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Circular Pathways to Sustainable Development: Understanding the Links between Circular Economy Indicators, Economic Growth, Social Well-Being, and Environmental Performance in EU-27

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Abstract: The transition towards the circular economy (CE) is one of the major priorities of the European Union (EU). By observing its benefits through the prism of sustainable development, this study aims to reveal the intricate relationships between the CE and the economy–society–environment nexus across 27 EU countries during the period from 2012 to 2020. Utilizing an extensive dataset comprising 243 observations drawn from the EUROSTAT database, we employed a panel data analysis. In this research, we quantified the impact of CE indicators on key dependent variables: GDP per capita (economic dimension), mortality, morbidity, and the welfare cost associated with exposure to environment-related risks (social dimension) and greenhouse gas (GHG) emissions in the environmental realm. The findings of our study illuminate the multifaceted connections between circular economy practices and the broader goals of sustainable development within the EU-27 context. The CE indicators aggregated at the EU level not only have a beneficial impact on the economy but also on society and the environment. The analysis reveals that each of the six explanatory variables incorporated into the models exhibits the anticipated relationship with at least one of the outcome variables. This research contributes valuable insights for policymakers, public authorities, and other stakeholders seeking to enhance the circular economy landscape in respective countries.

Keywords: circular economy; indicators; sustainable development; policy insights; panel data; EU-27

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1. Introduction

The increasing demand for material goods and services conflicts with the finite nature of resources. To address this challenge, there is a need to make a transition from a linear economic model to a circular economy (CE) framework [1]. In this context, the "production-consumption-waste" sequence should be transformed towards a more regenerative set of economic activities, where materials can be reused and recovered [2].

The concept of CE has been the focus of many scholars, practitioners, and policy-makers. It is considered as an important pipeline to operationalize business activities through innovation and design [3]. Conversely, the definition of CE remains unclear, with a multitude of interpretations found in the literature [4]. These various viewpoints are presented by experts, contingent upon their specific areas of knowledge and the sectors which CE is affiliated with. Moreover, context dependence, the evolution of understanding, and diverse business strategies make it even more complex to draw a holistic picture of the CE. However, there is a consensus on some aspects of CE in the literature. By enlarging the number of studies on the definitions of CE, it can be noted that the major characteristic of all is the "closed loop" system as a significant prerequisite for achieving circularity [2]. This essentially solves a few major problems: resource scarcity and pollution. In closed-loop systems, the need for new materials can be significantly reduced; thus, the pollution followed by resource extraction is also eliminated. For instance, the adoption of a circular economy model within the mobility, food, and built environment sectors is projected to result in a noteworthy reduction in emissions. By the year 2030, emissions are estimated to decrease by 38% in the built environment sector with CE practices. Similarly, within the realm of agriculture, making a transition to regenerative farming methods, cutting down on food wastage, and incorporating improved and repurposed ingredients in our food offerings have the potential to reduce food system emissions by half by the year 2050 [5]. Furthermore, the European Union's circular economy package is anticipated to yield cost savings of approximately EUR 600 billion through initiatives like waste prevention, eco-design, and re-use. It is expected that CE will also stimulate job creation within the same timeframe [6].

1.1. CE and Sustainable Development

The CE is frequently regarded as a mechanism conducive to achieving sustainable development by addressing its three-dimensional pillars. Numerous scholars and institutions have proffered definitions and characterizations of the CE that exhibit a significant nexus with the principles of sustainable development. For instance, Korhonen et al. emphasize that the CE is an initiative focused on sustainable development, aiming to reduce the linear flow of materials and energy in societal production–consumption systems [7]. Murray et al. describe the circular economy as an economic model that optimizes planning, resourcing, procurement, production, and reprocessing to enhance ecosystem functioning and human well-being [8]. Geissdoerfer et al. characterize the circular economy as a regenerative system that minimizes resource input and waste, emissions, and energy leakage by slowing, closing, and narrowing material and energy loops [9]. Achieving this involves practices such as long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. The EU Action Plan for the Circular Economy underscores the importance of maintaining the value of products and materials for as long as possible, minimizing waste and resource use, and retaining resources within the economy to create further value when products reach the end of their lives [6]. On the other hand, the Ellen MacArthur Foundation envisions a circular economy as one designed to be restorative and regenerative, with a focus on maximizing the utility and value of products, components, and materials, while minimizing waste [5]. However, Kirchherr et al. (2017), in a systematic literature review of the CE definitions and perceptions, suggest that not all of the aspects of sustainable development are equally reflected in the framework of the CE [2]. For instance, they suggest that economic prosperity appears to be the key objective of the circular economy, especially among practitioners. Geissdoerfer et al. (2017, p. 765), Lieder and Rashid (2016, p. 46), and Sauvé et al. (2016, p. 54), however, mention that the existing discussions around CE focus more on environmental performance and quality [9–11]. Various review articles on the topic prove that social equity is often omitted from the discussions of the CE or that less attention is given to that aspect [12]. Nevertheless, the CE has a decisive role in accelerating the transition towards the regenerative, green, and socially just economic growth of the EU, "leaving no one behind". It is a government-level priority of the EU countries, which ensures a "climate-neutral, resource-efficient and competitive economy [6]".

