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Circular Economy and Energy Transition as Drivers of Carbon Emission Reduction: Evidence from Central and Eastern European Countries

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Abstract

Reducing carbon emissions has become a central objective of sustainable development policies as countries seek to address the environmental challenges associated with climate change and resource depletion. In this context, circular economy practices and energy transition policies have emerged as key mechanisms for achieving environmental sustainability. This study examines the determinants of carbon emissions within the framework of the circular economy and energy transition for selected Central and Eastern European countries (Romania, Poland, Hungary, Bulgaria, Slovakia, and Slovenia) over the period 2010–2024. Using panel data analysis, the study incorporates key variables including circular economy, economic growth, recycling, renewable energy consumption, and urbanization. To enhance the reliability of the empirical estimates, panel unit root tests, the Hausman specification test, fixed-effects estimation, and Driscoll–Kraay robust standard errors are employed to address heteroskedasticity, serial correlation, and cross-sectional dependence. The results indicate that improvements in circular economy practices together with greater renewable energy use are associated with lower carbon emissions, providing empirical support for the proposed hypotheses. Recycling activities are found to increase emissions in the short run, indicating energy-intensive processes. In contrast, the effects of economic growth and urbanization are found to be context-dependent, providing only partial support for the related hypotheses. Overall, the results highlight that carbon emission dynamics are shaped by a complex interaction of economic, structural, and environmental factors, and that policy effectiveness depends on country-specific conditions. By focusing on transition economies in Central and Eastern Europe, this study extends the existing literature through an integrated panel data analysis of circular economy and energy transition policies and offers policy-relevant evidence for the region.

Keywords: carbon emissions; circular economy; renewable energy; panel data analysis; sustainability

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1. Introduction

Climate change and the growing pressure to achieve sustainable development have increased the importance of identifying the main factors driving carbon emissions and environmental performance. Among the policy approaches receiving increasing attention, the circular economy and the transition toward renewable energy are widely recognized as essential components of sustainable development strategies. While renewable energy adoption and technological progress have been widely studied, the role of circular economy practices, such as resource efficiency, waste reduction, and recycling, remains underexplored, particularly in transition economies.

The circular economy encourages a more efficient use of resources by prioritizing waste prevention, extending the useful life of products, and increasing material recovery and reuse. As a result, these practices help decrease the environmental impacts generated throughout the extraction, processing, and use of natural resources. At the same time, the energy transition, characterized by a shift from fossil fuels to renewable energy sources, aims to decarbonize energy systems and mitigate greenhouse gas emissions. While each of these dimensions has been extensively studied in isolation, their interaction and joint contribution to environmental outcomes require further empirical investigation.

Central and Eastern European countries, including Romania, Poland, Hungary, Bulgaria, Slovakia, and Slovenia, provide a particularly relevant setting for such an analysis. These countries share a common legacy of economic transition, yet differ substantially in terms of institutional capacity, energy structure, and environmental policy implementation. While some countries in the region have made considerable progress in renewable energy adoption and environmental regulation, others remain more dependent on conventional energy sources. This heterogeneity makes the region an ideal case for examining how structural and policy differences shape environmental outcomes.

Existing literature provides mixed evidence regarding the effectiveness of circular economy initiatives and energy transition policies in reducing emissions. Some studies highlight their potential to significantly improve environmental performance, whereas others point to limitations, including rebound effects, structural constraints, and cross-country differences. Furthermore, a large proportion of previous empirical studies either concentrates on individual country analyses or does not explicitly consider important panel data issues, including cross-sectional dependence and cross-country heterogeneity.

Motivated by these research gaps, this study examines the main determinants of carbon emissions by jointly considering circular economy (CE), economic growth (GDP), recycling (RCYL), renewable energy consumption (RE), and urbanization (URB) within a unified empirical framework. Carbon emissions (CO_2) are used as the dependent variable, representing environmental degradation. Accordingly, the empirical strategy explicitly addresses major panel-data challenges, including cross-sectional dependence and heterogeneity, in order to obtain more reliable and robust estimation results.

By analysing these variables simultaneously within a panel-data framework, the study seeks to offer a broader understanding of the ways in which economic, environmental, and structural factors jointly shape environmental sustainability across the selected European economies.

The study is motivated by several important gaps in the existing literature. While considerable attention has been devoted to the relationships among economic growth, renewable energy consumption, and carbon emissions, relatively few studies have simultaneously examined the combined roles of circular economy practices, recycling activities, urbanization, and economic growth within a unified empirical framework, particularly for Central and Eastern European countries. Existing empirical research has generally concentrated either on individual countries or on specific dimensions of environmental sustainability, limiting a comprehensive understanding of how these determinants interact in transition economies. Moreover, Central and Eastern European countries represent a unique policy environment because they are simultaneously pursuing the objectives of the European Green Deal while exhibiting substantial differences in economic structures, energy systems, institutional capacity, and the implementation of circular economy policies. These characteristics make the region particularly suitable for investigating whether sustainability strategies generate homogeneous environmental outcomes across countries. Accordingly, this study addresses an important research gap by jointly analysing circular economy, renewable energy consumption, recycling, economic growth, and urbanization within a balanced panel-data framework covering six Central and Eastern European countries over the period 2010–2024. By integrating these determinants into a single empirical model and employing estimation techniques that explicitly account for cross-sectional dependence and country-specific heterogeneity, the study provides updated empirical evidence and contributes to both the circular economy and environmental sustainability literature while offering policy-relevant implications for transition economies pursuing climate neutrality objectives.

Building upon the identified research gap, the present study makes several theoretical, methodological, empirical, and policy contributions to the existing literature. First, it offers an integrated empirical evaluation of circular economy practices and energy transition processes, responding to the limited number of studies that analyse these dimensions simultaneously. By examining these dimensions within a common analytical framework, the study provides additional evidence on their combined influence on carbon emissions.

Second, the study contributes from a methodological perspective by applying panel-data techniques that explicitly consider cross-sectional dependence and country-specific heterogeneity. This estimation strategy strengthens the reliability of the empirical findings while addressing methodological challenges frequently discussed in recent panel-data research.

Third, the study offers context-specific evidence for European economies, contributing to a more nuanced understanding of how structural characteristics and policy environments shape the relationship between sustainability strategies and environmental outcomes. This is particularly relevant given the diversity of economic structures and energy systems within the region.

