOGSE (Black Line), representing education, follows a stable trajectory with no sudden changes. LOGTI (Purple Line), representing technological development, remains at a high level but experiences occasional small fluctuations. Overall, in Figure 3, while economic growth experiences a sharp decline, carbon emissions exhibit minor fluctuations. However, variables such as education, renewable energy, and life expectancy remain relatively stable. Additionally, technological development remains at a generally high level, suggesting that declines in economic growth may not have a significant impact on environmental and social factors or that the effects may emerge with a delay.

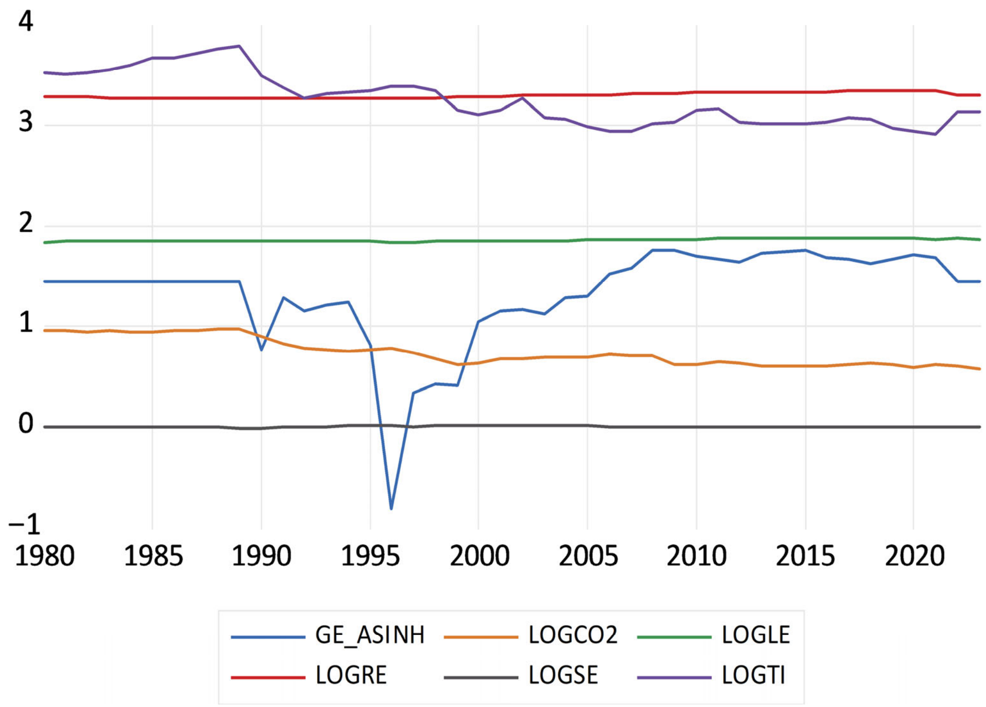

Figure 3. The course of data for Romania over time.

4.1. Unit Root Tests

Unit root tests are applied to determine whether economic time series are stationary. Non-stationary series do not fluctuate around a specific mean in the long run but instead exhibit random variations over time. In this study, the Augmented Dickey–Fuller (ADF) unit root test was applied to examine whether the variables were stationary. Table 3 presents the ADF test results.

Table 3. ADF Unit Root Test Results at Level and First Difference.

Variables	**T Statics**	
	Level	1st Difference
Turkey		
GE_asinh	−2.341239	7.962200 ***
$LOGCO_2$	−1.45665	7.4152 ***
LOGLE	−1.81251	−14.278 ***
LOGRE	−2.094651	6.007085 ***
LOGSE	−2.666222	−13.05598 ***
LOGTI	−2.066354	−8.014363 ***
Romania		
GE_asinh	−2.523007	−8.241920 ***
$LOGCO_2$	−1.052667	4.554042 ***
LOGLE	−0.846410	−8.58778 ***
LOGRE	−0.914540	−5.908994 ***
LOGSE	−2.374527	3.749929 ***
LOGTI	−1.340782	5.545259 ***

Note: *** denotes statistical significance at the 1% levels. Prob-values denote the MacKinnon approximate *p*-values. H0: the time series is non-stationary.