It should be noted that the effectiveness of the CE model cannot be adequately monitored and evaluated without the generation of sufficient information and data about the system [13]. In this context, the CE indicators play pivotal roles in comprehending trends, development potentials, and transitional phases. These indicators not only aid in collecting exploratory data but also bolster the process of economic modeling to obtain more robust scientific insights on policy measures. The latter facilitates an assessment of the extent to which the expectations of policymakers have been realized and evaluate the efficiency of some strategic documents such as CE action plans. For instance, an extensive review of the literature revealed a growing number of scientific publications that have tried to estimate the impact of CE indicators on the economy since 2019. However, to the best of our knowledge, only a handful of scholars have undertaken quantitative modeling that integrates environmental and social perspectives into their work. Geissdoerfer et al. (2017) mentioned that a few dimensions of social benefits have been discussed in the literature on CE, such as employment opportunities. However, current studies lack an empirical focus, and they have not identified the relationship between a CE and human well-being [9]. Certainly, the reflection on the job creation through the CE is an important social aspect; however, it is also important to reveal how the well-being of people is influenced.

To fill this gap, this study will analyze the impact of CE indicators on all three aspects of sustainability within the context of the European Union from 2012 to 2020 through the estimation of a panel regression model.

1.2. Literature Review

EU waste production reaches up to 2.2 billion tons annually; thus it aims at implementing legislative measures on waste management to promote a more sustainable CE model [14]. Within the past decade, the EU has introduced ambitious targets for recycling and landfilling. For example, according to the European Environmental Agency, the EU plans to have a 60% recycling and reusing rate of municipal waste by 2030 [15]. To achieve these targets, the continent has a goal to apply the practices and principles of a CE. In 2018, the EU introduced four major categories to measure resource use and the CE. Those categories are production and consumption, waste management, secondary raw materials, competitiveness, and innovation. Each category has a set of quantitative indicators for the European countries, which are used to measure the CE-related actions and their efficiencies. These measures will be used to model the economic, environmental, and social impacts of CE. The table below (Table 1) summarizes some of the indicators in the mentioned categories [14].

Table 1. Circular economy indicators proposed by the European Union (source: EUROSTAT).

Category	Indicators with EUROSTAT Codes and Abbreviations	Measurement Unit
Production and Consumption	• Material footprint (cei_pc020) (MF)	• Tons per capita
	• Resource productivity (cei_pc030) (RP)	• Euro per capita
	• Waste generation per capita (cei_pc034) (WG^a)	• Kilograms per capita
	• Generation of waste excluding major mineral wastes per GDP unit (cei_pc032) (WG^b)	Kilograms per million Euro of GDP
Waste Management	• Recycling rate of municipal waste (cei_wm011) (RRMW)	Percentage (%)
	• Recycling rate of all waste excluding major mineral waste (cei_wm010) (RRW) (RRW)	Percentage (%)
Secondary Raw Materials	• Circular material use rate (cei_srm030) (CMU)	Percentage (%)
	• Trade in recyclable raw materials (cei_srm020) (TRRM)	Thousand EUR
Competitiveness and Innovation	• Private investment and gross added value related to circular economy sectors (cei_cie012) (PI/GAV)	Million EUR
	• Persons employed in circular economy sectors (cei_cie011) (CEEMP)	Number of persons employed

Based on these indicators, numerous studies have suggested that the outcomes of the transition to CE exhibit noteworthy disparities among various EU nations. Notably, Germany, France, the Netherlands, Italy, and Luxembourg emerge as leaders across most of these indicators (Figures 1–3, Figure A1 in Appendix B).

These countries also boast well-structured and comprehensive CE action plans that encompass a diverse spectrum of industries. It is worth highlighting that the Netherlands stands out with the highest average CMU and TRRM between 2012 and 2020, whereas Germany claims the top position concerning CEEMP, PI/GAV, and environmental tax revenues during the same timeframe. The database provided by the EUROSTAT has enabled many researchers to dig deeper into the impact of CE on diverse aspects of sustainability by applying various methodologies.