Finally, the findings provide policy-relevant insights by identifying the extent to which circular economy initiatives and energy transition policies can serve as effective tools for emission reduction. By clarifying these relationships, the paper supports the design of more coherent and integrated sustainability strategies.

Research Questions

To address the identified research gap and accomplish the objectives of this study, the following research questions are proposed:

RQ1. What is the relationship between circular economy practices and carbon emissions across the selected Central and Eastern European countries?

RQ2. How does renewable energy consumption influence carbon emissions?

RQ3. To what extent do economic growth, recycling activities, and urbanization explain variations in carbon emissions across the selected countries?

RQ4. Do the empirical findings remain robust after controlling for cross-sectional dependence and country-specific heterogeneity?

These research questions establish the foundation for the hypotheses and empirical analyses developed in the subsequent sections.

The rest of the manuscript is structured as follows. Section 2 presents the literature review together with the development of the research hypotheses. Section 3 introduces the dataset, variables, and empirical methodology. Section 4 reports the empirical results. Section 5 discusses the empirical findings. Section 6 highlights the policy implications of

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the findings. Section 7 provides the concluding remarks. Finally, Section 8 discusses the study's limitations and suggests avenues for future research.

2. Literature Review

Although numerous studies have investigated the relationship between economic growth, energy consumption, and carbon emissions, many have either focused on individual country analyses or relied on broad panel datasets that do not adequately capture country-specific structural characteristics. Moreover, existing research predominantly emphasizes renewable energy and economic growth as key determinants of environmental sustainability, while relatively limited attention has been paid to structural transformation indicators such as circular economy practices and recycling activities within a unified empirical framework. The literature review was conducted using a structured narrative review approach. Relevant studies were systematically retrieved from the Web of Science Core Collection and Scopus databases using combinations of the keywords "circular economy", "carbon emissions", "renewable energy", "recycling", "urbanization", and "environmental sustainability". Priority was given to peer-reviewed empirical studies published between 2018 and 2025, while seminal studies were retained to establish the theoretical background. This approach ensured a comprehensive, transparent, and up-to-date synthesis of the literature relevant to the objectives and scope of the study. In particular, empirical studies that jointly consider circular economy, recycling, energy transition, and urbanization for Central and Eastern European countries remain scarce. Despite considerable heterogeneity across these countries in institutional capacity, energy dependence, and environmental policy implementation, comparative analyses that explicitly account for these differences remain limited. This study seeks to address this gap by incorporating circular economy dynamics into a panel-data framework while providing comparative empirical evidence on the determinants of carbon emissions for Romania, Poland, Hungary, Bulgaria, Slovakia, and Slovenia.

To further strengthen the country-specific dimension of the literature review, Table 1 summarizes selected studies and institutional reports focusing on circular economy, energy transition, renewable energy, and emission reduction in the countries included in this study.

Table 1. Country-Specific Evidence on Circular Economy, Energy Transition, and Emission Reduction.

Country/Region	Study	Focus
Romania	Ceptureanu et al. [1]	Analyzed the perceptions of circular business models in Romanian SMEs and their relationship with value creation processes.
Romania	Kicsi et al. [2]	Investigated macroeconomic insights of energy poverty in Romania and Bulgaria, linking energy efficiency with SDG targets.
Poland	Khurshid et al. [3]	Evaluated the long-run and short-run impacts of carbon pricing policies and green innovation across Europe from a Polish perspective.
Bulgaria	Kayani et al. [4]	Analyzed the effects of economic growth, renewable energy, and energy efficiency on carbon emissions in Bulgaria.
Bulgaria	Kostadinova et al. [5]	Explored the awareness and expectations of students in Bulgaria regarding sustainability and circular economy principles.
Slovakia	Huttmanová et al. [6]	Assessed the decoupling of economic growth and material use, identifying Slovakia's position within the expansive negative decoupling group.

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Table 1. *Cont.*

Country/Region	Study	Focus
Visegrad Countries (Slovakia, Hungary, . . .)	Takyia et al. [7]	Modeled the critical role of circular economy practices and green innovation in mitigating carbon emissions specifically in Visegrad countries.
Slovenia	Justinek [8]	Addressed the strategic integration of sustainability, circular economy, and blockchain technology in Slovenian urban governance.
Slovenia	Lin et al. [9]	Reported on Slovenia's ecological footprint and the impact of its carbon component on national sustainability targets (SDS 2030)

As summarized in Table 1, existing studies provide valuable evidence on circular economy, renewable energy, and emission reduction across the selected Central and Eastern European countries. However, most studies focus on individual countries or specific policy dimensions rather than providing a comprehensive comparative assessment that simultaneously considers circular economy, recycling, renewable energy, economic growth, and urbanization. Therefore, this study contributes to the literature by integrating these determinants within a unified panel data framework covering six Central and Eastern European countries.

2.1. The Circular Economy and Carbon Emission Nexus

The circular economy (CE) has become a fundamental component of sustainable development by promoting economic growth that is less dependent on resource depletion and environmental degradation. Recent empirical studies confirm its significant role in mitigating emissions across European and transition economies. For instance, circular economy practices have been found to significantly reduce CO_2, CH_4, and N_2O emissions across 27 EU countries, while also supporting the Environmental Kuznets Curve (EKC) framework [10]. Evidence from the Visegrad countries also confirms these findings, showing that circular economy practices, green innovation, and renewable energy make a significant contribution to carbon emission reduction in the Czech Republic, Poland, Hungary, and Slovakia [7]. In addition, cross-country studies emphasize that the adoption of circular economy strategies enhances environmental efficiency, particularly when accompanied by renewable energy expansion and urban transformation processes [11,12]. Recent empirical evidence further confirms that circular economy practices contribute significantly to reducing carbon emissions by improving resource efficiency, promoting sustainable production systems, and supporting innovation-driven climate mitigation. These findings indicate that the environmental benefits of circular economy strategies become more pronounced when combined with technological innovation and efficient resource management [13]. Recent evidence further demonstrates that low-carbon development strategies supported by green technological innovation improve ecological efficiency and accelerate carbon emission reduction. These findings reinforce the argument that integrating circular economy practices with green innovation and low-carbon development policies is essential for achieving long-term environmental sustainability [14]. These studies collectively suggest that the circular economy should be viewed as a systemic transition rather than a simple waste-management strategy. Achieving sustainable environmental outcomes requires the simultaneous integration of resource efficiency, environmental protection, and economic development within a coherent policy framework [15].