According to the ADF unit root test results in Table 3, the examined variables for Turkey and Romania are not stationary at level and have unit roots. However, after taking their first differences, all variables become stationary, indicating that the series are integrated of order one, I(1). For Turkey: The variables GE_asinh (−2.341239), $LOGCO_2$ (−1.45665), LOGLE (−1.81251), LOGRE (−2.094651), LOGSE (−2.666222), and LOGTI (−2.066354) are found to be non-stationary at level, as their test statistics do not exceed the critical values of the Augmented Dickey–Fuller test. However, after taking their first differences, **GE_asinh** (7.962200 *), $LOGCO_2$ (7.4152 *), LOGLE (−14.278 *), LOGRE (6.007085 *), LOGSE (−13.05598 *), and LOGTI (−8.014363 *) become statistically significant and stationary at conventional significance levels. For Romania: The variables **GE_asinh** (−2.523007), LOGCO2 (−1.052667), LOGLE (−0.846410), LOGRE (−0.914540), LOGSE (−2.374527), and LOGTI (−1.340782) are found to be non-stationary at level, as their test statistics do not exceed the critical values of the Augmented Dickey–Fuller test. After taking their first differences, **GE_asinh** (−8.241920 *), $LOGCO_2$ (4.554042 *), LOGLE (−8.58778 *), LOGRE (−5.908994 *), LOGSE (3.749929 *), and LOGTI (5.545259 *) became statistically significant and stationary. These results indicate that all variables in Turkey and Romania are not stationary at level but become stationary after taking their first differences. This finding highlights the necessity of differentiating in time series analyses to ensure stationarity. Although the ADF unit root test provides initial evidence regarding the stationarity properties of the series, it does not account for potential structural breaks that may arise from major economic or institutional shocks. Therefore, to ensure the robustness of the stationarity analysis and to capture possible endogenous structural changes in the time series, the Zivot–Andrews (1992) [41] unit root test with a single structural break is additionally employed. Table 4 presents the results of the Endogenous Structural Break Dates Identified by the Zivot–Andrews Test.

Table 4. Endogenous Structural Break Dates Identified by the Zivot–Andrews Test.

Country	Variable	Model	Selected Break Year	Economic Interpretation
Turkey	GE_asinh	Intercept & Trend (Model C)	2008	Global financial crisis, contraction in industrial output and energy demand
Romania	GE_asinh	Intercept & Trend (Model C)	2007	EU accession and alignment with EU environmental and energy policies

The Zivot–Andrews unit root test is employed to account for potential structural breaks in the time series. The results reveal different endogenous break dates for Turkey and Romania, reflecting country-specific economic and institutional transformations. For Turkey, the structural break is identified in 2008, which corresponds to the global financial crisis that significantly affected economic activity, energy consumption patterns, and environmental dynamics. For Romania, the break year is detected as 2007, coinciding with the country's accession to the European Union. This event marked a major institutional shift as Romania began aligning its environmental regulations and energy policies with EU standards. These structural changes may have influenced the long-run behavior of the variables, particularly carbon emissions and environmentally sustainable growth. Therefore, accounting for structural breaks is important for obtaining reliable unit root test results. The detailed results of the Zivot–Andrews unit root test are reported in Table 5.

The Zivot–Andrews unit root test is employed to account for potential structural breaks in the time series. The results indicate that the structural break occurred in 2008 for Turkey and in 2007 for Romania. These break dates correspond to major economic and institutional events, namely the global financial crisis in Turkey and Romania's accession to the European Union. The results further suggest that most variables remain non-stationary at their level form even after allowing for a single endogenous structural break. This finding is consistent with the Augmented Dickey–Fuller test results and supports the application of the ARDL bounds testing approach, which allows for the estimation of models with variables integrated of order I(0) and I(1). Taken together, the ADF and Zivot–Andrews results suggest a mixed I(0)/I(1) structure across the variables, while providing no evidence of integration of order two, I(2). This combined evidence justifies the use of the ARDL bounds testing approach, which is appropriate when regressors are integrated of order zero or one.

Table 5. Zivot–Andrews Structural Break Unit Root Test Results for Turkey and Romania.

Country	Variable	Break Year	ZA Test Statistic	Critical Value (5%)	Results
Turkey	LOGCO_2	2008	−3.89	−4.80	Non-stationary
	GE_asinh	2008	−3.35	−4.80	Non-stationary
	LOGLE	2008	−3.48	−4.80	Non-stationary
	LOGRE	2008	−4.11	−4.80	Non-stationary
	LOGSE	2008	−3.77	−4.80	Non-stationary
	LOGTI	2008	−4.02	−4.80	Non-stationary
Romania	LOGCO_2	2007	−4.10	−4.80	Non-stationary
	GE_asinh	2007	−4.69	−4.80	Stationary with break
	LOGLE	2007	−3.88	−4.80	Non-stationary
	LOGRE	2007	−4.03	−4.80	Non-stationary
	LOGSE	2007	−3.91	−4.80	Non-stationary
	LOGTI	2007	−4.02	−4.80	Non-stationary

Notes: Critical values are based on Zivot and Andrews.