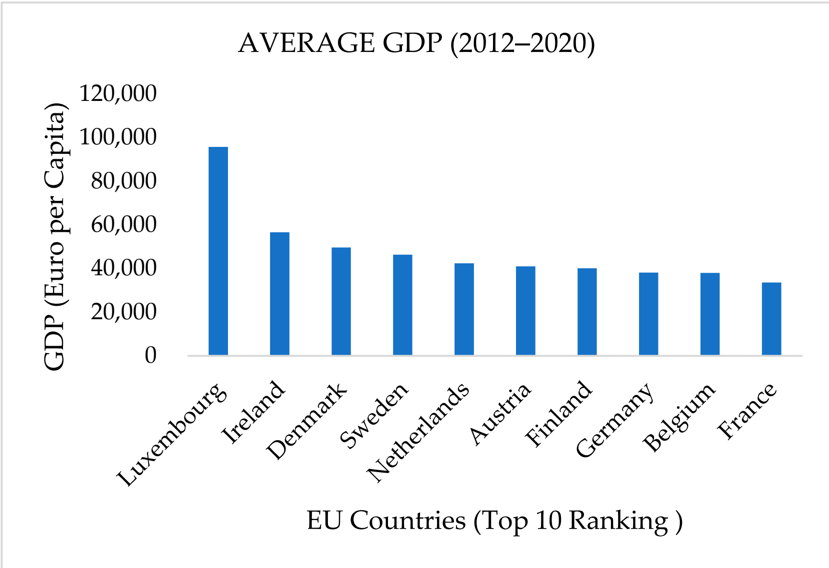

Figure 1. Bar charts of the CE indicators for EU countries between 2012 and 2020 on average; average of GDP (source: EUROSTAT).

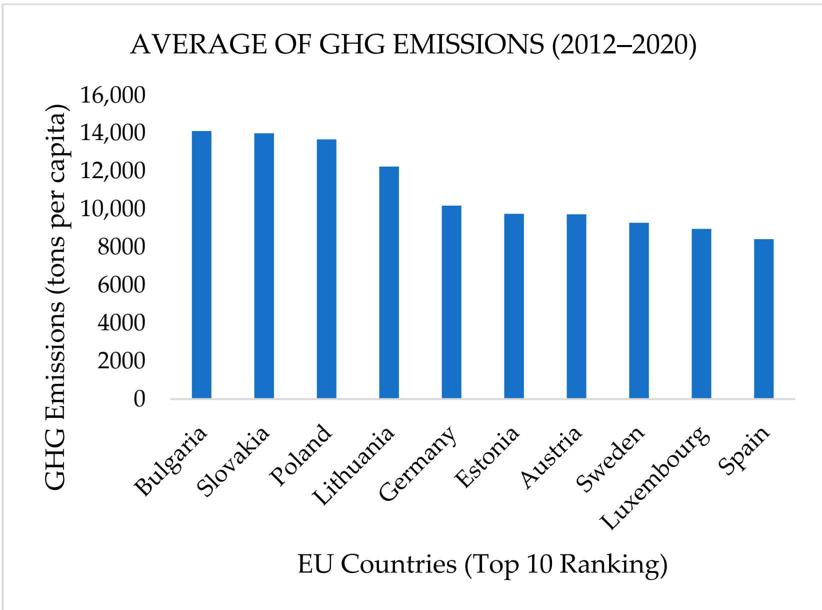

Figure 2. Bar charts of the CE indicators for EU countries between 2012 and 2020 on average; average of GHG (source: EUROSTAT).

