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Does Circular Economy Mitigate Environmental Emissions Among European Union (EU) Countries?

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Abstract

Given the growing concern about the circular economy as a strategy for combating carbon emissions, it is critical to understand its impact on other environmental gases. Hence, this study aims to examine the impact of the circular economy on three main gases that contribute to climate change and global warming, namely carbon dioxide, methane, and nitrous oxide emissions. Further, the current study explores the mitigating effect of the circular economy on the Environmental Kuznets Curve for environmental emissions to provide strong evidence for its existence. This study employs a panel data technique, specifically panel ARDL, for the period spanning from 2000 to 2020 across 27 European Union countries. The empirical results suggest that circular economy practices have a negative impact on carbon dioxide, methane, and nitrous oxide emissions, signifying their role in emissions reduction and confirming the existence of the Environmental Kuznets Curve. Meanwhile, robustness checks with the addition of control variables and alternative estimation techniques also confirmed that the circular economy addresses environmental emissions. Therefore, the governments of other nations, as well as those of the European Union, should implement or expand fiscal incentives to encourage sectors to adopt circular economy strategies, and environmental regulations should incorporate circular economy principles to ensure sustainability and emission reduction.

Keywords: Circular Economy; Environmental Emissions; European Union; Panel ARDL

1. Introduction

Globally, countries are continuously stepping up their efforts to cut greenhouse gas emissions and move towards low-carbon, more sustainable economies in response to the urgent threat posed by climate change. Adopted in 2015 as an aspect of the United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement is a significant global agreement designed to mitigate the severe effects of climate change, such as extreme weather events, sea-level rise, and ecosystem disruptions, to keep global warming well below 2°C above pre-industrial levels. The agreement signifies a joint commitment from countries to implement diverse policies and guidelines customized to each country's distinct circumstances, encompassing increasing the consumption of renewable energy and improving energy efficiency, as well as imposing emission standards on transportation and industries.

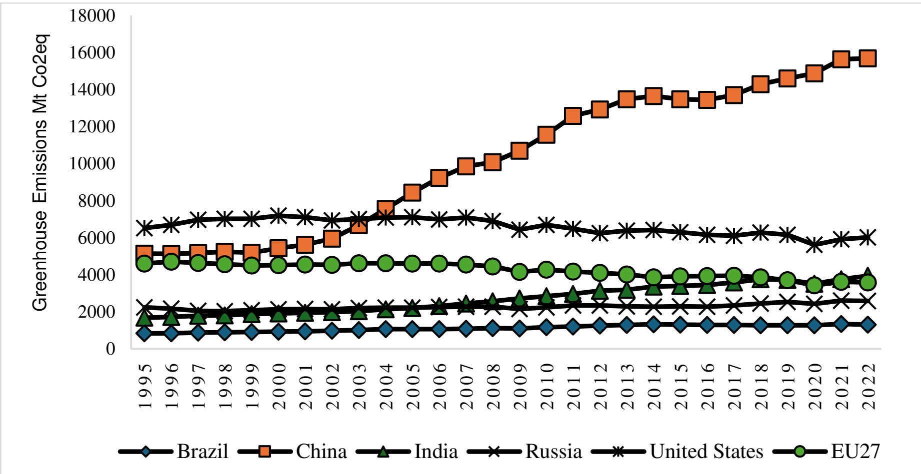

Figure 1: Greenhouse Emissions among top emitters
Source: Climate Watch (2023)

Along with these continuous efforts, the trend of emissions has shown that countries are facing different trends in emissions, with some experiencing rising emissions and others experiencing falling emissions. As illustrated in Figure 1, the top emitters of emissions worldwide in 2022 were China, the US, India, the European Union (EU), Russia, and Brazil. Between 1995 and 2022, emission levels increased for China, Brazil, and India. In comparison to China and Brazil, India's greenhouse emissions increased by the greatest amount, from 1680.3862 Mt CO2eq to 2506.684 Mt CO2eq, or approximately 149%. India’s greenhouse gas emissions have surged due to rapid economic growth, driven by industrialization and urbanization, which demand increased energy consumption and eventually further rise the level of emissions (Khan et al., 2020). China and Brazil, two countries that have struggled to control urban sprawl and changes in land use, have similarly maintained relatively high levels of greenhouse gas emissions, which have increased emissions and exacerbated climate change (Matsumoto and Daudey, 2014). The top three emitters, Russia, the United States, and the European Union, on the other hand, show declining emissions in 2022, with the European Union declaring the greatest reduction (29%). Upon closer look at the European Union's (EU) emission mitigation strategies, Mazur-Wierzbicka (2021) found that the EU has been actively moving towards a circular economy framework since 2014 to increase Europe's competitiveness and cleanliness. By extending product lifecycles, reusing materials, and supporting remanufacturing and recycling initiatives, the EU has been able to reduce the carbon footprint associated with production and consumption, ease the burden on natural resources, foster sustainable growth to meet the EU's 2050 climate neutrality target, and hinder the loss of biodiversity. The effectiveness of EU circular economy principles in mitigating climate change is further demonstrated by policies that support the circular economy, such as extended producer responsibility programs and eco-design standards, which encourage businesses to adopt more sustainable practices and further reduce emissions.

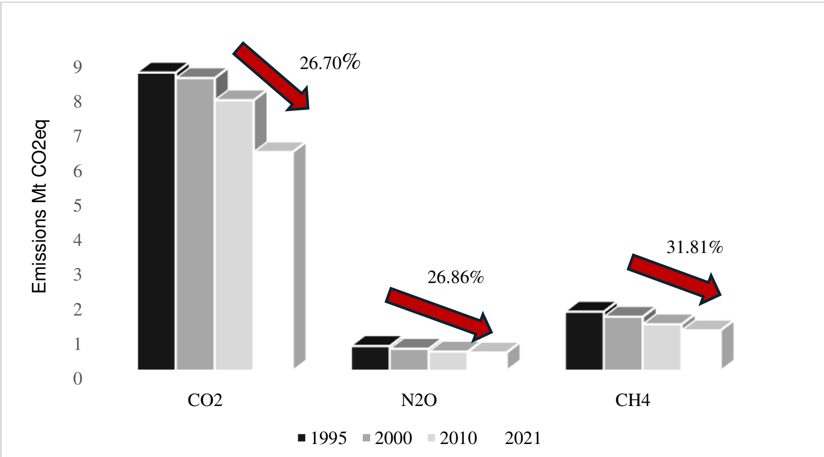

Figure 2: Trend of Greenhouse Emissions in 27EU countries
Source: Climate Watch (2023)

An extensive review of the trend of the primary contributors to greenhouse gas emissions, specifically in the European Union, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), is provided under Figure 2. This pattern highlights an important discovery that CH_4 accounted for a significant amount of the decreases, followed by N_2O and CO_2. A notable divergence from previous research has been discovered on circular economy and carbon emissions, as evidenced by studies like Mawutor et al. (2023), Liu et al. (2018), Tiwari et al. (2023), Khan and Khurshid (2020), Hailemariam and Erdiaw-Kwasie (2022), Cudjoe et al. (2021), Bayar et al. (2021), and Li et al. (2020), which primarily addressed the contribution of circular economy practices to declining carbon emissions. Consequently, this unexpected trend casts doubt on the commonly accepted notions about the effectiveness of circular economy efforts in reducing carbon emissions by itself. As such, the aim of this study is to contribute to the discussion of circular economy practices by conducting a thorough analysis of their impact on environmental emissions, specifically CO2, CH4, and N2O. We aim to offer a more comprehensive view of the possible contributions of circular economy principles to broader environmental sustainability goals through this enlarged lens.

The rest of the paper is organized as follows. Section 2 provides the literature review of the study. Section 3 presents the methodology. Section 4 describes the results and discussion. The last section, which is Section 5, highlights the conclusions and policy implications.

2. Literature review

The scholarly study on income and income squared-induced Environmental Kuznets Curve (EKC) and renewable energy-induced EKC from the past to today is extensive. Nevertheless, the concept of EKC resulting from the circular economy is relatively new, and not much research has been done on it.