4.2. ARDL Results for Turkey and Romania

Following the unit root analysis that accounts for potential structural breaks, the autoregressive distributed lag (ARDL) approach is employed to investigate the short-run and long-run relationships between carbon emissions and the selected economic and technological variables for Turkey and Romania. The ARDL methodology is particularly suitable in this context as it allows the estimation of dynamic relationships among variables that are stationary at levels and performs well in small samples. Moreover, the ARDL framework enables the simultaneous assessment of long-run equilibrium relationships and short-run adjustment dynamics through the error correction mechanism. Country-specific ARDL models are estimated to capture structural and institutional differences between Turkey and Romania, thereby providing more nuanced and reliable empirical evidence. The ARDL test results are presented in Table 6.

Table 6. ARDL Bounds Test and Error Correction Results for Turkey and Romania.

Country	Selected ARDL Model	F-Bounds Statistic	Cointegration	Error Correction Term (ECT)	ECT Coefficient
Turkey	ARDL (1, 0, 0, 2, 0)	2.736	Inconclusive	CoinEq (−1)	–0.442 ***
Romania	ARDL (1, 2, 1, 0, 0, 1)	3.191	Inconclusive	CoinEq (−1)	–0.807 ***

Notes: *** indicates statistical significance at the 1% level. The calculated F-statistics fall between the lower and upper bounds, indicating an inconclusive region. However, the negative and statistically significant error correction term (ECT) supports the presence of a stable long-run adjustment mechanism in both countries. The long-run coefficient estimates for Turkey and Romania are presented in Table 7.

Table 7. a. Long-Run Coefficient Estimates for Turkey and b. Long-Run Coefficient Estimates for Romania.

(a)		
Variable	Definition	Turkey
LOGCO_2	CO_2 Emissions	Statistically insignificant
LOGLE	Life Expectancy	Statistically insignificant
LOGRE	Renewable Energy	Statistically insignificant
LOGSE	School Enrollment	Positive and significant
LOGTI	Technology Innovation	Statistically insignificant
(b)		
Variable	Definition	Romania
LOGCO_2	CO_2 Emissions	Positive and significant
LOGLE	Life Expectancy	Positive and significant
LOGRE	Renewable Energy	Statistically insignificant
LOGSE	School Enrollment	Statistically insignificant
LOGTI	Technology Innovation	Statistically insignificant

Note: "Positive and significant" indicates a statistically significant positive long-run coefficient, whereas "statistically insignificant" indicates that the coefficient is not statistically different from zero at conventional significance levels.

The long-run coefficient estimates reveal heterogeneous patterns across the two countries. For Turkey, school enrollment emerges as the only statistically significant positive determinant of environmentally sustainable growth, whereas carbon emissions, life expectancy, renewable energy consumption, and technological innovation do not exhibit statistically significant long-run effects. In contrast, for Romania, carbon emissions and life expectancy display positive long-run associations with environmentally sustainable growth, while renewable energy, education, and technological innovation remain statistically insignificant. These findings indicate that the long-run drivers of environmentally sustainable growth differ between the two economies. The ARDL bounds testing results provide only suggestive evidence of a long-run relationship between green economic growth and its determinants in both Turkey and Romania. However, the magnitude, direction, and adjustment dynamics of this relationship differ considerably across the two countries. The ARDL bounds test results provide partial evidence regarding the existence of a long-run relationship among the variables. For Turkey, the calculated F-statistic (2.736) lies between the lower and upper critical bounds, indicating an inconclusive region. A similar outcome is observed for Romania, where the F-statistic (3.191) also falls between the critical bounds. However, the error correction term (ECT) is negative and statistically significant for both countries, suggesting that deviations from the long-run equilibrium are corrected over time. The estimated speed of adjustment is approximately 44% for Turkey and 80% for Romania, indicating a relatively faster convergence toward equilibrium in Romania.

4.3. Block Granger Causality Test

The Block Granger Causality Test is used to determine the causal relationships between the variables examined in this study. This test evaluates whether one variable significantly predicts another, identifying whether the relationship is unidirectional or bidirectional. If the past values of one variable significantly improve the prediction of another variable, the relationship is interpreted as Granger causality in a predictive sense. The findings obtained from the analysis are presented in Table 8, where the direction and significance of the causal links between the variables are examined in detail.

Table 8. Block Granger Causality Test Results.