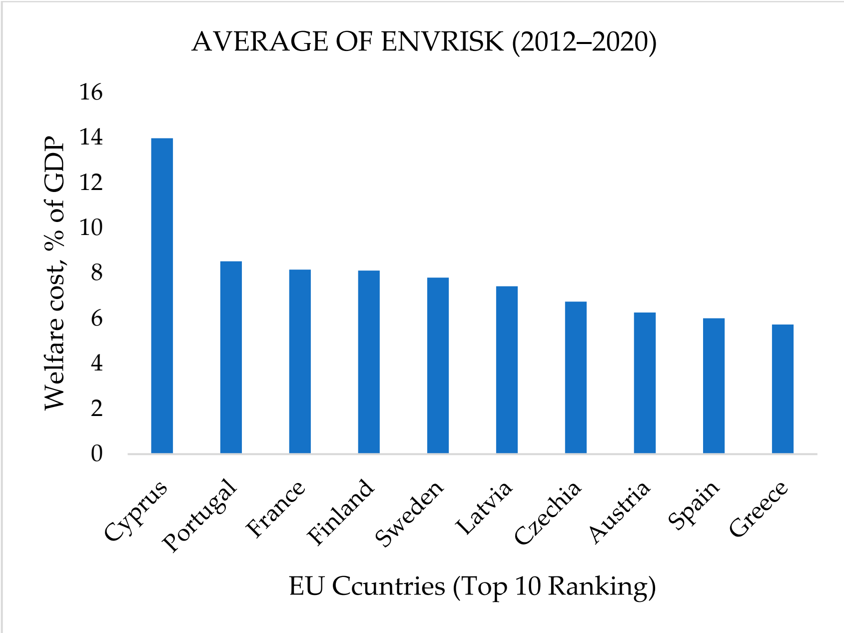

Figure 3. Bar charts of the CE indicators for EU countries between 2012 and 2020 on average; average of ENVRISK (source: EUROSTAT).

Table 2 summarizes the studies that have applied the above-mentioned indicators, with a few additions from the SDG indicators to build an econometric model. In these studies, researchers have identified the impact of the CE on the economy, environment, and society. Notably, most of the studies have included the timeframe until 2017 for the panel regression. The initial EU CE action plan was implemented in 2015, implying that substantial changes within just two years might not be readily apparent. Extending the timeframe until 2020 could offer a more comprehensive understanding of the developments and their impacts. Furthermore, the pooled OLS regression model prevails among the papers. Although the pooled OLS estimates can provide valuable information about the association between variables, bias and inconsistency may be present when there is serial correlation and endogeneity in the data.

Table 2. Summary of previous studies on the relationship between circular economy and sustainable development.

Authors	Time Period	Country/Region	Methodology
[16] Boubellouta and KuschBrandt (2020)	2000–2016	EU28 + 2	GMM
[17] Busu (2019)	2008–2017	EU-27	Pooled Regression
[1] Busu and Trica	2010–2017	EU-27	Pooled Regression
[18] Chen et al. (2022)	2010–2018	EU-25	Panel VECM
[19] Gardiner and Hajek (2020)	2000–2018	EU-28	Panel VECM
[20] Georgescu et al. (2022)	2000–2018	EU-25	Pooled OLS Regression
[21] Hysa et al. (2019)	2000–2017	EU-28	Panel Regression
[22] Magazzino et al. (2020)	1990–2017	Switzerland	Granger Causality Test
[23] Pineiro-Villaverde and García-Álvarez (2020)	2001–2018	EU-28	Pooled Regression

Table 2. *Cont.*

Authors	Time Period	Country/Region	Methodology
[24] Siminică et al. (2020)	2007–2018	EU-28	Panel Unrestricted VAR
[25] Sulich and Sołoducho (2022)	2009–2019	EU-28	Pooled Regression
[26] Sverko Grdic et al. (2020)	2008–2016	EU-28	Pooled Regression
[27] Tantau et al. (2018)	2010–2014	EU-28	Panel Regression
[28] Trica et al. (2019)	2007–2016	EU-27	Pooled Regression
[29] Vuţă et al. (2018)	2005–2016	EU-28	Panel Regression

The literature review suggests that the econometric model mostly aims at quantifying the relationship between the circular economy and economic growth. Only a handful of studies have included environmental and social indicators in the model. Trica and Busu discovered a significant connection between circular economy indicators and economic growth [28]. The verification of their model was accomplished through the pooled least square (PLS) technique. This analysis revealed that the most substantial impact on economic growth is attributed to real labor productivity. This is followed by resource productivity and the recycling rate of municipal waste. Additionally, Busu (2019) and Trica et al. (2019) separately conducted a comparable study utilizing the identical PLS model [17,28]. They arrived at the conclusion that environmental circular economy factors are notably linked to economic growth. Ferrante and Germani (2020) conducted two fixed-effects regressions with robust standard errors, revealing a robust connection between employment in the circular economy and socio-economic macro measures [30]. Apart from the economic dimension, Hailemariam et al. (2022) mentioned that a circular economy significantly improves environmental quality by reducing CO_2 emissions [31]. Thus, they suggest that businesses that stimulate recycling and circular economy practices play important roles, albeit from a distinct viewpoint.