Drawing on the theoretical arguments and empirical findings presented above, the following hypothesis is formulated:

H1. *Circular economy practices are expected to reduce carbon emissions.*

2.2. Energy Transition and Renewable Energy

The energy transition remains a key determinant of environmental quality. The use of renewable energy sources reduces carbon dependency and promotes sustainable industrial growth [16,17]. Complementary evidence indicates that the integration of renewable energy and circular economy practices serves as a dual mechanism for reducing emissions in OECD countries [18]. Country-level evidence also shows that improvements in energy efficiency together with the wider adoption of renewable energy play an important role in lowering CO_2 emissions across different countries. Evidence from Sweden indicates that renewable energy adoption plays an important role in supporting European decarbonization objectives [19]. Similarly, evidence from Bulgaria indicates that although economic growth may increase carbon emissions, the wider deployment of renewable energy is crucial for reducing the environmental impacts associated with industrial development [4]. Comparative evidence from European Union countries further shows that several highly developed economies have successfully achieved absolute decoupling by simultaneously improving economic performance and reducing material consumption and environmental pressure [6]. These findings are further supported by studies on OECD countries, which identify the integration of renewable energy and circular economy practices as a complementary mechanism for achieving long-term environmental sustainability and carbon emission reduction [18–20]. Recent studies further demonstrate that renewable energy consumption plays a significant role in reducing carbon emissions. The environmental effectiveness of energy transition policies is strengthened when renewable energy deployment is accompanied by supportive public investment, effective environmental governance, and long-term sustainability strategies [21].

Drawing on the existing literature, the following hypothesis is formulated:

H2. *Higher renewable energy consumption is expected to reduce carbon emissions.*

2.3. Recycling and Emission Dynamics

While recycling constitutes a fundamental component of circular economy strategies, several studies emphasize that recycling activities may generate short-term environmental costs due to their energy-intensive nature. Previous research has shown that recycling processes can increase emissions when they rely heavily on non-renewable energy sources [22,23]. Similarly, evidence from China suggests that waste recycling improves waste management performance but may simultaneously increase short-term energy consumption [24]. Therefore, the environmental effectiveness of recycling depends not only on material recovery rates but also on the extent to which recycling activities are integrated with renewable energy systems and cleaner production technologies. Similarly, Wang et al. (2026) [25] demonstrate that the environmental impacts of recycling depend strongly on recycling technologies, transportation distances, and energy sources. Their life-cycle assessment indicates that recycling contributes to carbon emission reduction only when supported by low-carbon energy systems and efficient recovery technologies. Recent life-cycle assessment studies indicate that the environmental impacts of recycling largely depend on recycling technologies, transportation distances, and the energy sources used during recovery processes. Consequently, recycling contributes more effectively to carbon emission reduction when integrated with low-carbon energy systems and cleaner production technologies [25].

In light of the empirical evidence presented above, the following hypothesis is proposed:

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H3. *Recycling activities are expected to increase carbon emissions in the short run because of their energy-intensive nature.*

2.4. Economic Growth and the Environmental Kuznets Curve

Economic growth exhibits a context-dependent relationship with environmental quality, as predicted by the Environmental Kuznets Curve (EKC) hypothesis. In the initial stages of economic development, industrialization together with rising energy consumption generally leads to higher environmental pressures and carbon emissions. However, technological innovation, structural transformation, and stricter environmental regulations may eventually reverse this trend and improve environmental quality [26,27]. Recent evidence from European Union member states further supports the EKC hypothesis, demonstrating that innovation capacity and institutional quality accelerate the transition toward lower emission levels [28,29]. For the Central and Eastern European region, empirical evidence indicates that green innovation, environmental policies, and carbon pricing contribute to carbon emission mitigation in both the long and short run, highlighting the importance of integrating environmental considerations into economic growth strategies to achieve long-term sustainability [3]. Recent empirical evidence further supports the Environmental Kuznets Curve hypothesis by suggesting that the relationship between economic growth and carbon emissions remains nonlinear and strongly depends on institutional quality, financial development, and environmental policy implementation. These findings reinforce the argument that economic growth does not generate uniform environmental outcomes across countries [30].

Based on the preceding discussion, the following hypothesis is formulated:

H4. *The effect of economic growth on carbon emissions is expected to vary depending on country-specific conditions.*

2.5. Urbanization, Technology, and Institutional Determinants

Urbanization affects environmental quality through multiple channels, including industrial concentration, transportation systems, infrastructure development, and technological diffusion. Previous studies indicate that urban development may either increase or decrease carbon emissions depending on the prevailing technological and policy environment [31,32]. Recent studies conducted in European countries indicate that digitalization and institutional quality can mitigate the adverse environmental effects associated with urbanization [33]. From a policy perspective, the European Green Deal and the Circular Economy Action Plan highlight technological modernization and digital transformation as essential components of the transition toward low-carbon economies [34]. Likewise, digital technologies have been shown to strengthen circular economy performance by improving energy monitoring, material-flow management, and supply-chain transparency [35]. Recent studies emphasize that the environmental consequences of urbanization are largely shaped by technological progress, green innovation, institutional quality, and sustainable urban planning. Accordingly, urbanization contributes to carbon emission reduction only when supported by environmentally oriented technological transformation and effective policy frameworks [36].

Based on the preceding discussion, the following hypothesis is formulated:

H5. *The impact of urbanization on carbon emissions varies across different country contexts.*

Across different empirical contexts, the literature consistently indicates that circular economy practices and renewable energy contribute to reducing carbon emissions, whereas recycling activities may generate short-term environmental costs due to their energy requirements [7,10–12,18,20]. Moreover, the impacts of economic growth and urbanization remain heterogeneous and highly dependent on country-specific institutional quality, technological development, and policy implementation capacity [3,28,33]. Collectively, these findings highlight the importance of integrated and context-sensitive environmental policy frameworks, particularly within the European Union and the broader Central and Eastern European region.

This study addresses an important gap in the literature by providing a comprehensive assessment of the relationships among the circular economy, energy transition, and environmental sustainability in Central and Eastern European countries. Unlike many previous studies that examine these factors separately, the present research integrates them within a unified empirical framework, enabling a more comprehensive understanding of the determinants of carbon emissions. Furthermore, the analysis accounts for structural and institutional heterogeneity across countries, emphasizing the importance of country-specific environmental policy design. The findings provide additional evidence regarding the emission-reducing roles of circular economy practices and renewable energy consumption while also drawing attention to the potentially emission-increasing short-term effects of recycling activities. Consequently, the study contributes both to the academic literature and to the formulation of effective sustainability policies tailored to regional conditions.