Pioneeringly, the Environmental Kuznets Curve (EKC) was introduced by Grossman and Krueger (1991) to show the linkages between income and environmental degradation, which is an extension from the Kuznet curve. The EKC postulates that environmental degradation rises in the initial stages of income due to urbanization and industrialization. Then, once income reaches a certain level, environmental degradation declines alongside the rise in income. This indicates an inverted U-shaped relationship between income and environmental degradation. From the past to now, numerous empirical studies have examined the linkages between income and environmental degradation from different methodological perspectives and countries (Tenaw and Beyene 2021; Wang et al., 2021; Pata and Yurtkuran, 2023; Islam and Rahaman, 2023; Kostakis et al., 2023; Wang et al., 2023; Wang et al., 2024; Li et al., 2024; Uddin et al., 2024). For instance, Alharthi et al. (2021) and Kostakis et al. (2023) for MENA countries, Tenaw and Beyene (2021) for sub-Saharan Africa, Li et al. (2021) and Pata (2021) for China, Balsalobre-Lorente et al. (2022) for Central and Eastern European countries, Pata and Yurtkuran (2023) for the European Union, and Islam and Rahaman (2023) for Gulf Cooperation

Council countries, all concerning the EKC and providing mixed results of inverted U-shapes, U-shapes, N- and inversed-N shaped relationships.

The inverted U-shapes validate the EKC hypothesis, while the U-shapes, N- and inversed-N shaped relationships reject the EKC hypothesis. Using Tapio's methodology, Wang et al. (2021) explored the existence of the EKC hypothesis for China and confirmed N-shaped and inverted N-shaped relationships between income and carbon emissions for different regions in China. The U-shaped relationship has been validated by Isik et al. (2021) for Sweden, Destek and Sinha (2020) for Austria, and Pata and Yurtkuran (2023) for the European Union, where initially, a rise in income reduces environmental degradation; however, further growth of income increases environmental degradation. Thus, past studies show inconclusive results for the linkages between income and environmental degradation.

Renewable energy sources, such as solar, geothermal, wind, biomass, and hydropower, preserve environmental quality by emitting zero greenhouse gases, according to Apergis and Payne (2012), Sharif et al. (2020), Khan et al. (2020), Muhammad et al. (2021), He et al. (2022), Khan et al. (2023), and Öztürk et al. (2023) have all advocated the consumption of renewable energy to reduce emissions, decrease dependency on fossil fuels, and ensure sustainability. The transition towards renewable energy is critical to meeting long-term emissions reduction targets, halting climate change, and harnessing clean, sustainable energy sources to eventually cut greenhouse gas emissions and build a more resilient and sustainable energy system for current and future generations.

Besides that, several studies have looked at renewable energy as a means of validating the Environmental Kuznets Curve (EKC). These studies include those conducted in BRICS (Danish et al., 2020), the United States (Kartal, 2023), South Korea (Pata and Kartal, 2023), East African Community (EAC) countries (Nabaweesi et al., 2023), and West African countries (Prempeh, 2024) showed mixed results. Danish et al. (2020), Pata et al. (2023), and Nabaweesi et al. (2023), for example, employed renewable energy as an explanatory variable to validate the presence of EKC and concluded that EKC exists for renewable energy. This suggests that greater consumption of renewable energy was linked to fewer emissions, corroborating the idea that environmental quality tends to improve as countries allocate more resources to renewable energy. Nonetheless, the findings of Prempeh (2024) for West African nations, Pata and Karlilar (2024) for a group of OECD nations, and Bilgili et al. (2016) for individual OECD countries do not support the existence of EKC when incorporating renewable energy in the model. This could challenge the generalizability of the EKC's existence by suggesting that other factors specific to these countries have greater significance in determining environmental emissions. Therefore, previous research indicates that renewable energy reduces environmental emissions; however, there are inconsistencies in the presence of EKC about renewable energy.

In addition, there is a growing number of studies on the linkages between energy efficiency and environmental emissions. Akram et al. (2020a) and Mirza et al. (2022) for developing countries, Ulucak and Khan (2020) for the United States, Shahbaz et al. (2020) and Lei et al. (2021) for China, Adebayo and Ullah (2023) for Sweden, and Bilgili et al. (2023) for EU countries acknowledge the contractionary results on the impact of energy efficiency on emissions. A key aspect of lowering emissions and improving energy security is energy efficiency (Akram et al, 2022; Adebayo and Ullah, 2023; Bilgili et al., 2023). Energy efficiency can be defined as using less energy to produce the same level of output. Growing investments in energy efficiency have the potential to reduce environmental emissions, enhance resource sustainability, alleviate electricity shortages by reducing operating costs, and improve energy security. Energy efficiency is highlighted by Mexico, Indonesia, Nigeria, and Turkey as a key component of clean growth policies to achieve the goal of minimizing greenhouse gas emissions through rapid industrialization, as well as meeting sustainable development goals, as noted by Bayar and Gavriletea (2019). Nonetheless, by examining the asymmetric effect of energy efficiency on carbon emissions, Lei et al. (2021), Wang et al. (2021), and Mirza et al. (2022) reported contractionary results. These studies demonstrate the rebound effect, where increases in efficiency cause an increase in energy consumption, which can counteract the positive effects and lead to higher emissions. Thus, there is a significant and uncertain effect of energy efficiency on emissions.

Recently, the circular economy has gained popularity recently among environmentalists to protect the environment by offering solutions for pollution, climate change, and biodiversity loss. By extending the lifespan of goods through practices such as recycling, reuse, and regenerative practices, a circular economy is a sustainable approach that seeks to reduce waste and maximize resource efficiency (Schroeder et al., 2019; Blomsma and Tennant, 2020). Regarding this, Liu et al. (2018) for China, Mawutor et al. (2023) for Ghana, Hailemariam and Erdiaw-Kwasie (2022) for European nations, Tiwari et al. (2023) for emerging nations, and Khan and Khurshid (20220) for the Netherlands examined the relationship between environmental emissions and circular economy practices, heading to the conclusion that such practices reduce emissions and enhance environmental quality. Reducing waste, maintaining sustainable production and consumption practices, and optimizing resources are all key components of circular economy strategies that help reduce emissions and advance environmental sustainability.

To investigate the impact of the circular economy on carbon emissions among emerging nations such as China, South Korea, Japan, the United Kingdom, and the United States, Tiwari et al. (2023) carried out a recent study. Results of a study by Tiwari et al. (2023) show that the generation of municipal waste as a measure of the circular economy has a major negative short- and long-term effect on carbon emissions. In a similar vein, Hailemariam and Erdiaw-Kwasie (2022) found that through lowering CO_2 emissions, the circular economy greatly enhances environmental quality. In contrast, the circular economy is found to have no significant effect on emissions by Li et al. (2020), Cudjoe et al. (2021), and Bayar et al. (2021). These studies explain that the use of energy efficiency, and waste recycling as proxies for the circular economy does not result in reductions in emissions in China, Nigeria, or EU countries. Thus, the impact of the circular economy on environmental emissions is inconclusive, indicating the need for further inquiry.

Particularly, the features of each study on the linkages between circular economy and emissions are highlighted in Table 1, including the country, methodology, and results. Studies investigating the relationship between environmental emissions and the circular economy have yielded inconsistent results, as evidenced by the literature. Hence, this study contributes to addressing these gaps as follows:

(i) While earlier research primarily focused on the impact of circular economy on CO_2 emissions, our study takes a more inclusive approach by considering the top three greenhouse gases of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). This more inclusive approach offers a deeper understanding of circular economy's role in environmental sustainability, addressing areas that have been underexplored in the past studies.

(ii) Bayar et al. (2021) and Hailemariam and Erdiaw-Kwasie (2022) explored circular economy's impact on carbon emissions in European nations, revealing inconsistent effects. To clarify these discrepancies, our study attempts to examine the impact of the circular economy on environmental emissions in European nations, focusing on the top three greenhouse gas emissions.

(iii) Unlike existing studies, this study uniquely measures the circular economy through private investment and gross added value in circular economy sectors. This innovative approach enhances the robustness and relevance of our findings.

(iv) Finally, this study also examines the mitigating effects of the circular economy on the EKC for three primary greenhouse gasses. This is essential for understanding how the circular economy can help reduce environmental emissions within the EKC framework.

By addressing these key areas, the study's findings will provide significant insights for European policymakers. Particularly, the findings can help optimize circular economy strategies to target specific types of emissions, thereby enhancing environmental sustainability across the region.

Table 1: Summary of studies on circular economy on environmental emissions

Author’s	**Country**	**Methodology**	**Proxy circular economy**	**Proxy environmental emissions**
		Negative relationship		
Mawutor et al. (2023)	Ghana	Autoregressive Distributed Lag		
Liu et al. (2018)	China	Decomposition analysis		
Tiwari et al. (2023)	Emerging economies	Quantile Autoregressive Distributed Lags	Waste recycling	Carbon emissions
Khan and Khurshid (20220)	Netherlands	Wavelet analysis		
Hailemariam and Erdiaw-Kwasie (2022)	European countries	Heteroscedastic-based instrument		
		No relationship		
Cudjoe et al. (2021)	China	Model equations method	Waste recycling	
Bayar et al. (2021)	European countries	panel cointegration and causality analysis		Carbon emissions
Li et al. (2020)	China and Nigeria	ARDL bound, and Bayesian VAR model	Energy efficiency	

Sources: Author’s creation

Conceptual Framework

The circular economy promotes environmental sustainability by lowering resource consumption, minimizing waste, and encouraging the efficient use of resources and energy. Figure 3 depicts how the circular economy can influence the reduction of the top three greenhouse gases: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

Circular economic practices such as energy efficiency, recycling, and renewable energy integration are known to cut carbon emissions. They also contribute to lowering carbon emissions by reducing the need for energy-intensive production processes, fossil fuel consumption, and material extraction. Recycling plastics, metals, and glass, for example, reduces the energy required for new material production, while using renewable energy (biomass recycling) reduces reliance on fossil fuels and lowers carbon emissions.