Sulich et al. (2022) endeavored to determine which Sustainable Development Goals (SDGs) could be supported by the CE and how they could contribute to the proliferation of green jobs (GJs) [25]. This aspect essentially represents the social facet of sustainability. This finding was also validated by Luca et al. (2019), who confirmed the hypothesis that resource efficiency in business can create more green job opportunities [32]. This proves, once again, that the integration of CE practices has a positive social impact as well. As a result of our literature review, we noted that there are not enough papers that estimated the impact of CE on social dimension with a quantitative methodology. While not overtly addressed, this observation aligns well with the statement by Sulich et al. (2022), which mentioned that "The GJs creation process in the literature is described mostly qualitatively" [25].

With this regard, this study will focus on the impact of CE on the Gross Domestic Product (GDP), greenhouse gas emissions (GHGs), and mortality, morbidity, and welfare costs from exposure to environment-related risks from economic, environmental, and social perspectives, respectively. To the best of our knowledge, no previous study has investigated the impacts of all of the same chosen CE indicators on the mentioned outcome variables.

The article is structured as follows: Section 2 presents the materials and methods applied in this study; Section 3 presents the results; Section 4 discusses the findings; and Section 5 draws the major conclusions.

2. Materials and Methods

In this paper, we analyzed annual statistical data collected from the EUROSTAT database for 27 EU countries for the 2012–2020 period. As a result, we acquired 243 observations. The selected dependent and independent variables are provided in Table 3.

Table 3. Variables included in the models.

SDG Dimension	Dependent Variables	Independent Variables
Economic	GDP per capita (EUR per capita)	• Resource productivity (RP) • Recycling rate of all waste excluding major mineral waste (RRW) • Circular material use rate (CMU) • Trade in recyclable raw materials (TRRM) • Private investment and gross added value related to circular economy sectors (PI/GAV) • Persons employed in circular economy sectors (CEEMP) • Energy productivity (EP) • Environmental tax (ET)
Social	Mortality, morbidity, and welfare cost from exposure to environment-related risks (ENVRISK) (% of GDP)	
Environmental	GHG emissions (tons per capita)	

The measurement units of the independent variables taken from the EUROSTAT website are presented in Table 1. It is noteworthy that EP and ET are not explicitly mentioned in the CE indicators list. Given that CE refers to the strategies, governance, and principles focused on maximizing the efficient utilization of resources, encompassing both energy and materials, we decided to include EP and ET as additional indicators in the model.

To gain a more comprehensive understanding of the data incorporated in the model for EU-27 countries, we conducted an analysis of descriptive statistics, which is summarized in Table 4.

The descriptive statistics provide valuable insights into several key variables related to the economy and the environment. On average, the GDP per capita stands at approximately EUR 28,268.8, with a relatively wide standard deviation of approximately EUR 19,255.8. The minimum GDP per capita observed is EUR 5780, while the maximum reaches EUR 102,650, reflecting substantial variation across the dataset. In terms of GHG emissions per capita, the average is approximately 7836.4 tons, with a standard deviation of approximately 2998.5 tons. The ENVRISK, as a percentage of GDP, averages around 4.5%, with a standard deviation of approximately 3.1%. The circular material use (CMU) percentage averages 8.8%, with a standard deviation of approximately 6.4%, implying variability in the extent to which circular materials are utilized within the economy. These statistics provide a foundational understanding of the economic and environmental indicators, shedding light on their central tendencies and variations in the dataset.

Table 4. Descriptive statistics of the variables included in the model.

Variable	Measurement Unit	Obs.	Mean	Std. Dev.	Min	Max
GDP	Euro per Capita	243	28,268.8	19,255.8	5780.0	102,650
GHG	Tones per Capita	243	7836.4	2998.5	3786.8	16,698.2
ENVRISK	% of GDP	243	4.5	3.1	0.5	14.6
CMU	Percentage, %	243	8.8	6.4	1.3	30
TRRM	Thousand Euro	243	1,463,359	1,879,035.1	738.4	8,490,835.7
CEEMP	Number of People	243	137,247	191,738.5	1722	764,770
ET	Million Euro	243	11,271.2	16,630.2	205.5	61,444.9
RP	Euro per kg	243	1.8	1.1	0.3	4.5
PI/GAV	Million Euro	243	3300.2	5754.7	33	34,489
RRW	Percentage, %	243	51.2	16.2	10	87
EP	Euro per kg	243	7	3.2	2.1	22.4

Note: In the table above, the "Obs." refers to the number of observations, and "Std. Dev." refers to standard deviation.