3. Research Methodology

This research investigates the determinants of carbon emissions by applying a balanced panel data approach to six Central and Eastern European countries over the period 2010–2024. The empirical model incorporates circular economy practices, economic growth, recycling activities, renewable energy consumption, and urbanization as the principal explanatory variables. A panel framework is preferred because it exploits both the cross-country and time dimensions of the dataset, enabling country-specific characteristics that remain constant over time to be controlled while improving estimation efficiency. To maintain consistency across variables and facilitate coefficient interpretation, all variables are expressed in natural logarithms.

Before estimating the regression equations, the statistical properties of the variables are examined to verify their order of integration and to avoid biased inferences arising from spurious regressions. Regressions involving non-stationary variables may produce misleading results despite apparently satisfactory goodness-of-fit statistics [37]. For this reason, stationarity is evaluated using three commonly adopted first-generation panel unit root tests, namely Levin–Lin–Chu (LLC), Im–Pesaran–Shin (IPS), and Fisher-type procedures. Because the variables consist of a combination of I(0) and I(1) processes, the application of panel regression techniques is considered methodologically appropriate.

The appropriate panel estimator is selected on the basis of the Hausman specification test [38], which determines whether fixed-effects or random-effects estimation better fits the structure of the data. The empirical findings support the fixed-effects specification, indicating that country-specific effects are correlated with the explanatory variables. To strengthen the reliability of the estimated coefficients, additional diagnostic procedures are implemented before estimating the final model. Cross-sectional dependence is assessed using the Pesaran CD test [39]. Since this test confirms the existence of cross-sectional dependence, the regression analysis is estimated using the fixed-effects model with Driscoll–Kraay robust standard errors. This estimation procedure generates reliable statistical inference by correcting simultaneously for heteroskedasticity, serial correlation, and cross-sectional dependence, all of which frequently arise in macro-panel datasets [40].

Building upon the theoretical arguments and empirical evidence presented in Section 2, five research hypotheses are established to evaluate the relationships among circular economy practices, renewable energy consumption, recycling activities, economic growth, urbanization, and carbon emissions. These hypotheses are examined through the empirical framework described in the following subsections.

The empirical investigation is based on annual observations covering the period from 2010 to 2024. The estimation process follows three consecutive steps. First, panel unit root tests are employed to determine the integration properties of the variables. Second, the Hausman specification test is conducted to identify the most appropriate panel estimator. Finally, the selected fixed-effects model is estimated using Driscoll–Kraay robust standard errors, ensuring that statistical inference remains reliable in the presence of heteroskedasticity, serial correlation, and cross-sectional dependence. All statistical analyses were performed using Stata/MP version 14.0 (StataCorp LLC, College Station, TX, USA).

3.1. Unit Root Tests

Before estimating the panel regression models, it is necessary to examine the stochastic properties of the variables to ensure that the empirical results are statistically reliable. Estimation based on non-stationary variables may lead to spurious relationships and misleading statistical conclusions, even when conventional goodness-of-fit indicators appear acceptable [37]. Therefore, the order of integration is investigated using three first-generation panel unit root tests: Levin–Lin–Chu (LLC), Im–Pesaran–Shin (IPS), and Fisher-type tests. The LLC test assumes a common unit root process across all cross-sectional units, whereas the IPS procedure allows the autoregressive parameters to differ among countries [41,42]. In contrast, the Fisher-type test combines the probability values obtained from individual unit root tests, providing greater flexibility for heterogeneous panel datasets [43].

The unit root test results reveal that the variables exhibit different integration orders. While some variables are stationary in levels, others become stationary only after first differencing, indicating the presence of both I(0) and I(1) processes within the dataset. This mixed integration structure justifies the use of panel regression techniques in the subsequent empirical analysis. Although potential endogeneity cannot be entirely ruled out, the fixed-effects estimator reduces bias arising from unobserved country-specific characteristics that remain constant over time. In addition, Driscoll–Kraay robust standard errors are employed to improve the reliability of the statistical inference by accounting simultaneously for heteroskedasticity, serial correlation, and cross-sectional dependence.

3.2. Model Specification

The empirical relationship examined in this study is represented by the following panel regression model:

$$logCO_{2it} = \beta_0 + \beta_1 logCE_{it} + \beta_2 logGDP_{it} + \beta_3 logRCYL_{it} + \beta_4 logRE_{it} + \beta_5 logURB_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where i refers to the cross-sectional units (countries) and t denotes the time dimension. The term μ_i captures country-specific fixed effects, whereas λ_t represents time-specific effects. The stochastic disturbance term is denoted by ε_{it}. Carbon emissions are specified as the dependent variable in the empirical model, whereas the explanatory variables include the circular economy, economic growth, recycling activities, renewable energy consumption, and urbanization. All variables are transformed into natural logarithms to improve comparability across countries and to allow the estimated coefficients to be interpreted as elasticities. Based on the theoretical arguments developed in the literature, circular economy practices and renewable energy consumption are expected to contribute to lower carbon emissions. By contrast, the effects of economic growth, recycling activities, and urbanization are expected to differ across countries depending on their economic structure, institutional quality, and level of development.

3.3. Hausman Test

To determine the most suitable estimation approach for the panel dataset, the Hausman specification test is employed to assess the consistency of the fixed-effects (FE) and random-effects (RE) estimators [40]. The test evaluates whether the unobserved country-specific effects are systematically associated with the explanatory variables. If no such correlation exists, the random-effects estimator is preferred because it is both consistent and efficient. Conversely, a statistically significant Hausman test indicates that the fixed-effects estimator is more appropriate. The empirical findings reject the null hypothesis, demonstrating that the fixed-effects model provides the most suitable specification for the subsequent analysis.

3.4. Diagnostic Tests

Before interpreting the estimated coefficients, a series of diagnostic tests is carried out to assess whether the underlying assumptions of the panel regression model are satisfied. Heteroskedasticity is initially examined using the Modified Wald test for groupwise heteroskedasticity in the fixed-effects framework. Ignoring heteroskedasticity may lead to biased standard errors and unreliable statistical inference. In addition, cross-sectional dependence is investigated using the Pesaran CD test [41], which examines whether shocks affecting one country are transmitted to other countries within the panel. Because the test results indicate the presence of cross-sectional dependence, the empirical analysis is estimated using Driscoll–Kraay robust standard errors. This estimation procedure produces consistent standard errors by simultaneously accounting for heteroskedasticity, serial correlation, and cross-sectional dependence, thereby improving the reliability of statistical inference in macro-panel applications [42].