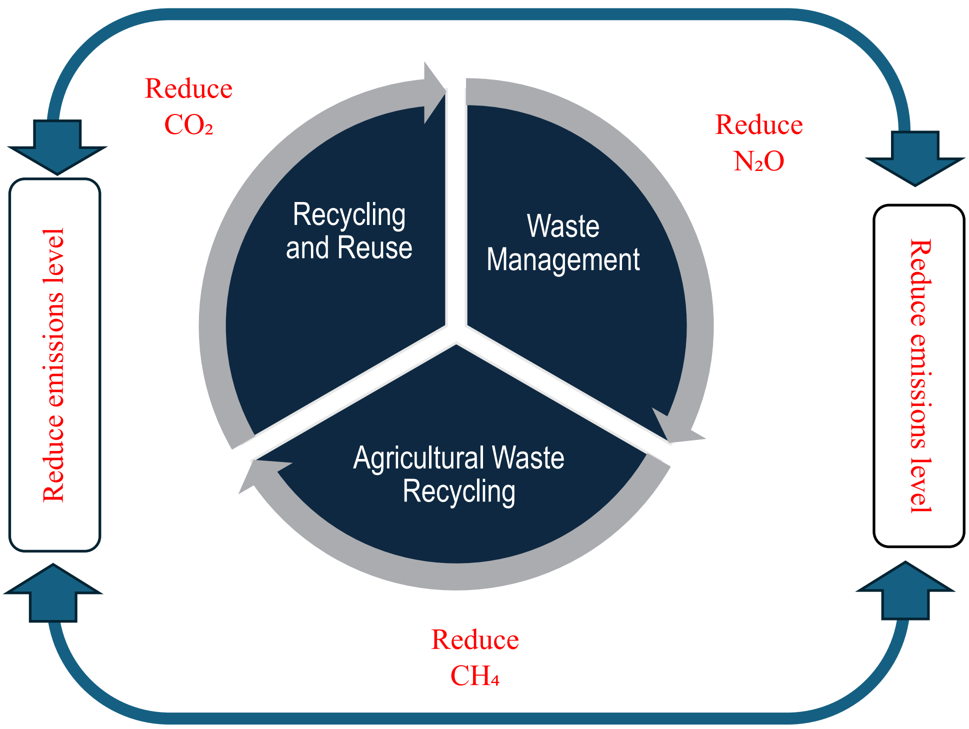

Figure 3: Linkages between circular economy and Greenhouse gas emissions
Source: Authors own illustration

Methane emissions (CH_4) from landfill waste decomposition and agricultural operations could be reduced by using a circular economy approach to waste management. Improving waste management through circular economy initiatives such as composting, biogas production, and diverting organic waste from landfills can significantly reduce methane emissions. Converting organic waste, for example, into compost and energy helps reduce methane emissions from traditional waste disposal methods.

Further, circular economy approaches in agriculture, such as sustainable land management, precision farming, and organic fertilizer recycling, improve soil nutrient efficiency. This, in turn, decreases the amount of nitrous oxide emitted, which is mostly caused by agricultural operations and fertilizer consumption. For example, recycling agricultural waste as biofertilizers reduces the need for synthetic fertilizers, while crop management improves nitrogen use efficiency and lowers nitrous oxide emissions.

To summarize, the circular economy reduces greenhouse gas emissions by focusing on mechanisms that reduce the environmental impact of production and waste. It reduces CO_2 emissions by lowering fossil fuel consumption and energy use, CH_4 emissions by minimizing landfill waste through composting and biogas production, and N_2O emissions through sustainable agricultural practices and effective fertilizer use. Thus, this framework ties circular economy practices to environmental sustainability, with a focus on reducing the three major greenhouse gases, thereby fostering a more sustainable and resource-efficient future.

3. Model and Data

Following Grossman and Krueger (1991), Islam and Rahaman (2023), Kostakis et al. (2023), Wang et al. (2023), Adebayo and Ullah (2023), Bilgili et al. (2023), Wang et al. (2024), Li et al. (2024), and Uddin et al. (2024), the environmental emission model is quantified as

$$EE_{it} = f(GDP_{it}, GDP^2{}_{it}, RE_{it}, ENEF_{it}, CE_{it}) \tag{1}$$

Where *EE, GDP, GDP*^{2}*, RE, ENEF, and CE* stand for environmental emissions, income, income square, renewable energy consumption, energy efficiency and circular economy, respectively. The subscripts *i* represent the cross section and *t* represent the time series. Then, *Eq. (1)* is transformed into a log-linear model due to the constant elasticity of dependent variables concerning explanatory variables (Gujarati and Porter, 2009). The estimated environmental emissions model in logarithmic form is rewritten as follows:

$$lnEE_{it} = \alpha_0 + \beta_1 lnGDP_{it+}\beta_2 lnGDP^2{}_{it+}\beta_3 lnRE_{it+}\beta_4 lnENEF_{it} + \beta_5 lnCE_{it} + \varepsilon_{it} \quad (2)$$

In *Eq. (2)*, the prefix "*ln*" refers to the natural logarithm, and ε is the error term. The EKC hypothesis will be valid when the coefficient of *GDP* is positive and GDP^2 is negative. As the relationship between renewable energy and the circular economy remains ambiguous, the expected sign of the coefficients for *RE*, *ENEF*and *CE* are significant.

The dependent and independent variables in this study are measured as follows: environmental emissions, as a dependent variable, are measured in carbon dioxide (*CO2*) emissions in metric tons per capita, methane (*CH4*) emissions in metric tons per capita, and nitrous oxide (*N2O*) emissions in metric tons per capita. The independent variables, renewable energy (*RE*), energy efficiency (ENEF) and circular economy (*CE*), are measured in the share of renewable energy in total energy consumption, GDP per unit of energy usage and private investment and gross added value related to circular economy sectors, respectively. Hence, Table 2 summarizes the measurement and sources for each variable. Besides that, the European Union countries included in this study are Austria, Belgium, Bulgaria, Croatia, the Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

Table 2: Data Sources

Variables	Symbols	Definition/ Measurement	Source
EE	*CO2*	Carbon dioxide emissions in metric tons per capita	World Bank (2023)
	CH4	methane (CH4) emissions in metric tons per capita	
	N20	nitrous oxide (N2O) emissions in metric tons per capita	
GDP	*GDP*	GDP per capita in constant 2010 US dollar	
RE	*RE*	share of renewable energy in total energy consumption	
ENEF	*ENEF*	GDP per unit of energy usage	
CE	*CE*	gross added value related to circular economy sectors	Eurostat (2023)

The present study employs the panel auto-regressive distributed lag (ARDL) approach to investigate the impact of independent variables on environmental emissions in both the short and long run.[1] To ascertain whether cross-sectional dependence exists, the preliminary cross-

[1] As proven by Pesaran et al. (1999) and Ali et al. (2017), the ARDL model is free from residual correlation, thus eliminating endogeneity problems and avoiding inconclusive inference due to appropriate lag selection. Additionally, this study conducted a robustness check using Dynamic Ordinary Least Squares (DOLS), where the

sectional (CD) test is conducted as follows. Panel data estimation assumes that disturbances are cross-sectionally independent; however, cross-country influences may arise from geography, politics, or the economy. Thus, the CD test needs to be employed to assess whether cross-sectional dependence exists. Once the CD was examined, the slope homogeneity was calculated to determine whether the slopes were homogeneous (Pesaran and Yamagata, 2008). Since there may be variations in a EU country's demography, economy and socioeconomic structure, it is crucial to look at slope homogeneity.