Diving deeper into the dataset, the following general forms have been applied for panel data analysis:

$$\text{Model 1}: \ln(\dot{GDP}it) = \beta_1 CMUit + \beta_2 Ln(TRRMit) + \beta_3 Ln(CEEMPit) + \beta_4 Ln(ETit) + \beta_5 Ln(RPit) + \beta_6 Ln(PI/GAVit) + \beta_7 RRWit + \beta_8 Ln(EPit) + \varepsilon$$

$$\text{Model 2}: \ln(\dot{GHG}it) = \beta_1 CMUit + \beta_2 Ln(TRRMit) + \beta_3 Ln(CEEMPit) + \beta_4 Ln(ETit) + \beta_5 Ln(RPit) + \beta_6 Ln(PI/GAVit) + \beta_7 RRWit + \beta_8 Ln(EPit) + \varepsilon$$

$$\text{Model 3}: \ln(\dot{ENVRISK}it) = \beta_1 CMUit + \beta_2 Ln(TRRMit) + \beta_3 Ln(CEEMPit) + \beta_4 Ln(ETit) + \beta_5 Ln(RPit) + \beta_6 Ln(PI/GAVit) + \beta_7 RRWit + \beta_8 Ln(EPit) + \varepsilon$$

The dependent variables and all other explanatory variables differ over time (t) and across countries (i). The variables that have measurement units other than percentages have been used in the log scale. β coefficients indicate the elasticity between explanatory variables and dependent variables. ε is the error term.

3. Results

Prior to performing the core regression analysis, we conducted a Pearson correlation analysis to assess the presence of multicollinearity among the selected variables.

Table 5 shows that ET is strongly correlated with the TRRM, CEEMP, as well as PI/GAV. The observed correlations may be attributed to the influence of environmental taxes, which serve as incentives for companies to be involved in sustainable practices such as recycling. When taxes are imposed on environmentally detrimental activities, businesses may find it economically beneficial to participate in recycling and engage in the trade of recyclable raw materials to mitigate tax liabilities. Moreover, the existence of environmental taxes often signifies robust regulatory frameworks, prompting companies to adhere more diligently to environmental regulations.

Furthermore, these regulatory frameworks can contribute to an enhanced market demand for recycled products, positioning them competitively against virgin products. As a result, the interplay of economic incentives, regulatory adherence, and market dynamics underscores the multifaceted impact of environmental taxes on fostering sustainable practices and influencing trade patterns in recyclable materials.

Table 5. Matrix of correlations.

Variables	CMU	TRRM	CEEMP	ET	RP	PI	RRW	EP
CMU	1.000							
TRRM	0.643	1.000						
CEEMP	0.386	0.662	1.000					
ET	0.558	0.721	0.906	1.000				
RP	0.650	0.592	0.309	0.523	1.000			
PI	0.526	0.614	0.799	0.879	0.467	1.000		
RRW	0.536	0.299	0.143	0.238	0.505	0.224	1.000	
EP	0.094	0.325	0.149	0.309	0.643	0.263	0.259	1.000

In the meantime, PI/GAV is also strongly correlated with CEEMP. This correlation can be explained by the fact that private investment results in the expansion or establishment of circular economy sectors, which typically leads to the creation of new job opportunities [6]. A growing circular economy often requires a skilled and diverse workforce, contributing to an increase in the number of people employed in these sectors.

To avoid multicollinearity in the data set, ET and CEEMP variables have been dropped for further modeling.

Afterward, the panel data were analyzed by Pooled OLS and Fixed (FE) and Random Effects (RE) approaches. The Pooled OLS regression model is simply a linear regression model that is applied to the panel data using the OLS technique. FE removes the effect of time-invariant characteristics, which enables us to assess the net effect of the predictors. In other words, time-invariant characteristics like culture, religion, gender, and race are omitted. RE, on the other hand, assumes that the variation across entities is random and uncorrelated with the predictor or independent variables included in the model [33]. To decide between pooled OLS and FE and RE approaches, the Hausmann test as well as the Breusch and Pagan Lagrangian multiplier test for random effects were applied. The results of the Hausmann test to decide between FE or RE are presented in Table 6.

Table 6. Results of Hausmann test.

	(Model 1)	**(Model 2)**	**(Model 3)**
	Coef.	**Coef.**	**Coef.**
Chi-square test value	86.401	30.21	1.34
p-value	0.0000	0.0000	0.9697

As observed in the table, for Models 1 and 2, the p-values are less than 0.05 (assuming a 5% significance level). This indicates strong evidence to reject the null hypothesis that random effects are appropriate for the study. Consequently, we can conclude that the Fixed Effects (FE) model should be preferred. However, in the case of Model 3, we do not have sufficient evidence to reject the null hypothesis, suggesting that the Random Effects (RE) approach is appropriate. Furthermore, it is worth noting that the Breusch and Pagan Lagrangian multiplier test supports the suitability of the FE model for Models 1 and 2 at a 5% significance level, with p-values below 0.05.