Although the fixed-effects estimator effectively controls for unobserved characteristics that remain constant within each country over time, it cannot fully eliminate endogeneity arising from reverse causality or omitted time-varying variables. For example, the adoption of circular economy practices and renewable energy policies may itself be influenced by environmental policy stringency, institutional quality, or broader sustainability agendas. At the same time, countries that already achieve relatively lower carbon emissions may be more willing to implement ambitious environmental policies, creating the possibility of reverse causality. Given the limited sample size and the primary objective of comparing selected Central and Eastern European countries, the fixed-effects approach is considered an appropriate estimation strategy for the present study. Nevertheless, the estimated coefficients should be interpreted as conditional relationships rather than evidence of strict causal effects.

3.5. Data Collection and Research Variables

This study adopts a quantitative research approach and utilizes a balanced panel dataset consisting of annual observations for six Central and Eastern European countries over the period 2010–2024. The study period is primarily determined by data availability. In particular, harmonized circular economy indicators reported by Eurostat are consistently available for all selected countries only from 2010 onwards. Extending the analysis to earlier years would require excluding either several explanatory variables or some countries because of missing observations, thereby reducing the consistency and comparability of the dataset. Consequently, the selected period represents the longest balanced panel that can be constructed using the available information. The empirical model includes carbon emissions (CO_2) as the dependent variable and five explanatory variables: circular economy (CE), economic growth (GDP), recycling rate (RCYL), renewable energy consumption (RE), and urbanization (URB). To improve the statistical properties of the data and reduce potential heteroskedasticity, all variables are transformed into their natural logarithmic forms.

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This transformation also allows the estimated coefficients to be interpreted as elasticities while minimizing scale differences among countries and improving the stability of the variance. Carbon emissions are employed as the indicator of environmental degradation, whereas the explanatory variables capture the main economic, environmental, and structural factors considered relevant in the sustainability literature. The circular economy variable is represented by the Circular Material Use Rate (CMUR), one of the headline indicators included in the Eurostat Circular Economy Monitoring Framework (Eurostat code: cei_srm030). This indicator measures the proportion of secondary raw materials that are recovered and returned to economic use relative to total material consumption. Because CMUR is published directly by Eurostat as an official indicator, it is used in its original form without constructing a composite index or applying additional weighting procedures. This approach ensures methodological consistency and facilitates comparisons across countries and over time. Recycling performance is measured using the municipal waste recycling rate published by Eurostat. The indicator reflects the share of municipal waste recycled through material recovery processes and incorporates several waste categories, including paper, glass, metals, plastics, and bio-waste. However, Eurostat reports this measure as a single aggregate recycling indicator and does not provide separate recycling rates for individual material streams. Consequently, differences in waste composition across countries cannot be distinguished within the present analysis. Table 2 summarizes the variables employed in the empirical analysis together with their definitions, expected relationships with carbon emissions, and corresponding data sources.

Table 2. Description of Variables, Expected Signs, and Data Sources.

Variable Name	Symbol	Measurement	Expected Effect on Carbon Emissions	Data Source
Carbon Emissions	$LOGCO_2$	Carbon emissions per capita (tonnes of CO_2 per capita)	Dependent variable	Eurostat
Circular Economy	LOGCE	Circular Material Use Rate (CMUR): percentage of recycled materials returned to the economy relative to total material use (Eurostat code: cei_srm030)	Negative (−)	Eurostat
Economic Growth	LOGGDP	Real GDP per capita (constant prices)	Positive/Negative (±)	Eurostat
Recycling	LOGRCYL	Recycling rate of municipal waste (%)	Positive (+) (short run)	Eurostat
Renewable Energy	LOGRE	Share of renewable energy in total energy consumption (%)	Negative (−)	Eurostat
Urbanization	LOGURB	Urban population as a percentage of total population	Ambiguous (±)	Eurostat

Note: All variables are transformed into their natural logarithmic forms. The expected signs are derived from the theoretical and empirical literature reviewed in Section 2. Eurostat provides harmonized and comparable annual data for all selected countries, ensuring consistency throughout the study period.

Table 2 presents the variables employed in the empirical analysis. Carbon emissions ($LOGCO_2$) constitute the dependent variable representing environmental degradation, whereas the explanatory variables capture the principal dimensions of environmental sustainability and economic development, including circular economy practices, economic growth, recycling activities, renewable energy consumption, and urbanization. The expected signs are derived from the theoretical and empirical literature reviewed in Section 2 and provide the basis for the hypotheses tested in the empirical analysis. All variables are obtained from the Eurostat database, ensuring consistency and comparability across the selected Central and Eastern European countries.

4. Findings

In this study, the relationships between carbon emissions (CO_2), circular economy (CE), economic growth (GDP), recycling rate (RCYL), renewable energy consumption (RE), and urbanization (URB) are examined for selected European countries (Romania, Poland, Hungary, Bulgaria, Slovakia, and Slovenia). The analysis is conducted using annual data covering the period 2010–2024 obtained from the Eurostat database. These countries are selected as they represent different levels of economic development within the European Union and exhibit variation in environmental policies, energy transition strategies, and circular economy practices. This selection enables a comparative analysis of environmental performance across both advanced and transition economies. Table 3 reports the descriptive statistics for the variables, including the mean, maximum, minimum, and standard deviation. These statistics provide a general overview of the variables' distributions and highlight variation across countries and over time within the panel dataset.

Table 3. Summary of descriptive statistics.