Then, CADF, CIPS of unit root tests are conducted in this study to verify the stationarity of the variables before the main estimation technique of the panel ARDL. All of these unit root tests are conducted with the null hypothesis of non-stationarity, and the lag length is chosen using the Bayesian-Schwarz criteria. Once preliminary tests are checked, cointegration is evaluated to ascertain the existence of a long-run relationship using Pedroni (1996). Rejecting the null hypothesis of the cointegration test, which states "there is no cointegration," indicates the presence of cointegration in at least one individual unit. As a final step, this study conducted panel ARDL test using long run and short run models as depicted in *Eq. (3) and (4)*

$$ln\Delta EE_{it} = \alpha_1 + \sum_{k=1}^{p} \beta_{ij}\, lnEE_{it-j} + \sum_{k=0}^{q} \delta_{ij}\, lnX_{it-j} + \varepsilon_{it} \tag{3}$$

$$\Delta lnEE_{it} = \theta_i + \sum_{k=1}^{p} M_{ij}\, \Delta lnEE_{it-j} + \sum_{k=0}^{q} Z_{ij}\, \Delta lnX_{it-j} + \emptyset_{ij} ECT_{t-i} + \varepsilon_{it} \tag{4}$$

Where *i, t and j* stand for cross-sectional unit, time periods and optimal lags, respectively, X_{it} is the exogenous variables, p and q are the optimal lag orders. The error correction term (ECT) in *Eq.(4)* captures the short-run shocks and indicates the rate of adjustment for the long-run equilibrium; the coefficient in this case needs to be significantly negative.

4. Results and Discussion

Initially, this study conducted descriptive statistics and correlation analysis, and the result was reported in Table 3. The statistics shows that the average for income and methane emissions is 10.314 and 5.157, the average for renewable energy is 4.737, and the average for the circular

main advantage of the DOLS estimation is that it addresses potential endogeneity and small sample bias (Ali et al., 2017).

economy is 3.405. All the variables' standard deviation values show that there is considerable variation in the data for these variables. Regarding correlation analysis, the findings show notable correlations between the variables. This indicates a significant correlation between income, income square, renewable energy, energy efficiency the circular economy, and environmental emissions.

Table 3: Descriptive statistics and Correlation Analysis

	$lnCO_2$	*lnN_2O*	*lnCH4*	*lnGDP*	*lnRE*	*lnENEF*	*lnCE*
Mean	4.771	4.342	5.157	10.314	4.737	2.161	3.405
Max	0.743	1.780	0.975	1.950	1.060	1.081	1.201
Min	0.426	0.618	0.240	5.281	0.808	0.360	0.811
Std. Dev.	5.366	5.974	6.146	12.297	5.878	2.92	5.323
	$lnCO_2$	*lnN_2O*	*lnCH4*	*lnGDP*	*lnRE*	*lnENEF*	*lnCE*
$lnCO_2$	1.000						
lnN_2O	0.068	1.000					
lnCH4	0.474	0.128	1.000				
lnGDP	-0.084	-0.047	-0.083	1.000			
lnRE	-0.427	-0.135	-0.278	0.058	1.000		
lnENEF	0.187	-0.505	-0.271	0.098	0.039	1.000	
lnCE	-0.485	-0.049	-0.357	0.056	0.069	0.019	1.000

This study used the cross-sectional (CD) to determine whether cross-sectional dependence exists, as was covered in the model estimation. As a preliminary analysis, the CD test and slope homogeneity are carried out; the outcomes are shown in Table 4 below. Table 4 shows that the existence of highly dependent countries, where a shock in one country will affect other countries, is supported by the rejection of the null hypothesis that there is no CD at the 1% significance level. Therefore, it was determined that CD existed among the variables.

Table 4. Cross-Sectional (CD)test

Variables	**CD test**	***p*-value**
$lnCO_2$	13.370	0.000
lnN_2O	19.701	0.000
lnCH4	29.230	0.000
lnGDP	220.057	0.000
$lnGDP^2$	190.761	0.000
lnRE	84.570	0.000
lnENEF	29.42	0.000
lnCE	12.057	0.000

Table 5: Slope Homogeneity Test

Slope homogeneity Test	**Δ statistic**	***P-value***
$\widetilde{\Delta_{test}}$	9.445***	0.000
$\Delta_{\widetilde{adj\ test}}$	25.058***	0.000

Note: Asterisks *, ** and*** denote 10%, 5% and 1% levels of significance, respectively

The results of Pesaran and Yamagata (2008) slope homogeneity test are display in Table 5. It shows that model suffer from the problem of heterogenous, as shown by the significant value of the delta and adjusted delta. This indicates that the model are heterogenous, and the slope varies across countries.

Subsequently, the panel unit root tests for each variable are tested in this study, and Table 6 presents the results. The results demonstrate that, except RE, which is *I(0), CO2, CH4, N2O, GDP, GDP^2, ENEF and CE* are integrated of order one, or *I(1).* Except for RE, all of these variables are stationary at *I(1).* This shows that while other variables became stationarity at the first difference, the variables RE constituted the unit root problems at the level.

Table 6: Panel unit root tests

Variables	**CIPS Test**		**CADF Test**	
	Level	*1st difference*	*Level*	*1st difference*
$lnCO_2$	1.022	3.476***	2.561	-4.194***
lnN_2O	-2.477	-4.908***	-0.388	1.741***
lnCH4	-1.144	-7.472***	-2.768	-2.212***
lnGDP	0.508	1.231***	1.516	1.561***
$lnGDP^2$	2.090	1.751***	1.407	3.295***
lnRE	1.509	-2.229***	1.309	4.241***
lnENEF	2.280	1.173***	1.442	2.160***
lnCE	-1.628	-4.844***	-2.557	-4.498***

Note: **, *** refers to statistical significance at the 5% and 1% levels, respectively

To determine whether there are long-term relationships between the variables, Pedroni cointegration tests are performed. Table 7 contains the results of the cointegration tests. At the one percent significance level, it demonstrates that each statistic is significant, supporting the rejection of the null hypothesis that there is no cointegration. As a result, the findings supported the presence of panel cointegration between the *GDP, RE, CE, EE, ENEF and GDP^2*.

Table 7: Pedroni Cointegration Tests

	Model 1: $EE = CO2$		Model 2: $EE = CH4$		Model 3: $EE = N2O$	
	Statistic	Weighted statistic	Statistic	Weighted statistic	Statistic	Weighted statistic
Within- dimension:						
$Panel\ PP - statistic$	-3.802***	-4.129***	-7.602***	-8.055***	-7.657***	-9.025***
$Panel\ ADF - statistic$	-4.440***	-4.659***	-9.923***	-11.132***	-9.804***	-8.020***
Between –dimension:						
$Group\ PP - statistic$	-2.020***		-9.5***		-5.816***	
$Group\ ADF - statistic$	-4.606***		-6.610***		-7.222***	

Note: Asterisks *, **, and*** denote 10%, 5% and 1% levels of significance, respectively.

After the above preliminary tests were confirmed, the ARDL estimation was applied to test the direction of each independent variable on the level of environmental emission in EU countries. The results of the long run and short run ARDL estimation are given in Table 8. Initially, we validated the model with four diagnostic tests: the LM test for autocorrelation, the Breusch-Pagan-Godfrey test for heteroscedasticity, the Jarque-Bera test for normality, and the Ramsey RESET test for stability. As none of the assumptions were violated according to the findings from these diagnostic tests, which are shown at the bottom of Table 8, the models appear to be reliable. With the model's validity established, the long-run equation results, which are the main focus of this study and are shown in Table 8, can now be discussed.

From the Table 8, all the independent variable's *GDP*, GDP^2, *RE, ENEF and CE* have a significant long-term influence on emission levels into the environment. This study found that *GDP and* GDP^2 significantly affect environmental emissions positively and negatively, respectively. According to the statistics, for every 1% increase in *GDP, CO2* rises by 1.38 percent up to a certain point and then decreases with an 8.02 percent increase in GDP^2. The findings are consistent with previous studies by Ulucak et al. (2020), Alharthi et al. (2021), Kostakis et al. (2023), Tenaw and Beyene (2021), Li et al. (2021), Pata (2021), and Balsalobre-Lorente et al. (2022).