The next step was checking the existing heteroscedasticity In the data. We ran the Modified Wald test for groupwise heteroskedasticity, and as a result, we rejected the null hypothesis, having strong evidence of heteroskedastic observations. To address this issue and potential autocorrelation, we applied a robust covariance matrix estimation across all panels.

As depicted in Table 7, our analysis reveals four variables exhibiting significant outcomes at the $p < 0.01$ significance level for Model 1: TRRM, PI/GAV, EP, and RWM. Notably, these variables display positive coefficients, indicating a positive correlation with the GDP. Specifically, 1% increases in TRRM, PI/GAV, EP, and RWM correspond to average GDP increases of 0.07%, 0.13%, 0.7%, and 0.004%, respectively. EP exerts the most substantial impact on the GDP, while RWM has the least influence.

Shifting our focus to Model 2, in which GHG emissions serve as the dependent variable, two variables—CMU and EP—yield statistically significant coefficients at the $p < 0.1$ and $p < 0.05$ levels, respectively. Remarkably, 1% growths in CMU and EP result in an average reduction in GHG emissions by 0.01% and 0.5%, respectively. Once again, EP emerges as the most influential variable affecting GHG emissions in this model.

In Model 3, the explanatory variables RP, PI/GAV, and EP exhibit varying levels of significance. A 1% increase in these variables translates to decreases in ENVRISK by 0.8%, 0.4%, and 1.1%, respectively. Additionally, it can be noted that R^2 differs for the three models, having the highest indicator (74%) for Model 1, 26% for Model 2, and 28% for Model 3. Notably, at least two of the variables have significant impacts on either of the dependent variables.

Table 7. Regression results for designed models.

Variables	**(1)**	**(2)**	**(3)**
	GDP	GHG	ENVRISK
CMU	−0.002	−0.009 *	−0.006
	(0.004)	(0.005)	(0.027)
TRRM	0.078 ***	−0.04	0.059
	(0.027)	(0.059)	(0.246)
RP	0.085	−0.088	−0.839 ***
	(0.092)	(0.118)	(0.296)
PI	0.129 ***	0.034	−0.412 ***
	(0.031)	(0.04)	(0.151)
EP	0.761 ***	−0.52 **	−1.146 *
	(0.15)	(0.221)	(0.592)
RRW	0.004 ***	0	−0.01
	(0.001)	(0.002)	(0.009)
Constant	6.544 ***	10.267 ***	9.513 ***
	(0.412)	(0.884)	(2.806)
Observations	243	243	243
R^2	0.74	0.26	0.28

Robust standard errors are in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4. Discussion

The circular economy has gained wide recognition in the private sector, public institutions, and academia. The benefits of a circular economy, as "an industrial system that is restorative or regenerative by intention and design" [2], has been discussed at different levels. The widely known system framework of the CE integration is composed of three major levels: micro, meso, and macro. The micro level mostly concentrates on enhancing the environmental performance of a specific organization, such as by decreasing resource usage, minimizing waste emissions, or creating products that are more environmentally conscious. At the meso level, the role of eco-industrial networks is emphasized, where the waste generated by one company is utilized as the raw material by another. On the other hand, the macro level refers to the CE integration at the national level through policies, regulations, or other government-led incentives [34].

The research context for this Investigation centered on the European Union (EU), recognized as a pioneering region in the advancement and promotion of circularity across the entire continent with a macro-level assessment.

The European Commission has a comprehensive array of policy measures and an action plan as a main building block of the European Green Deal. It is a set of legislative and non-legislative actions to ensure sustainable growth across the continent [35]. Furthermore, a circular economy monitoring framework has been established to facilitate the systematic assessment of the extent to which these actions effectively fulfill their overarching goals with regard to the economy, environment, and society.

Vasileios Rizos et al. (2017), in their research report "The Circular Economy: A Review of Definitions, Processes and Impacts", mention that the circular economy is often criticized due to the lack of emphasis on social dimensions, while Demailly and Novel (2014) argued that the net environmental impact of the circular economy is not visible [12,36]. Contributing to the discourse of the circular economy benefits, this paper suggests that the circular economy has a positive influence on sustainable economic development while addressing environmental and social aspects.

Model 1 reveals that the recycling rates of all waste, excluding major mineral waste, trade in recyclable raw materials, private investment, and gross added value related to circular economy sectors and energy productivity, positively influence the economies of EU countries. This finding is supported by a few similar studies such as those by Tantau et al. (2018), Busu (2019), as well as Busu and Trica et al. (2018) [1,17,27].