Turkey				**Romania**			
Dependent Variable: GE_asinh				**Dependent Variable: GE_asinh**			
	Chi-sq	df	Prob		Chi-sq	df	Prob
$LOGCO_2$	11.764	4	0.019 **	$LOGCO_2$	9.772	4	0.044 **
LOGLE	8.288	4	0.081 *	LOGLE	12.363	4	0.014 **
LOGRE	6.559	4	0.161	LOGRE	14.193	4	0.006 ***
LOGSE	36.887	4	0.000 ***	LOGSE	11.046	4	0.026 **
LOGTI	20.006	4	0.000 ***	LOGTI	8.840	4	0.065 **
All	80.276	20	0.000 ***	All	52.958	20	0.000 ***
Dependent Variable: $LOGCO_2$				Dependent Variable: $LOGCO_2$			
GE_asinh	1.986	4	0.738	GE_asinh	7.077	4	0.131
LOGLE	5.52	4	0.202	LOGLE	2.546	4	0.636
LOGRE	7.787	4	0.099 *	LOGRE	5.218	4	0.265
LOGSE	6.664	4	0.154	LOGSE	25.24	4	0.000 ***
LOGTI	3.302	4	0.508	LOGTI	6.735	4	0.150
All	51.366	20	0.000 ***	All	61.666	20	0.000 ***
Dependent Variable: LOGLE				Dependent Variable: LOGLE			
GE_asinh	2.566	4	0.632	GE_asinh	3.904	4	0.419
$LOGCO_2$	4.089	4	0.394	$LOGCO_2$	9.414	4	0.051 *
LOGRE	25.803	4	0.000 ***	LOGRE	8.477	4	0.075 *
LOGSE	3.191	4	0.526	LOGSE	9.730	4	0.045 **
LOGTI	3.028	4	0.553	LOGTI	0.372	4	0.984
All		20	0.000 ***	All	37.760	20	0.000 ***
Dependent Variable: LOGRE				Dependent Variable: LOGRE			
GE_asinh	9.854	4	0.042 **	GE_asinh	12.775	4	0.012 **
$LOGCO_2$	3.967	4	0.410	$LOGCO_2$	14.069	4	0.012 **
LOGLE	67.516	4	0.000 ***	LOGLE	85.411	4	0.000 ***
LOGSE	4.964	4	0.291	LOGSE	4.908	4	0.296
LOGTI	8.645	4	0.070 *	LOGTI	8.693	4	0.069 *
All	143.696	20	0.000 ***	All	133.611	20	0.000 ***
Dependent Variable: LOGSE				Dependent Variable: LOGSE			
GE_asinh	5.059	4	0.281	GE_asinh	4.782	4	0.310
$LOGCO_2$	3.024	4	0.553	$LOGCO_2$	0.351	4	0.986
LOGLE	14.005	4	0.007 ***	LOGLE	2.903	4	0.574
LOGRE	3.665	4	0.453	LOGRE	1.912	4	0.751
LOGTI	2.423	4	0.658	LOGTI	2.177	4	0.703
All	46.719	20	0.006 ***	All	14.773	20	0.789
Dependent Variable: LOGTI				Dependent Variable: LOGTI			
GE_asinh	8.143	4	0.086	GE_asinh	0.844	4	0.932
$LOGCO_2$	10.075	4	0.039 **	$LOGCO_2$	1.138	4	0.888
LOGLE	3.220	4	0.521	LOGLE	1.679	4	0.794
LOGRE	3.942	4	0.413	LOGRE	2.133	4	0.711
LOGSE	2.390	4	0.664	LOGSE	3.979	4	0.408
All	61.095	20	0.000 ***	All	16.514	20	0.684

Note: Probabilities refer to Wald χ^2 statistics. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 8 reports the results of the block Granger causality test for Turkey and Romania. For Turkey, significant short-run causality is detected from carbon emissions (LOGCO_2), education (LOGSE), and technological development (LOGTI) to environmentally sustainable growth (GE_asinh). In contrast, life expectancy (LOGLE) and renewable energy consumption (LOGRE) do not exhibit statistically significant causal effects on green economic growth. For Romania, the results indicate that carbon emissions (LOGCO_2), renewable energy consumption (LOGRE), and education (LOGSE) Granger-cause environmentally sustainable growth in the short run. Regarding carbon emissions as the dependent variable, the results show that the explanatory variables do not significantly predict emissions in Turkey, whereas education appears to have a statistically significant effect on emissions in Romania. With respect to life expectancy, renewable energy consumption significantly influences life expectancy in Turkey, while carbon emissions display a marginal effect in Romania. Overall, the findings suggest that the short-run causal relationships among the variables differ across the two countries.

The causality results further reveal heterogeneous dynamics across the two countries. In Turkey, renewable energy consumption significantly affects life expectancy, while education appears to play an important role in explaining variations in life expectancy. In contrast, for Romania, carbon emissions are strongly influenced by life expectancy, suggesting that demographic and health-related improvements may be associated with changes in environmental pressures. Overall, these findings indicate that the structure of causal interactions differs between the two economies, reflecting differences in institutional frameworks, environmental policies, and energy transition dynamics. The diagnostic and stability test results for the estimated ARDL–ECM models are presented in Table 9.

Table 9. Diagnostic and Stability Test Results.