Table 8: Long-run and Short-run estimates

	Model 1: *EE = CO2*	Model 2: *EE=CH4*	Model 3: *EE = N2O*
Long-run equation			
lnGDP	1.384***	1.192*	2.730***

	[2.40]	[2.09]	[3.11]
lnGDP²	-8.028**	4.600***	-2.230***
	[-2.19]	[-3.81]	[-2.67]
lnRE	-0.173**	-0.028*	-0.044**
	[2.11]	[-2.08]	[2.21]
lnENEF	-0.507***	- 0.086***	-0.109
	[-2.58]	[-2.41]	[-2.26]
lnCE	-0.042***	-0.157***	-0.063*
	[-2.92]	[-2.97]	[-2.39]
Short-run equation			
Δ*lnGDP*	2.431*	4.437***	2.568**
	[1.52]	[3.56]	[2.27]
Δ*lnGDP²*	-7.202**	-2.054***	-2.012***
	[-2.43]	[-4.09]	[-3.27]
Δ*lnRE*	-0.068***	-0.229*	-0.059*
	[-2.61]	[1.98]	[-2.25]
Δ*lnENEF*	-2.125***	-0.505**	-0.265***
	[-3.39]	[2.29]	[2.78]
Δ*lnCE*	-0.055*	- 2.432***	-0.123**
	[-2.08]	[-2.50]	[-2.36]
ECT(− 1)	− 0.125**	-0.311**	-0.177**
	[-2.40]	[2.32]	[-2.58]
Diagnostic tests			
Autocorrelation	0.810[0.52]	0.265[0.58]	2.838[0.29]
Heteroscedasticity	1.569[0.18]	1.134[0.24]	0.225[0.62]
Normality	1.827[0.43]	0.606[0.69]	0.458[0.78]
Stability	0.889[0.63]	0.372[0.54]	1.033[0.33]

Note: Asterisks *, **, and*** denote 10%, 5% and 1% levels of significance, respectively.

In addition, this study provides empirical evidence for the significant impact of renewable energy on environmental emissions in EU countries. The effect of renewable energy on environmental emissions is negative and significant at the 5% level. This implies that a 1% increase in renewable energy consumption leads to a reduction of 0.17% in CO2 emissions, 0.02% in CH4 emissions, and 0.04% in N2O emissions in EU countries. As highlighted by Sulaiman et al. (2013), Cerdeira Bento and Moutinho (2016), Danish et al. (2020), Pata et al. (2023), and Nabaweesi et al. (2023), transitions towards renewable energy sources such as solar, wind, and hydropower not only reduce reliance on fossil fuels but also curb environmental emissions. Meanwhile, the results support the presence of the Environmental Kuznets Curve (EKC) when incorporating renewable energy in the model for three alternative measures of environmental emissions.

The coefficient of the circular economy shows a significant negative effect on environmental emissions in EU countries. In contrast to the findings of Cudjoe et al. (2021) for China, Bayar et al. (2021) for European countries, and Li et al. (2020) for China and Nigeria, this study finds that the circular economy reduces environmental emissions. This finding is in line with the results reported by Mawutor et al. (2023), Hailemariam and Erdiaw-Kwasie (2022), Liu et al. (2018), Tiwari et al. (2023), and Khan and Khurshid (2020). For instance, a 1% increase in circular economy practices results in a 0.04% reduction in CO_2 emissions. Based on a comparison of the three emissions, it can be observed that the circular economy has a greater impact on CH_4 emissions than on N_2O and CO_2 emissions, as shown in Figure 2. This pattern is a direct result of concentrated efforts on waste management and agricultural techniques that target sources of CH_4, such as livestock and landfills. Through resource efficiency, waste minimization, energy savings, material substitution, and behavioral changes in consumers, circular economy practices help reduce emissions. These practices include: i) Circular economy approaches that prioritize recycling, reuse, and remanufacturing minimize emissions related to production processes and lessen the need for virgin resource extraction; ii) By extending the lifespan of materials and products and encouraging energy-efficient practices, circular economy strategies lower emissions and energy consumption throughout the lifecycle of the product; and iii) By encouraging behaviors like sharing, renting, and repairing goods, overall consumption is reduced, linked to lower emissions.

Table 9 also shows that, concerning the short-run effect, the direction of the independent variables is nearly the same as that of the long-run effect. The sign of the lagged error correction term (ECT) coefficient suggests a long-term relationship between the endogenous and exogenous variables. Particularly, the ECT−1 coefficient is -0.311, indicating that the rate at which the variations in environmental emission levels between the short- and long-term equilibrium are controlled is roughly 0.31% per year. The ARDL panel approach, in summary, validates the long-term negative and significant relationships *between* GDP^2*, RE, ENEF and CE* and environmental emissions of *CO2, CH4, and N2O* in EU countries. *GDP*, however, also causes emissions to rise because it fuels urbanization and rapid industrialization, both of which worsen the environment. Based on these findings, we propose that to reduce emissions and pave the way towards zero emissions in the future, EU countries should prioritize and promote the adoption of circular economies.

Table 9: Long-run and Short-run estimates for EKC specification

	Model 1: *EE = CO2*	Model 2: *EE=CH4*	Model 3: *EE = N2O*
Long-run equation			
lnGDP	0.243** [2.15]	0.269*** [3.36]	0.284*** [2.58]

$lnGDP^2$	-0.662*** [2.70]	- 0.114** [-2.15]	-0.036* [2.02]
lnRE	-0.508*** [3.54]	- 0.085** [-2.32]	-0.053* [-2.16]
lnENEF	- 0.2300** [-2.14]	-0.036** [2.73]	-0.045** [2.27]
lnGDP X CE	0.129** [2.29]	0.152* [2.0]	0.181** [2.02]
$ln\ GDP^2\ X\ CE$	-0.361 *** [-2.92]	-0.046*** [2.40]	- 0.111 *** [-3.11]
Short-run equation			
Δ*lnGDP*	0.302*** [3.70]	0.115*** [2.36]	0.167* [2.11]
$\Delta lnGDP^2$	-0.130*** [-2.87]	-0.084*** [-2.19]	-0.093*** [-2.45]
Δ*lnRE*	-0.256** [-2.36]	-0.064** [-2.12]	-0.063*** [-3.09]
Δ*lnENEF*	-0.191* [-1.97]	-0.088** [-2.38]	-0.060** [-2.44]
Δ*lnGDP X CE*	0.238*** [3.19]	0.059 * [1.97]	0.079** [2.28]
$\Delta lnGDP^2\ X\ CE$	-0.124*** [-2.56]	-0.138*** [-2.94]	-0.042** [2.15]
ECT(− 1)	-0.115*** [-3.21]	-0.209** [-2.27]	-2.350*** [-4.59]
Diagnostic tests			
Autocorrelation	2.017[0.87]	1.022[0.78]	0.465[0.99]
Heteroscedasticity	1.028 [0.95]	0.157[0.89]	0.221[0.58]
Normality	1.072[0.56]	0.064[0.28]	0.083[0.62]
Stability	1.045[0.62]	0.059[0.22]	0.062[0.96]

In addition, this study examines the mitigating effect of the circular economy on the EKC, and the results are reported in Table 9. The coefficient of GDP is 0.243 - (0.129 x CE_i), while the coefficient of GDP^2 is -0.662 + (-0.361 x CE_i). Notably, both interaction terms are significant, confirming that the circular economy influences the EKC. Promoting resource efficiency, waste reduction, and sustainable practices tends to lower environmental emissions as income rises, according to the significance of the interaction term. In other words, the EKC shifts downward as circular economy practices are enhanced in EU countries. As a result, the findings imply that the circular economy does influence the EKC's shape by promoting better environmental quality and reducing the effects of emissions as the economy grows.

Robustness checks

The sensitivity of the results to additional explanatory variables and estimation techniques is investigated through a series of robustness checks. First, using the additional explanatory variables of trade (TR) and foreign direct investment (FDI), the robustness check is carried out. All the coefficients in Table 10 have the same sign as those in Table 8. There is a negative relationship between ED and the variables TR and FDI. Our findings support the pollution halo hypothesis, which holds that increased foreign direct investment (FDI) improves environmental quality by encouraging the use of clean technologies and increasing energy efficiency (Ansari et al., 2019; Duodu et al., 2021). Similarly, we also note that trade reduces environmental emissions. Given that the technique and composition effects outweigh the scale effect, this suggests that increasing TR reduces emissions (Le et al., 2016; Khan et al., 2022). In all three models, the circular economy coefficient is negative when examining the core variable. By prolonging product lifecycles, reducing waste, and promoting reuse and recycling, the circular economy aims to reduce emissions and lessen environmental impact.