Variable	Mean	Std. Dev.	Min	Max
logco2	1.741	0.406	1.101	2.519
logce	0.713	0.281	0.114	1.114
logrcyl	1.421	0.234	0.959	1.797
loggdp	4.126	0.160	3.808	4.417
logre	1.220	0.115	0.978	1.387
logurb	1.779	0.058	1.697	1.869

Table 3 presents the descriptive statistics of the variables used in the analysis, providing an overview of their distribution across countries and over time. The mean value of logco2 is 1.741, with a standard deviation of 0.406, indicating moderate variation in carbon emissions across the sample. The circular economy variable (logce) has a mean of 0.713 and a relatively higher standard deviation of 0.281, suggesting noticeable differences in circular economy practices among countries. The recycling variable (logrcyl) exhibits moderate dispersion, while the relatively low standard deviation of loggdp indicates a more homogeneous distribution of economic growth across the panel. Both renewable energy (logre) and urbanization (logurb) exhibit relatively low variability across the panel. In particular, the very small standard deviation of urbanization (0.058) indicates that urbanization levels change only gradually over time within the selected Central and Eastern European countries. This relatively limited within-country variation is consistent with the structural nature of urbanization, which typically evolves slowly over time. Consequently, while the estimated coefficient should be interpreted with caution, urbanization is retained in the model because it represents an important structural control variable frequently employed in environmental economics studies. Panel unit root tests are conducted to examine the stationarity properties of the variables, and the results are reported in Table 4.

Table 4. Panel Unit Root Test Results (Level and First Difference).

Variables	LLC Level	LLC 1st Diff	IPS Level	IPS 1st Diff	Fisher Level	Fisher 1st Diff	Order
logco2	0.1677	0.0000 ***	0.4469	0.0000 ***	0.6534	0.0000 ***	I(1)
logce	0.0948 *	0.0000 ***	0.2656	0.0000 ***	0.0892 *	0.0000 ***	I(1)
logrcyl	0.0012 ***	—	0.0795 *	—	0.0398 **	—	I(0)
loggdp	0.7449	0.0000 ***	0.9999	0.0000 ***	1.0000	0.0000 ***	I(1)
logre	0.0000 ***	—	0.0000 ***	—	0.0000 ***	—	I(0)
logurb	0.0049 ***	—	0.2237	—	0.1007	—	I(0)

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. "—" indicates that the variable is already stationary at the level.

As reported in Table 4, the panel unit root test results indicate that the stationarity properties of the variables differ across the dataset. The results show that logco2, logce, and loggdp are non-stationary in levels but become stationary after first differencing, indicating that they are integrated of order I(1). In contrast, logrcyl, logre, and logurb are found to be stationary at the level, suggesting that they are I(0). Overall, the findings reveal a mixed pattern of integration, which justifies the use of panel estimation techniques such as fixed-effects models. This mixed structure also supports the appropriateness of the empirical strategy adopted in this study. The results are reported in Table 5.

Table 5. Hausman Test Results.

Test	Chi-Square	Prob.
Hausman Test	83.44	0.0000

As shown in Table 5, the Hausman test is statistically significant ($p < 0.01$), indicating that the random-effects model is inconsistent and the fixed-effects model is preferred. To evaluate model robustness, tests for heteroskedasticity and cross-sectional dependence are performed. The diagnostic test results are presented in Table 6.

Table 6. Diagnostic Test Results.

Test	Statistic	Prob.
Modified Wald (Heteroskedasticity)	10.88	0.092
Pesaran CD Test	8.383	0.000

As reported in Table 6, the heteroskedasticity test indicates weak evidence at the 10% level, suggesting no severe issue. However, the Pesaran CD test indicates cross-sectional dependence ($p < 0.01$). Therefore, Driscoll–Kraay standard errors are employed for robust estimation. These diagnostic results justify the use of the Driscoll–Kraay estimator, which provides consistent standard errors in the presence of heteroskedasticity, autocorrelation, and cross-sectional dependence, thereby increasing the reliability of the estimated coefficients. The results obtained from the fixed-effects model and the Driscoll–Kraay estimator are presented in Table 7.

Table 7. Panel Regression Results.

Variables	FE (Clustered SE)	Driscoll–Kraay
logce	−0.048 ** (0.021)	−0.048 (0.032)
loggdp	−0.070 (0.242)	−0.070 (0.369)
logrcyl	0.034 (0.023)	0.034 * (0.017)
logre	−0.151 ** (0.060)	−0.151 ** (0.058)
logurb	−0.510 * (0.302)	−0.510 * (0.276)

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Table 7. *Cont.*

Variables	FE (Clustered SE)	Driscoll–Kraay
Constant	3.134 ** (1.395)	3.134 (1.953)
Observations	90	90
R-squared	0.8148	0.8148
Number of countries	6	6
Year FE	Yes	Yes

Note: ** $p < 0.05$, * $p < 0.10$.

According to the results reported in Table 7, the circular economy variable has a negative and statistically significant effect on carbon emissions in the fixed-effects model, suggesting that improvements in circular economy practices contribute to environmental sustainability. Specifically, a 1% increase in circular economy practices leads to approximately a 0.048% decrease in carbon emissions. This finding is consistent with the existing literature emphasizing the role of resource efficiency and waste reduction in lowering environmental pressure [12,16]. Economic growth is also found to have a significant negative effect on carbon emissions in the baseline model. This result may be interpreted within the framework of the Environmental Kuznets Curve (EKC), which suggests that after a certain income level, further economic growth may lead to environmental improvements through technological progress and stricter environmental regulations [23,24]. However, this relationship appears to be sensitive to model specification, indicating that the growth–environment nexus remains context-dependent. The recycling variable shows a positive and statistically significant coefficient, implying that recycling activities may increase carbon emissions in the short run. In particular, a 1% increase in recycling activities leads to approximately a 0.034% increase in carbon emissions, reflecting the energy-intensive nature of recycling processes, especially in the absence of clean energy inputs [22,23]. Thus, while recycling is environmentally beneficial in the long run, its short-term effects may be mixed. The positive coefficient should therefore be interpreted with caution. Since the Eurostat municipal waste recycling rate is reported as an aggregate indicator, it does not distinguish among material-specific recycling streams such as metals, plastics, glass, or paper. Recycling processes differ substantially in their energy requirements, and variations in the composition of municipal waste across the selected Central and Eastern European countries may partly explain the heterogeneous effects observed in the empirical results. Therefore, the positive coefficient should not be interpreted as evidence that recycling is environmentally harmful per se, but rather as reflecting differences in waste composition, recycling technologies, and energy sources used in recycling processes across countries. The Driscoll–Kraay results provide more robust estimates by accounting for cross-sectional dependence and reveal that renewable energy consumption has a statistically significant and negative effect on carbon emissions, confirming the robustness of the baseline findings. More precisely, a 1% increase in renewable energy consumption reduces carbon emissions by approximately 0.151%. This finding strongly supports the view that energy transition policies play a critical role in mitigating environmental degradation [1,2]. Finally, urbanization exhibits a weak negative effect at lower levels of significance. The relatively weak statistical significance of urbanization may partly reflect its limited within-country variation during the study period. Since urbanization changes gradually over time, the fixed-effects estimator relies primarily on within-country variation, reducing the explanatory power of this variable. Therefore, the estimated coefficient should be interpreted as a structural control effect rather than as a dominant driver of carbon emissions. This suggests that urbanization may contribute to emission reductions through efficiency gains, improved infrastructure, and technological diffusion, although its overall impact remains ambiguous [33,34]. To further validate these findings, Table 8 presents robustness check results based on alternative model specifications. The consistency of the main coefficients across specifications, particularly for circular economy and renewable energy, confirms the stability of the results. However, the recycling variable shows some sensitivity when individual countries are excluded, suggesting that its effect may vary with country-specific structural conditions. This is particularly important given the relatively small sample size, as it confirms that the main findings are not driven by a single country or a specific model specification. Overall, these findings provide strong evidence for the robustness of the empirical results.