Test	**Turkey**	**Romania**
Breusch–Godfrey LM (Serial Correlation)	Prob > 0.05	Prob > 0.05
ARCH Heteroskedasticity Test	Prob > 0.05	Prob > 0.05
Jarque–Bera Normality Test	Prob > 0.05	Prob > 0.05
Ramsey RESET Test	Prob > 0.05	Prob > 0.05
CUSUM Stability Test	Stable	Stable
CUSUMSQ Stability Test	Stable	Stable

The diagnostic test results indicate that the estimated ARDL–ECM models are statistically well specified for both Turkey and Romania. The Breusch–Godfrey LM test suggests that there is no evidence of serial correlation in the residuals, while the ARCH test indicates the absence of heteroskedasticity. In addition, the Jarque–Bera test confirms that the residuals follow a normal distribution. The Ramsey RESET test further suggests that there is no functional form misspecification in the estimated models. Finally, the CUSUM and CUSUMSQ stability tests show that the estimated coefficients remain stable over the sample period. Overall, these results confirm that the estimated ARDL–ECM models are statistically well specified, stable, and free from major econometric problems. The stability of the estimated ARDL models is further examined using the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) tests. The corresponding plots are presented in Figures 4–7.

The CUSUM plot for Turkey remains within the 5% critical bounds throughout the sample period, indicating that the estimated coefficients are stable over time. This result suggests that the ARDL model for Turkey does not suffer from structural instability.

The CUSUMSQ test results for Turkey also remain within the critical bounds, confirming the stability of the variance of the residuals and supporting the overall reliability of the estimated model.

The CUSUM plot for Romania lies within the 5% significance bounds over the entire sample period. This indicates that the estimated coefficients remain stable and that there is no evidence of parameter instability in the Romanian model.

The CUSUMSQ results also confirm the stability of the Romanian ARDL model, as the cumulative sum of squared residuals remains within the critical bounds throughout the sample period.

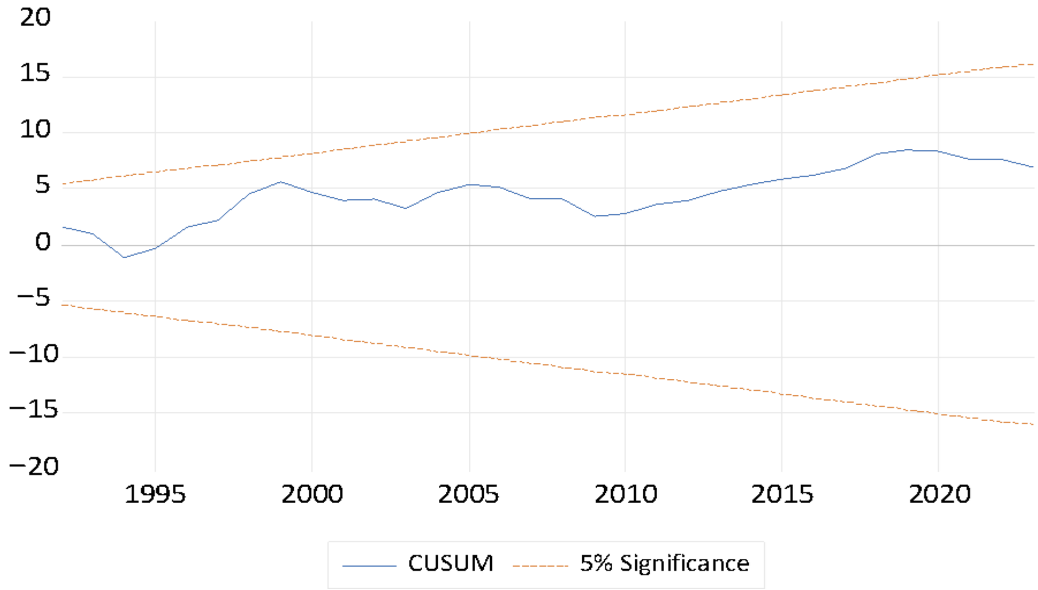

Figure 4. CUSUM Stability Test for Turkey. Note: The straight lines represent the 5% significance bounds.