Table 10: Long-run and Short-run estimates with additional controlled variables

	Model 1: *EE = CO2*	Model 2: *EE=CH4*	Model 3: *EE = N2O*
Long-run equation			
lnGDP	3..010***	1.218***	4.886***
	[2.94]	[4.69]	[7.06]
lnGDP^2	-1.030***	-0.032***	-2.006***
	[-2.54]	[-3.34]	[-3.54]
lnRE	-0.063**	-0.049***	-0.067***
	[-1.98]	[-2.77]	[3.44]
lnENEF	-0.051***	-0.036***	-0.014*
	[-2.09]	[-3.36]	[-2.08]
lnCE	-0.075***	-0.073***	-0.030***
	[-2.63]	[-2.80]	[-2.43]
lnFDI	-0.049***	-0.036**	-0.082***
	[-2.75]	[-2.19]	[-2.48]
lnTR	-0.065***	-0.011**	0.026***
	[2.68]	[-2.21]	[-2.29]
Short-run equation			
Δ*lnGDP*	2.693***	2.274***	3.270***
	[7.77]	[6.17]	[2.57]
Δ*lnGDP*^{2}	-0.056***	-0.048***	-2.209***
	[-2.42]	[-2.34]	[-3.79]
Δ*lnRE*	-0.036**	-0.019*	-0.043*
	[-2.29]	[-2.05]	[-1.84]
Δ*lnENEF*	-0.016***	-0.075***	-0.047***
	[-2.81]	[-2.83]	[-2.69]
Δ*lnCE*	-0.092***	-0.084***	-0.029***
	[-2.36]	[-3.82]	[-2.35]
Δ*lnFDI*	-0.020**	-0.0132***	0.014***
	[-2.24]	[4.08]	[-2.56]
Δ*lnTR*	-0.032***	-0.0647***	-0.088***
	[-3.56]	[-5.27]	[-4.43]
ECT(− 1)	-0.083***	-0.025*	-0.020**
	[-2.84]	[-2.78]	[-2.14]

Diagnostic tests			
Autocorrelation	0.014[0.48]	0.013[0.37]	0.016[0.84]
Heteroscedasticity	0.088[0.29]	0.054[0.77]	0.065[0.72]
Normality	0.049[0.51]	0.034[0.74]	0.041[0.35]
Stability	0.033[0.25]	0.085[0.69]	0.085[0.55]

Note: Asterisks *, **, and*** denote 10%, 5% and 1% levels of significance, respectively. TR and FDI stand for trade and foreign direct investment, respectively.

In the second robustness check, we employed alternative estimation techniques, namely panel fully modified ordinary least squares (FMOLS) and panel dynamic ordinary least squares (DOLS), to confirm the sensitivity of the estimated outcomes. The results are reported in Table 11 and Table 12. According to the estimation results, we conclude that there is strong evidence indicating that the circular economy significantly reduces environmental emissions, resulting in better environmental quality in European countries. Furthermore, the findings provide evidence that emission levels tend to be lower in EU countries with higher adoption of circular economy practices and validate the EKC in the presence of the circular economy. To sum up, the empirical findings reveal that environmental emissions decline with the promotion of circular economy practices and the enhancement of environmental protection.

Table 11: FMOLS and DOLS estimates

	Model 1: *EE = CO2*		Model 2: *EE=CH4*		Model 3: *EE = N2O*	
	FMOLS	DOLS	FMOLS	DOLS	FMOLS	DOLS
lnGDP	2.123*** [2.35]	3.469*** [6.79]	4.636*** [6.59]	1.516*** [7.41]	2.330*** [9.14]	2.422*** [6.54]
lnGDP^2	-0.093*** [-2.95]	-0.073*** [-4.20]	-1.172*** [-3.08]	-0.487*** [-2.09]	-0.381*** [-2.87]	-0.876*** [-2.34]
lnRE	-0.015** [-2.25]	-0.015* [-2.06]	-0.074** [-2.15]	-0.099*** [-3.49]	-0.0645*** [-2.3]	-0.036** [-2.27]
lnENEF	-0.039** [-2.38]	-0.052*** [-3.24]	-0.035*** [-2.66]	-0.081*** [-2.88]	-0.080* [-3.08]	-0.044*** [-3.34]
ln CE	-0.076** [2.14]	-0.080** [-2.32]	-0.089* [-1.99]	-0.085* [-2.00]	-0.096*** [-2.72]	-0.019* [-3.19]
R-squared	0.81	0.74	0.53	0.87	0.81	0.71
Adjusted R-squared	0.64	0.63	0.86	0.77	0.73	0.76

Note: Asterisks *, **, and*** denote 10%, 5% and 1% levels of significance, respectively.

Table 12: FMOLS and DOLS estimates for EKC specification

	Model 1: *EE = CO2*		Model 2: *EE=CH4*		Model 3: *EE = N2O*	
	FMOLS	DOLS	FMOLS	DOLS	FMOLS	DOLS
lnGDP	3.365*** [6.38]	1.732*** [2.61]	4.471*** [3.09]	3.083*** [6.97]	2.865*** [4.44]	1.827*** [2.92]

$lnGDP^2$	-1.125*** [-2.95]	-0.656*** [-2.33]	-2.562*** [-4.93]	-1.892*** [-2.76]	-0.205*** [-2.52]	-0.138*** [-2.65]
lnRE	-0.097*** [-2.76]	-0.045*** [-2.40]	-0.029** [-2.12]	-0.091** [-2.24]	-0.045** [-2.38]	-0.051** [-3.23]
lnENEF	-0.067** [-2.34]	-0.030** [-2.18]	-0.085*** [-2.66]	-0.083** [-2.33]	-0.069** [-2.32]	-0.051*** [-2.61]
lnGDP X CE	0.081** [2.11]	0.019* [2.07]	0.047** [2.17]	0.850*** [3.37]	0.032*** [2.95]	1.207*** [3.07]
$lnGDP^2$ X CE	-0.051** [-2.26]	-0.168** [-2.19]	-0.101*** [-2.57]	-0.074** [-2.16]	-0.055*** [-2.66]	-0.732*** [-5.70]
R-squared	0.92	0.73	0.88	0.76	0.98	0.87
Adjusted R-squared	0.74	0.86	0.78	0.67	0.64	0.65

Note: Asterisks *, **, and*** denote 10%, 5% and 1% levels of significance, respectively.

5. Conclusion

The present work aimed to examine the impact of the circular economy on environmental emissions in a panel of EU countries. This study, in contrast to previous research, employs three measures of environmental emissions of *CO2, CH4, and N2O* to conduct a thorough analysis for countries in the European Union on the relationship between the circular economy and environmental emissions for the years 2000 to 2020. The result shows that there is a long-term relationship between income, income square, renewable energy, circular economy, and environmental emissions using the Pedroni cointegration test. Subsequently, the ARDL estimation is utilized to investigate both short- and long-term impacts on environmental emissions. The results validate the existence of the Environmental Kuznets Curve (EKC) in EU countries and demonstrate that income, income squared, and renewable energy have positive and negative effects on environmental emissions, respectively. More significantly, ARDL's findings show that environmental emissions and the circular economy have negative effects over the long and short term. This suggests that through lowering carbon, methane, and nitroxide emissions, circular economy practices enhance environmental quality.

The discovery that a circular economy can reduce emissions and improve the quality of the environment suggests two policy implications for the EU as well as other countries, as follows:

1. This study recommends that governments implement targeted fiscal incentives for renewable energy adoption and circular economy production systems. For example, industries that contribute significantly to greenhouse emissions may receive grants or tax breaks, particularly for adopting circular practices. These measures will prioritize sectors with the highest emission intensity as identified in country-level analyses. For

example, in the energy sector, governments can provide tax credits to encourage the adoption of renewable energy, focusing on reducing CO_2 emissions. In waste management, grants can be offered for implementing methane capture systems to mitigate CH_4 emissions. Similarly, in agriculture, subsidies can be introduced for technologies that lower N_2O emissions, such as precision farming and organic waste recycling.

2. Given the significant impact of the circular economy on emissions, environmental regulations should mandate a minimum recycling rate and set standards for recycling rates, waste reduction, and the use of recycled materials in manufacturing processes. Additionally, policymakers may require companies to submit environmental performance reports to ensure transparency and compliance with circular economy principles. By integrating circular economy practices into regulatory frameworks, governments can ensure that companies in all industries contribute to environmental sustainability and the reduction of emissions. For instance, policymakers should mandate recycling standards with clear benchmarks, like requiring a minimum of 40% recycled content in manufacturing by 2030 and Enforcing methane capture from landfills that exceed a threshold of CH_4 emissions.

One promising avenue for future study is to examine how the circular economy is affecting various economic sectors, including manufacturing, agriculture, and services. Gaining a better understanding of sector-specific findings would help identify the practices that work best in various situations, enabling more specialized and sector-appropriate policy recommendations.

Data availability

The dataset generated and analyzed during the current study are not publicly available but are anonymized and available from the corresponding author on reasonable request.

References

Adebayo, T. S., & Ullah, S. (2024). Towards a sustainable future: The role of energy efficiency, renewable energy, and urbanization in limiting CO2 emissions in Sweden. Sustainable Development, 32(1), 244-259.

Alharthi, M., Dogan, E., & Taskin, D. (2021). Analysis of CO 2 emissions and energy consumption by sources in MENA countries: evidence from quantile regressions. Environmental Science and Pollution Research, 28, 38901-38908.

Akram, R., Chen, F., Khalid, F., Ye, Z., & Majeed, M. T. (2020). Heterogeneous effects of energy efficiency and renewable energy on carbon emissions: Evidence from developing countries. Journal of cleaner production, 247, 119122.