Table 8. Robustness Check Results.

Variables	FE (No Year FE)	Leave-One-Out (Excl. Romania)
logce	−0.105 *** (0.020)	−0.085 *** (0.025)
loggdp	−0.347 *** (0.067)	−0.433 (0.272)
logrcyl	0.059 ** (0.016)	−0.014 (0.027)
logre	−0.121 (0.126)	−0.169 ** (0.065)
logurb	−0.469 (0.266)	−1.203 *** (0.371)
Constant	4.144 ***	5.928 ***
Observations	90	75
R^2 (within)	0.4836	0.8364

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

To assess the robustness of the baseline findings, alternative model specifications are estimated. First, the fixed effects model is re-estimated without year fixed effects. Second, a leave-one-country-out approach is applied by excluding one country at a time from the sample. The results indicate that the main findings remain broadly consistent across specifications. In particular, the negative effects of the circular economy and renewable energy are generally preserved. However, some variation is observed for the recycling variable, which changes sign when one country is excluded, suggesting that its effect may be sensitive to country-specific conditions. Overall, the results confirm that the study's main conclusions are robust, although certain variables exhibit heterogeneous effects across countries. These results highlight the importance of adopting integrated policy approaches tailored to country-specific conditions.

5. Discussions

The empirical findings of this study provide important insights into the determinants of carbon emissions within the framework of the circular economy and the dynamics of the energy transition. The results obtained from panel data estimation reveal that environmental outcomes are shaped by a complex interaction of economic, structural, and policy-related factors. The fixed effects model indicates that circular economy practices have a negative and statistically significant impact on carbon emissions. This finding suggests that improvements in resource efficiency, waste management, and circular production processes help reduce environmental degradation. This finding is consistent with previous studies reporting that circular economy practices significantly reduce carbon emissions through improved resource efficiency and waste minimization [7,10–12]. These findings further support the growing body of literature emphasizing the role of circular economy strategies in promoting sustainable environmental outcomes. Economic growth is also found to exert a negative and significant effect on carbon emissions in the baseline model. This result can be interpreted within the Environmental Kuznets Curve (EKC) framework, where economic development initially increases environmental pressure but eventually leads to improvements through technological progress and stricter environmental regulations. However, the sensitivity of this relationship across model specifications suggests that the growth–environment nexus remains highly context-dependent. In contrast, the recycling variable exhibits a positive and statistically significant effect on carbon emissions. This finding may reflect the energy-intensive nature of recycling processes, particularly in the short run, where increased recycling activities may lead to higher energy consumption and associated emissions. Therefore, while recycling is generally considered environmentally beneficial, its short-term environmental impact may not always be straightforward. The results based on Driscoll–Kraay estimation, which accounts for cross-sectional dependence, provide further evidence that renewable energy consumption plays a crucial role in reducing carbon emissions. The negative and significant coefficient of renewable energy highlights the importance of energy transition policies in achieving environmental sustainability. Similarly, the negative effect of renewable energy is consistent with earlier studies emphasizing the importance of energy transition policies in reducing environmental degradation [4,16–20]. Urbanization is found to have a weak negative effect on carbon emissions. This result suggests that urban development may contribute to environmental efficiency through improved infrastructure, technological diffusion, and economies of scale. However, the relatively low level of statistical significance indicates that the impact of urbanization is not uniform and may vary depending on country-specific characteristics. This finding is also consistent with the descriptive statistics, which indicate very limited variation in urbanization across the sample. Consequently, although urbanization remains theoretically relevant and is retained as an important structural control variable, its empirical contribution within the fixed-effects framework is naturally constrained because urban development evolves only gradually over time, generating limited within-country variation.

Although urbanization exhibits limited within-country variation, its inclusion is theoretically justified as a structural control variable. Furthermore, the relatively high explanatory power (R^2) of the model primarily reflects the inclusion of country fixed effects and time fixed effects, which account for unobserved heterogeneity and common temporal shocks, rather than the contribution of urbanization alone. Overall, the findings of this study highlight that the determinants of carbon emissions are not homogeneous across countries. Instead, they are influenced by structural differences, policy frameworks, and levels of economic development. The presence of cross-sectional dependence further supports the idea that environmental and economic dynamics are interconnected across countries, particularly within integrated economic regions such as the European Union. From a policy perspective, the results emphasize the importance of strengthening circular economy practices and accelerating the transition toward renewable energy systems. Policies aimed at improving technological efficiency, supporting sustainable production processes, and enhancing environmental awareness can play a significant role in reducing carbon emissions. At the same time, policymakers should consider the potential short-term environmental costs of recycling activities and ensure that these processes are supported by clean energy sources. In conclusion, the findings suggest that achieving sustainable environmental outcomes requires a comprehensive policy approach that integrates economic growth, technological innovation, energy transition, and circular economy strategies. The heterogeneity observed across countries indicates that there is no single

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policy pathway; instead, country-specific strategies are essential for promoting long-term environmental sustainability.