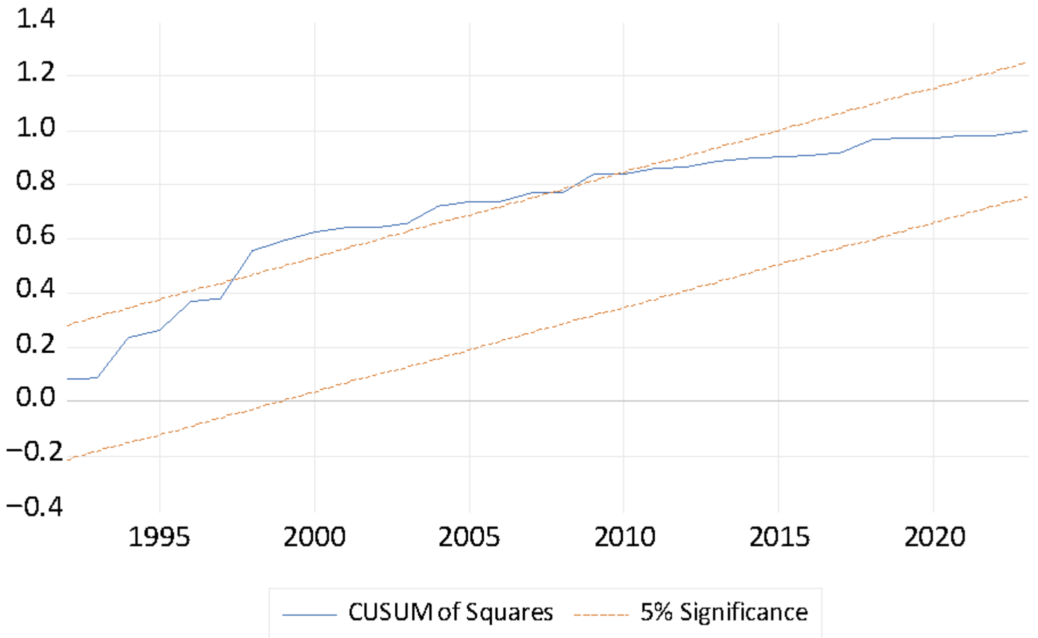

Figure 5. CUSUMSQ Stability Test for Turkey. Note: The straight lines represent the 5% significance bounds.

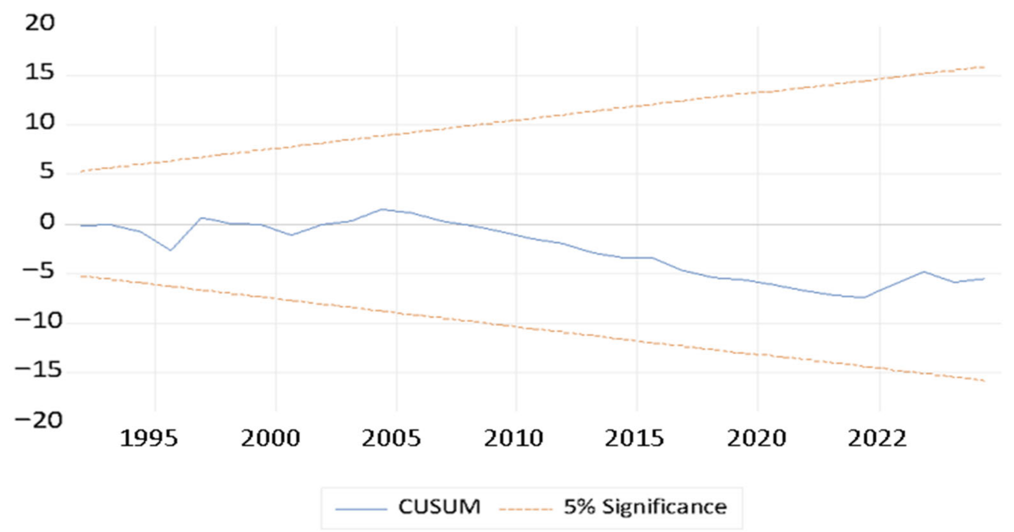

Figure 6. CUSUM Stability Test for Romania. Note: The straight lines represent the 5% significance bounds.