Akram, R., Majeed, M. T., Fareed, Z., Khalid, F., & Ye, C. (2020a). Asymmetric effects of energy efficiency and renewable energy on carbon emissions of BRICS economies: evidence from nonlinear panel autoregressive distributed lag model. Environmental science and pollution research, 27, 18254-18268.

Akram, R., Umar, M., Xiaoli, G., & Chen, F. (2022). Dynamic linkages between energy efficiency, renewable energy along with economic growth and carbon emission. A case of MINT countries an asymmetric analysis. Energy Reports, 8, 2119-2130.

Ansari, M. A., Khan, N. A., & Ganaie, A. A. (2019). Does foreign direct investment impede environmental quality in Asian countries? A panel data analysis. OPEC Energy Review, 43(2), 109-135.

Apergis, N., & Payne, J. E. (2012). Renewable and non-renewable energy consumption-growth nexus: Evidence from a panel error correction model. Energy economics, 34(3), 733-738.

Balsalobre-Lorente, D., Ibáñez-Luzón, L., Usman, M., & Shahbaz, M. (2022). The environmental Kuznets curve, based on the economic complexity, and the pollution haven hypothesis in PIIGS countries. Renewable Energy, 185, 1441-1455.

Bayar, Y., Gavriletea, M. D., Sauer, S., & Paun, D. (2021). Impact of municipal waste recycling and renewable energy consumption on CO2 emissions across the European Union (EU) member countries.Sustainability, 13(2), 656

Bayar, Y., & Gavriletea, M. D. (2019). Energy efficiency, renewable energy, economic growth: evidence from emerging market economies. Quality & Quantity, 53, 2221-2234.

Bento, J. P. C., & Moutinho, V. (2016). CO2 emissions, non-renewable and renewable electricity production, economic growth, and international trade in Italy. Renewable and sustainable energy reviews, 55, 142-155.

Bilgili, F., Koçak, E., & Bulut, Ü. (2016). The dynamic impact of renewable energy consumption on CO2 emissions: a revisited Environmental Kuznets Curve approach. Renewable and Sustainable Energy Reviews, 54, 838-845.

Bilgili, F., Balsalobre-Lorente, D., Kuşkaya, S., Alnour, M., Önderol, S., & Hoque, M. E. (2023). Are research and development on energy efficiency and energy sources effective in the level of CO2 emissions? Fresh evidence from EU data. Environment, Development and Sustainability, 1-37.

Blomsma, F., & Tennant, M. (2020). Circular economy: Preserving materials or products? Introducing the Resource States framework. Resources, Conservation and Recycling, 156, 104698.

Climate Watch (2023). Climate Watch. Retrieved January 2024 from: https://www.climatewatchdata.org/

Cudjoe, D., Wang, H., & Zhu, B. (2021). Assessment of the potential energy and environmental benefits of solid waste recycling in China. Journal of Environmental Management, 295, 113072

Danish, and Recep Ulucak. "The pathway toward pollution mitigation: does institutional quality make a difference?." Business Strategy and the Environment 29.8 (2020): 3571-3583.

Destek, M. A., & Sarkodie, S. A. (2019). Investigation of environmental Kuznets curve for ecological footprint: the role of energy and financial development. Science of the total environment, 650, 2483-2489.

Destek, M. A., & Sinha, A. (2020). Renewable, non-renewable energy consumption, economic growth, trade openness and ecological footprint: Evidence from organisation for economic Co-operation and development countries. Journal of cleaner production, 242, 118537.

Duodu, E., Kwarteng, E., Oteng-Abayie, E. F., & Frimpong, P. B. (2021). Foreign direct investments and environmental quality in sub-Saharan Africa: the merits of policy and institutions for environmental sustainability. Environmental Science and Pollution Research, 28, 66101-66120.

Eurostat (2023). Database. Retrieved January 2024 from: https://ec.europa.eu/eurostat.

Grossman, G. M., & Krueger, A. B. (1991). Environmental impacts of a North American free trade agreement.

Hailemariam, A., & Erdiaw-Kwasie, M. O. (2023). Towards a circular economy: Implications for emission reduction and environmental sustainability. Business Strategy and the Environment, 32(4), 1951-1965.

Islam, M. S., & Rahaman, S. H. (2023). The asymmetric effect of ICT on CO2 emissions in the context of an EKC framework in GCC countries: the role of energy consumption, energy intensity, trade, and financial development. Environmental Science and Pollution Research, 30(31), 77729-77741.

Isik, C., Ongan, S., Ozdemir, D., Ahmad, M., Irfan, M., Alvarado, R., & Ongan, A. (2021). The increases and decreases of the environment Kuznets curve (EKC) for 8 OECD countries. Environmental Science and Pollution Research, 28, 28535-28543.

Khan, K., Su, C. W., Tao, R., & Hao, L. N. (2020). Urbanization and carbon emission: causality evidence from the new industrialized economies. Environment, development and sustainability, 22, 7193-7213.

Kartal, M. T., Erdogan, S., Alola, A. A., & Pata, U. K. (2023). Impact of renewable energy investments in curbing sectoral CO2 emissions: Evidence from China by nonlinear quantile approaches. Environmental Science and Pollution Research, 30(52), 112673-112685.

Khan, S. A. R., Yu, Z., Belhadi, A., & Mardani, A. (2020). Investigating the effects of renewable energy on international trade and environmental quality. Journal of Environmental management, 272, 111089.

Khan, K., & Khurshid, A. (2024). Are technology innovation and circular economy remedy for emissions? Evidence from the Netherlands. Environment, Development and Sustainability, 26(1), 1435-1449.

Khan, S. A. R., Zia-Ul-Haq, H. M., Ponce, P., & Janjua, L. (2023). Re-investigating the impact of non-renewable and renewable energy on environmental quality: A roadmap towards sustainable development. Resources Policy, 81, 103411.

Khan, H., Weili, L., & Khan, I. (2022). Environmental innovation, trade openness and quality institutions: an integrated investigation about environmental sustainability. Environment, Development and Sustainability, 1-31.

Kostakis, I., Armaos, S., Abeliotis, K., & Theodoropoulou, E. (2023). The investigation of EKC within CO2 emissions framework: Empirical evidence from selected cross-correlated countries. Sustainability Analytics and Modeling, 3, 100015.

Le, T. H., Chang, Y., & Park, D. (2016). Trade openness and environmental quality: International evidence. Energy policy, 92, 45-55.

Lei, W., Xie, Y., Hafeez, M., & Ullah, S. (2022). Assessing the dynamic linkage between energy efficiency, renewable energy consumption, and CO 2 emissions in China. Environmental Science and Pollution Research, 1-13.

Liu, Z., Adams, M., & Walker, T. R. (2018). Are exports of recyclables from developed to developing countries waste pollution transfer or part of the global circular economy?. Resources, Conservation and Recycling, 136, 22-23.

Matsumoto, T., & Daudey, L. (2014). Urban green growth in dynamic Asia: a conceptual framework.

Mawutor, J. K. M., Sogah, E., & Gborse, F. C. (2023). Circular economy and carbon emissions: Threshold effect of quality of governance. Management of Environmental Quality: An International Journal.

Mazur-Wierzbicka, E. (2021). Circular economy: advancement of European Union countries. Environmental Sciences Europe, 33, 1-15.

Mirza, F. M., Sinha, A., Khan, J. R., Kalugina, O. A., & Zafar, M. W. (2022). Impact of energy efficiency on CO2 Emissions: Empirical evidence from developing countries. Gondwana Research, 106, 64-77.

Muhammad, B., Khan, M. K., Khan, M. I., & Khan, S. (2021). Impact of foreign direct investment, natural resources, renewable energy consumption, and economic growth on environmental degradation: evidence from BRICS, developing, developed and global countries. Environmental Science and Pollution Research, 28, 21789-21798.

Nabaweesi, J., Kigongo, T. K., Buyinza, F., Adaramola, M. S., Namagembe, S., & Nkote, I. N. (2024). Investigating the modern renewable energy-environmental Kuznets curve (REKC) hypothesis for East Africa Community (EAC) countries. Technological Sustainability, 3(1), 76-95.

Öztürk, S., Han, V., & Özsolak, B. (2023). How do renewable energy, gross capital formation, and natural resource rent affect economic growth in G7 countries? Evidence from the novel GMM-PVAR approach. Environmental Science and Pollution Research, 30(32), 78438-78448.

Pata, U. K. (2021). Renewable and non-renewable energy consumption, economic complexity, CO 2 emissions, and ecological footprint in the USA: testing the EKC hypothesis with a structural break. Environmental Science and Pollution Research, 28, 846-861.