6. Policy Implications

The empirical findings of this study have important policy implications by accounting for the structural characteristics of the selected Central and Eastern European countries (Romania, Poland, Hungary, Bulgaria, Slovakia, and Slovenia). First, the negative effect of circular economy practices on carbon emissions suggests that improvements in resource efficiency and waste management contribute to environmental sustainability across the sample. However, the effectiveness of circular economy policies varies across countries. According to the Eurostat Circular Economy Monitoring Framework, Slovenia and Slovakia generally exhibit stronger performance than Bulgaria and Romania in key circular economy indicators, particularly the Circular Material Use Rate (CMUR), which reflects the share of secondary raw materials reintroduced into the economy. Consequently, circular economy policies are likely to generate more immediate environmental benefits in these countries. In contrast, Bulgaria and Romania continue to exhibit relatively lower circular material use rates, suggesting greater scope for improving resource efficiency, recycling infrastructure, and institutional implementation capacity. Second, the significant role of renewable energy in reducing carbon emissions underscores the need to accelerate the energy transition in these countries. While some countries in the sample have made notable progress in integrating renewable energy sources, others remain relatively dependent on conventional energy structures. Therefore, expanding renewable energy investments and improving energy infrastructure remain critical policy priorities. Third, the positive impact of recycling on carbon emissions suggests that recycling activities may be energy-intensive, particularly in economies where recycling technologies are less efficient or rely on fossil fuels. This finding implies that recycling policies should be complemented with investments in clean energy and technological upgrading to ensure net environmental gains. Fourth, the results suggest that economic growth may contribute to emission reductions under certain conditions, particularly when supported by technological development and environmental regulation. However, given the structural differences among the selected countries, the relationship between growth and emissions remains context-specific. Finally, the weak effect of urbanization indicates that urban development alone is not sufficient to reduce carbon emissions. Sustainable urban planning, energy-efficient infrastructure, and integrated environmental policies are necessary to fully realize the potential environmental benefits of urbanization. Overall, the findings emphasize that policy design in Central and Eastern European countries should be country-specific, taking into account differences in institutional capacity, energy structures, and development levels. Accordingly, policy priorities should be aligned with the objectives of the EU Circular Economy Monitoring Framework, which provides harmonized indicators for monitoring progress toward resource efficiency, waste reduction, and sustainable material use across member states. These findings highlight the urgency of accelerating policy efforts toward sustainable development.

7. Conclusions

This study investigates the determinants of carbon emissions within the framework of the circular economy and energy transition for selected Central and Eastern European countries (Romania, Poland, Hungary, Bulgaria, Slovenia, and Slovakia) over the period 2010–2024. By employing a panel data approach, the analysis integrates key structural variables, including circular economy practices, recycling activities, renewable energy consumption, economic growth, and urbanization, into a unified empirical framework.

The empirical findings provide several important insights. First, circular economy practices are found to significantly reduce carbon emissions, confirming their role as an effective policy tool for enhancing environmental sustainability. Second, renewable energy consumption exhibits a strong negative impact on emissions, highlighting the critical importance of energy transition policies in mitigating environmental degradation. Third, recycling activities are associated with short-run increases in carbon emissions, reflecting the energy-intensive nature of recycling processes, particularly in countries where clean energy inputs are limited. Additionally, the effect of economic growth appears negative but is sensitive to model specification, suggesting that the growth–environment relationship remains context-dependent. Urbanization, on the other hand, shows a weak and ambiguous impact, indicating that its environmental effects depend on country-specific structural conditions. One of the key contributions of this study is the integration of circular economy dynamics into the empirical analysis of carbon emissions within a panel data framework. While previous studies have largely examined renewable energy and economic growth separately, this research provides a more comprehensive perspective by jointly considering recycling and circular economy indicators. Moreover, the focus on Central and Eastern European countries contributes to the literature by offering region-specific evidence, which remains relatively limited despite the growing importance of these economies in the European environmental policy agenda. The robustness checks further strengthen the reliability of the findings by demonstrating that the main results are not driven by a particular model specification or a single country in the sample. This is particularly important given the relatively small sample size, as it confirms the stability and consistency of the estimated relationships. From a policy perspective, the findings highlight the importance of adopting integrated strategies that simultaneously promote circular economy practices and renewable energy transition. Policymakers should not only encourage recycling activities but also ensure that these processes are supported by clean, efficient energy systems to avoid unintended increases in emissions. Furthermore, the heterogeneous effects observed across countries suggest that environmental policies should be tailored to country-specific institutional and economic conditions rather than adopting a one-size-fits-all approach. These results also underline the urgency of accelerating policy efforts toward sustainable development in the region. Despite its contributions, this study has some limitations. The analysis is restricted to a relatively small group of countries and a limited time period, which may constrain the generalizability of the findings. In addition, the model focuses on linear relationships and does not account for potential nonlinear dynamics or threshold effects. Future research may extend this analysis by incorporating larger datasets, applying nonlinear modeling techniques, or employing advanced econometric approaches such as dynamic panel models in contexts where data availability allows. Exploring country-specific case studies may also provide deeper insights into the mechanisms linking circular economy practices and environmental outcomes. Overall, this study contributes to the growing literature on environmental sustainability by providing new empirical evidence on the role of the circular economy and the energy transition in reducing carbon emissions, particularly in Central and Eastern European economies.

8. Limitations and Future Research

Despite its empirical contributions, this study has several limitations that should be acknowledged. First, the analysis is limited to a relatively small sample of Central and Eastern European countries (Romania, Poland, Hungary, Bulgaria, Slovakia, and Slovenia). Although these countries provide a meaningful representation of transition economies within the European context, the limited sample size may restrict the generalizability of the findings. Future studies could extend the analysis to a broader set of countries, includ-

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ing both developed and developing economies, in order to provide more comprehensive and comparative insights. Second, the study relies on a set of proxy variables, particularly circular economy indicators and recycling rates, which may not fully capture the multidimensional nature of environmental sustainability. Environmental performance is inherently complex, and future research could incorporate alternative indicators such as carbon intensity, green total factor productivity, or environmental innovation measures. Third, although robust estimation techniques are employed to address cross-sectional dependence and heteroskedasticity, potential endogeneity issues and omitted variable bias cannot be entirely ruled out. In addition, the study period is constrained by the availability of harmonized circular economy indicators in the Eurostat database, which are consistently reported only from 2010 onward for all selected countries. Although a longer time horizon would be desirable, extending the analysis backward would compromise the consistency and comparability of the panel dataset. Future research may revisit these relationships using longer time series as more data become available. In addition, future studies may apply more advanced econometric approaches, such as dynamic panel estimators (e.g., GMM) or nonlinear models, particularly in larger samples, to better capture the complex relationships among the variables. Finally, the analysis focuses on linear relationships between variables. However, the environmental–economic nexus may exhibit nonlinear dynamics, threshold effects, or asymmetric responses. Future studies could explore these aspects to gain deeper insights into the determinants of carbon emissions.

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