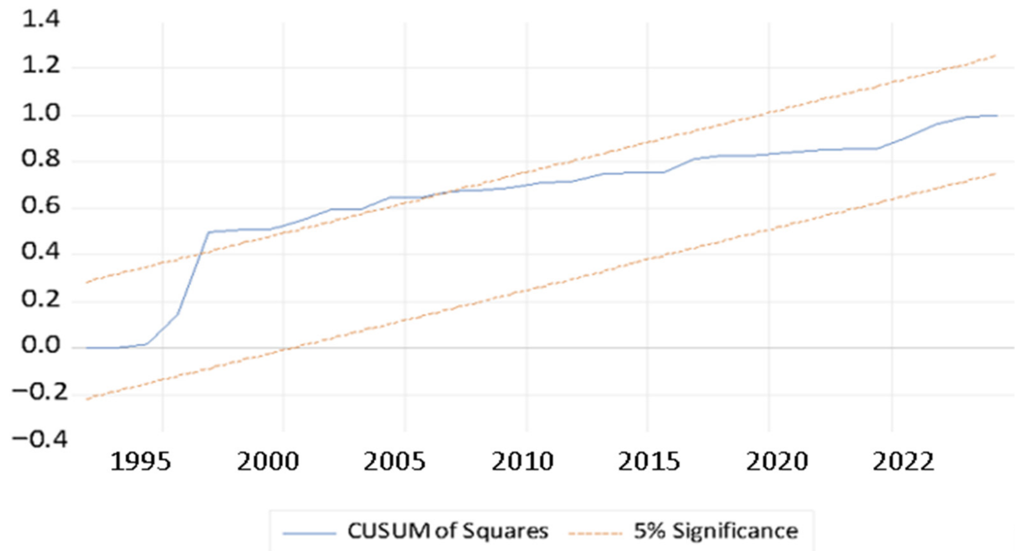

Figure 7. CUSUMSQ Stability Test for Romania. Note: The straight lines represent the 5% significance bounds.

5. Discussions

The empirical findings of this study provide important insights into the determinants of environmentally sustainable growth in Turkey and Romania. The ARDL bounds testing results offer partial evidence of long-run relationships among environmentally sustainable growth, carbon emissions, life expectancy, renewable energy consumption, education, and technological innovation. Although the calculated F-statistics fall within the inconclusive region for both countries, the error correction terms are negative and statistically significant. This finding indicates that short-run deviations from equilibrium are corrected over time, supporting the presence of a stable long-run adjustment mechanism in both economies. The estimated speed of adjustment suggests that the convergence toward equilibrium occurs more rapidly in Romania than in Turkey, indicating differences in the structural dynamics of the two economies.

The long-run coefficient estimates reveal heterogeneous patterns between the two countries. In the case of Turkey, the education proxy measured by the secondary school enrollment gender parity index (LOGSE) emerges as the only statistically significant determinant of environmentally sustainable growth, whereas carbon emissions, life expectancy, renewable energy consumption, and technological innovation do not exhibit statistically significant long-run effects. This result suggests that improvements in educational outcomes may play an important role in supporting environmentally sustainable development by strengthening human capital and increasing environmental awareness. At the same time, the limited significance of other variables may indicate that Turkey's transition toward a green economic growth trajectory remains in a relatively early stage, where the potential benefits of renewable energy investments and technological innovation may take longer to materialize.

In contrast, the results for Romania suggest a different pattern of long-run relationships. Carbon emissions and life expectancy display statistically significant positive relationships with environmentally sustainable growth, whereas renewable energy consumption, education, and technological innovation do not appear as statistically significant long-run determinants. These findings may reflect Romania's structural transformation following its accession to the European Union, which accelerated policy alignment with EU environmental regulations and energy transition strategies. As a result, institutional reforms and regulatory frameworks may have played a significant role in shaping the country's environmentally sustainable growth dynamics.

The short-run dynamics further highlight cross-country differences. The block Granger causality analysis indicates that, for Turkey, carbon emissions, education, and technological innovation exhibit predictive power for environmentally sustainable growth. In Romania, renewable energy consumption, carbon emissions, and education are found to Granger-cause environmentally sustainable growth in the short run. These results suggest that the short-run drivers of green economic growth differ across the two countries, reflecting variations in institutional capacity, environmental policies, and energy transition pathways.

The findings of this study are broadly consistent with previous empirical research emphasizing the importance of human capital development, technological innovation, and renewable energy transition as key drivers of environmentally sustainable economic growth. For instance, studies such as Khan et al. and Apergis and Payne highlight the role of renewable energy adoption and technological progress in supporting environmentally sustainable economic performance. Similarly, previous studies in the green growth literature emphasize that improvements in human capital and innovation capacity can facilitate the transition toward low-carbon and environmentally sustainable economic structures. These results are also consistent with more recent contributions such as Liu et al. (2024) [12] and Ahmad et al. (2025) [24], which highlight the importance of renewable energy transition and technological innovation in promoting sustainable economic development.

However, the results of this study also indicate that the effects of these factors are not uniform across countries. While some studies suggest homogeneous relationships between environmental indicators and economic development, the findings presented here demonstrate that the magnitude and significance of these relationships vary across national contexts. This divergence supports the argument that green growth dynamics are shaped by country-specific institutional structures, policy frameworks, and stages of economic development.

Several structural factors may explain the observed differences between Turkey and Romania. Romania's accession to the European Union has accelerated its alignment with EU environmental regulations, renewable energy targets, and climate policy frameworks. This process has contributed to stronger institutional coordination and policy consistency in areas such as renewable energy development and environmental governance. In contrast, Turkey's transition toward environmentally sustainable growth has followed a more gradual path, influenced by domestic economic priorities, energy dependence, and evolving environmental policy frameworks.