Pata, U. K., & Kartal, M. T. (2023). Impact of nuclear and renewable energy sources on environment quality: Testing the EKC and LCC hypotheses for South Korea. Nuclear Engineering and Technology, 55(2), 587-594.

Pata, U. K., & Yurtkuran, S. (2023). Is the EKC hypothesis valid in the five highly globalized countries of the European Union? An empirical investigation with smooth structural shifts. Environmental Monitoring and Assessment, 195(1), 17.

Pata, U. K., & Yurtkuran, S. (2023). Is the EKC hypothesis valid in the five highly globalized countries of the European Union? An empirical investigation with smooth structural shifts. Environmental Monitoring and Assessment, 195(1), 17.

Pata, U. K., & Karlilar, S. (2024). The integrated influence of energy security risk and green innovation on the material footprint: An EKC analysis based on fossil material flows. Journal of Cleaner Production, 435, 140469.

Pedroni, P. (1996). Fully modified OLS for heterogeneous cointegrated panels and the case of purchasing power parity. Manuscript, Department of Economics, Indiana University, 5, 1-45.

Prempeh, K. B. (2024). The role of economic growth, financial development, globalization, renewable energy and industrialization in reducing environmental degradation in the economic community of West African States. Cogent Economics & Finance, 12(1), 2308675.

Schroeder, P., Anggraeni, K., & Weber, U. (2019). The relevance of circular economy practices to the sustainable development goals. Journal of Industrial Ecology, 23(1), 77-95.

Shahbaz, M., Shafiullah, M., Khalid, U., & Song, M. (2020). A nonparametric analysis of energy environmental Kuznets Curve in Chinese Provinces. Energy Economics, 89, 104814.

Sharif, A., Mishra, S., Sinha, A., Jiao, Z., Shahbaz, M., & Afshan, S. (2020). The renewable energy consumption-environmental degradation nexus in Top-10 polluted countries: Fresh insights from quantile-on-quantile regression approach. Renewable Energy, 150, 670-690.

Tenaw, D., & Beyene, A. D. (2021). Environmental sustainability and economic development in sub-Saharan Africa: A modified EKC hypothesis. Renewable and Sustainable Energy Reviews, 143, 110897.

Tiwari, S., Mohammed, K. S., Mentel, G., Majewski, S., & Shahzadi, I. (2023). Role of circular economy, energy transition, environmental policy stringency, and supply chain pressure on CO2 emissions in emerging economies. Geoscience Frontiers, 101682.

Uddin, M. M. M., Sharif, T., Islam, A. R. M., & Abedin, M. Z. (2024). Moderating impact of FDI on the growth-environment nexus in the pre-COVID-19 eras. Research in International Business and Finance, 67, 102114.

United Nations Framework Convention on Climate Change (2015). INDC submission. Retrieved from http://unfccc.int/focus/indc_portal/items/8766.php

Ulucak, Z. Ş., İlkay, S. Ç., Özcan, B., & Gedikli, A. (2020). Financial globalization and environmental degradation nexus: evidence from emerging economies. Resources Policy, 67, 101698.

Wang, Q., Li, C., & Li, R. (2023). Could the digital economy increase renewable energy and reduce carbon emissions? Empirical research on EKC in 67 countries. Environmental Science and Pollution Research, 30(31), 77150-77164.

Wang, Q., Wang, X., Li, R., & Jiang, X. (2024). Reinvestigating the environmental Kuznets curve (EKC) of carbon emissions and ecological footprint in 147 countries: a matter of trade protectionism. Humanities and Social Sciences Communications, 11(1), 1-17.

Wang, R., Wang, Q., & Yao, S. (2021). Evaluation and difference analysis of regional energy efficiency in China under the carbon neutrality targets: Insights from DEA and Theil models. Journal of environmental management, 293, 112958.

World Bank (2023). World Development Indicators. Retrieved January 2024 from: http://data.worldbank.org/indicator.

Appendix A

Table A1: Long-run and Short-run estimates with alternative measure of circular economy

	Model 1: *EE = CO2*	Model 2: *EE=CH4*	Model 3: *EE = N2O*
Long-run equation			
lnGDP	2.181*** [2.83]	1.108*** [3.25]	1.830*** [3.96]
$lnGDP^2$	-0.048* [-1.92]	-0.885*** [-3.38]	-0.277*** [-2.46]
lnRE	-0.021** [-2.21]	-0.047* [-1.93]	-0.048*** [-2.41]
lnENEF	-0.042** [-2.16]	-0.109** [-2.33]	-0.073** [-2.39]
lnCE	-0.074*** [-3.13]	-0.013* [-2.09]	-0.032* [-2.11]
Short-run equation			
Δ*lnGDP*	3.035*** [5.16]	1.881*** [3.59]	1.010** (2.12)
$\Delta lnGDP^2$	2.507*** [-5.51]	-0.663*** [-2.45]	-0.037** [-2.26]
Δ*lnRE*	-0.073*** [-2.40]	-0.020 * [-2.07]	-0.011* [-1.92]
Δ*lnENEF*	-0.081** [-2.17]	-0.032*** [-3.15]	-0.002*** [-3.08]
Δ*lnCE*	-0.025** [-2.16]	-0.082* [-2.00]	-0.047*** [-2.66]
ECT(− 1)	-0.695** [-2.56]	-0.039*** [-2.89]	-0.054* (-2.02)
Diagnostic tests			
Autocorrelation	0.400[0.45]	0.022[0.32]	0.597[0.52]

Heteroscedasticity	0.094[0.42]	0.306[0.55]	0.069[0.20]
Normality	0.058[0.33]	0.013[0.77]	0.037[0.69]
Stability	0.290[0.97]	0.037[0.28]	0.074[0.85]

Note: Asterisks *, **, and*** denote 10%, 5% and 1% levels of significance, respectively. The circular economy is proxied by Circular material use rate (percentage).

Table A2 : Long-run and Short-run estimates with additional controlled variables

	Model 1: $EE = CO2$	Model 2: $EE=CH4$	Model 3: $EE = N2O$
Long-run equation			
lnGDP	2.420*** [2.55]	1.065** [2.26]	2.710*** [4.22]
$lnGDP^2$	-0.278** [-2.25]	-0.659*** [3.18]	-1.483** [-2.18]
lnRE	- 0.086* [-1.99]	- 0.014* [-2.05]	- 0.291*** [-2.94]
lnENEF	-0.054* [-2.06]	- 0.085** [-2.23]	- 0.071* [-2.09]
lnCE	-0.043** [-2.25]	-0.163** [-2.30]	-0.047*** [-3.19]
lnEPRI	-0.062 [2.00]	-0.052* [-2.11]	-0.013*** [-2.47]
lnTC	-0.008*** [-3.54]	-0.046*** [-2.39]	-0.082** [-2.14]
lnEP	- 0.030* [-2.94]	-0.261** [-2.24]	-0.049** [-2.10]
Short-run equation			
$\Delta lnGDP$	1.682*** [3.69]	2.365*** [3.56]	1.732*** [3.91]
$\Delta lnGDP^2$	-0.486** [-2.24]	-0.825*** [-2.56]	-0.656** [-2.34]
$\Delta lnRE$	- 0.003** [-2.18]	-0.097* [-1.96]	-0.045** [-2.20]
$\Delta lnENEF$	-0.084** [-2.31]	-0.087*** [-2.44]	-0.130* [-2.05]
$\Delta lnCE$	-0.076* [-2.12]	-0.081** [-2.31]	-0.019*** [-2.45]
$\Delta lnEPRI$	-0.035*	-0.021**	-0.068**

	[1.96]	[-2.26]	[-2.29]
$\Delta lnTC$	-0.1821* [-2.02]	-0.013** [-2.27]	-0.037** [-2.18]
$\Delta lnEP$	-0.082*** [-3.19]	-0.035** [-2.38]	-0.032*** [-3.05]
ECT (− 1)	-0.058*** [-2.75]	-0.068*** [-3.69]	-0.027*** [-3.09]
Diagnostic tests			
Autocorrelation	0.010[0.25]	0.009[0.17]	0.028[0.39]
Heteroscedasticity	0.095 [0.18]	0.012[0.26]	0.071[0.92]
Normality	0.045[0.29]	0.069[0.89]	0.031[0.15]
Stability	0.053[0.82]	0.082[0.62]	0.058[0.55]

Note: Asterisks *, **, and*** denote 10%, 5% and 1% levels of significance, respectively. Energy price (EPRI) proxy by electricity prices (Kilowatt-hour), technology changes (TC) proxy by public energy technology research, development, and demonstration budgets in per capita terms (Euro millions current PPPs) and environmental regulations (EP) proxy by Environmental Policy Stringency Index (index)