From a policy perspective, the findings highlight the importance of country-specific strategies in promoting environmentally sustainable growth. In Turkey, strengthening the effectiveness of education systems and innovation policies may help enhance the role of human capital in supporting green economic transformation. Policies aimed at expanding renewable energy investments, improving technological capabilities, and integrating environmental objectives into economic planning may accelerate the transition toward sustainable growth. For Romania, maintaining stable renewable energy policies and strengthening technological innovation capacity appear particularly important for sustaining environmentally sustainable growth in the long run.

Overall, the results suggest that environmentally sustainable growth emerges from a complex interaction between economic, social, technological, and environmental factors. The observed differences between Turkey and Romania demonstrate that green economic transformation does not follow a single universal pathway. Instead, the effectiveness of green growth strategies depends largely on institutional capacity, policy coherence, and structural characteristics specific to each country.

6. Policy Implications

The findings of this study offer several important policy implications. For Turkey, the rapid adjustment toward long-run equilibrium suggests a flexible economic structure; however, the limited contribution of education and technological innovation indicates the need for policies that better align human capital development with green economic objectives. Strengthening green R&D incentives and improving the effectiveness of education–labor market linkages are crucial for enhancing sustainable growth. For Romania, the significant role of renewable energy and technological innovation highlights the effectiveness of EU-aligned environmental and energy policies. Continued investment in renewable energy infrastructure and innovation-supporting institutions is essential to sustain green economic growth. Policymakers should also address demographic and structural challenges that may hinder long-term sustainability.

7. Conclusions

This study investigates the determinants of green economic growth in Turkey and Romania over the period 1980–2023 by integrating economic, environmental, and social dimensions within a unified empirical framework. Using unit root tests that account for structural breaks and the ARDL bounds testing approach, the analysis captures both long-run equilibrium relationships and short-run dynamics. The findings suggest the presence of potential long-run interactions between green economic growth and carbon emissions, life expectancy, renewable energy consumption, education, and technological innovation in both countries. The empirical results reveal substantial cross-country heterogeneity in green growth dynamics. Turkey is characterized by a relatively fast speed of adjustment toward long-run equilibrium, indicating a flexible but crisis-sensitive economic structure. However, the long-run contributions of education and technological innovation to green economic growth remain limited, suggesting structural inefficiencies in transforming human capital and innovation capacity into sustainability-oriented outcomes. In contrast, Romania's green economic growth is predominantly driven by renewable energy adoption and technological innovation, reflecting the effectiveness of EU-aligned environmental and energy policies. These differences highlight the importance of institutional quality, policy coherence, and structural conditions in shaping green growth trajectories. Overall, the empirical findings provide suggestive evidence of long-run associations between green economic growth and its key economic, environmental, and social determinants. Renewable energy consumption, technological innovation, and education emerge as central elements within the green growth system, although their effects differ across countries depending on institutional and structural conditions. While renewable energy and technological innovation contribute positively to green economic growth—particularly in Romania—their impacts are more limited and context-dependent in Turkey. The relationship between carbon emissions and life expectancy does not exhibit a robust and stable long-run pattern, suggesting that health outcomes are shaped by broader socio-economic and policy factors rather than direct environmental channels alone. Taken together, these findings provide partial empirical support for the proposed hypotheses and highlight the heterogeneous and interconnected nature of green economic growth dynamics. Despite its contributions, this study has certain limitations. The analysis focuses on two countries, which may limit the generalizability of the results, and relies on proxy variables—particularly adjusted net savings and patent applications—that may not fully capture the multidimensional nature of green economic growth. Future research could extend this framework by incorporating a broader set of countries, alternative green growth indicators, and institutional quality measures, as well as by employing panel or nonlinear modeling approaches. Such extensions would provide deeper insights into the diverse pathways through which sustainable and green economic growth can be achieved across different economic and institutional settings. Overall, these findings highlight the importance of country-specific institutional structures and policy frameworks in shaping environmentally sustainable growth trajectories.

8. Limitations and Future Research

Despite its empirical contributions, this study has several limitations. First, the analysis focuses on only two countries, which may restrict the generalizability of the findings. Second, the use of proxy variables—particularly adjusted net savings as an indicator of environmentally sustainable growth and patent applications as a measure of technological innovation—may not fully capture the multidimensional nature of sustainable development. In particular, the education variable reflects gender parity in school enrollment rather than the level or quality of human capital, while total patent applications may not fully capture domestic innovation capacity, as the measure also includes nonresident patents.

In addition, potential endogeneity and omitted variable bias cannot be entirely ruled out in time-series analyses. Future research may therefore compare the present findings with alternative indicators such as carbon intensity, green total factor productivity, or other environmental sustainability measures. Furthermore, extending the analysis to a broader set of countries and incorporating additional institutional or policy variables could provide deeper insights into the determinants of environmentally sustainable growth. Future studies may also apply panel data techniques or nonlinear modeling approaches to further explore the dynamics of green economic growth.

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