The results of Model 1 show that policies to stimulate private investment in the circular economy, trade in recyclable materials, as well as recycling itself are very important for economic growth.

In this regard, the role of private investment is decisive to the transition towards a circular economy. This can be achieved by the actions of impact investors, who are ready to take a below-market rate of return and often lower liquidity. Circular business models are usually perceived as risky; thus, the government should take an action to de-risk investment in priority areas for private investors. Ideally, this can be carried out through improving the public funding schemes and combining the efforts with the private sector through public–private partnerships (PPP). Integrating circular economy principles and financing through PPPs can facilitate the transition to a circular economy. Moreover, establishing global partnerships is at the core of the Sustainable Development Goals (SDG17). This model also reveals that the EU should facilitate the trade of recyclable raw materials by eliminating barriers to waste import and export [37].

It is noteworthy that the coefficients have the signs, as it was expected. Additionally, energy productivity proved to be an important factor for economic growth. Improved energy productivity can be due to energy efficiency and technological advancements. Energy efficiency reduces the cost of energy services, leaving available resources for households, businesses, and governments. The EU strives to increase the share of the renewables in energy mix as well; however, the cost of integrating renewable energy into the power grid has recently been on the rise. Therefore, the EU has adopted the motto of "efficiency first", as energy efficiency is the most affordable way to reduce GHG emissions, improve energy security, and enhance the social standing of its citizens amid the escalating energy costs [38].

In Model 2, the circular material use rate (CMU) proved to have a significant impact on GHG emissions and, as expected, with a negative sign. This finding is consistent with those of Harris et al. (2021), Kathan et al. (2016), Knaeble et al. (2022), who proved that recycling and sharing economy help to reduce GHG emissions, which is an important indicator in terms of sustainable development [39–41]. Along with CMU, the EP also has a negative impact on GHG emissions. Notably, processing recycled materials is associated with lower energy and carbon intensity compared to the processing of raw materials, resulting in a decreased overall energy requirement within the industry and consequently reducing greenhouse gas emissions [15].

Model 3 highlighted the impact of CE indicators on mortality, morbidity, and welfare costs from exposure to environment-related risks (ENVRISK). CE policies focused on waste management seek to mitigate environmental and health consequences. When waste generation is inevitable, the policies seek to encourage its reimagining as a valuable resource, leading to increased levels of recycling and the secure and responsible disposal of waste. To the best of our knowledge, previous studies have not included this variable in their model, which we selected to reflect the social benefits of the circular economy.

Our findings show that resource productivity, private investment, and energy productivity have negative relationships with the ENVRISK, as expected. Padilla-Rivera et al. (2020) and Valencia et al. (2023) have provided comprehensive insights into the social aspects of circularity in conjunction with sustainable development [42,43]. Among the benefits outlined, ENVRISK aligns with the "Labor Practices and Decent Work" category, including subcategories such as "Occupational Health and Safety" and "Quality and Well-Being" [42]. Additionally, Valencia et al. (2023) have placed physical and mental health, safety, and security within the "Quality of Life" category [43]. Hence, it is evident that the circular economy also delivers social advantages.

After highlighting the positive impacts of a circular economy, it is essential to recognize that, like any complex system, it is not without its limitations. While many CE indicators show promising relationships with the selected outcome variables, there are some environmental risks associated with circular practices. One of the limitations is connected to the second law of thermodynamics, e.g., the recycling of materials will always require energy from the search of inputs to the processing of the final product. Thus, complete recycling without waste and emissions is not impossible [7]. Transportation over long distances, as an important part of this process, can result in increased carbon emissions and environmental impacts. However, to tackle this challenge, renewable energy sources can be applied in the form of biofuel, solar and wind energy, etc. In addition, projects should be monitored and carefully analyzed to assess their sustainability impacts ahead of the implementations.

Another potential challenge can be the increasing trading amounts of recyclable materials. Although this indicator itself positively impacts economic growth, it can be a displacement rather than a solution to the existing problems [7]. Some countries may accept recyclable materials; however, they might lack the necessary environmental regulations, facilities, and infrastructure to treat the materials in a sustainable manner. As a result, the materials can be disposed of improperly and cause environmental hazards. Therefore, both for exporting and importing countries, the transparency and traceability measures need to be ensured by the public authorities to make sure that materials are treated responsibly.

Last but not the least, the CE investment projects can focus on the short-term impact rather than the long-term sustainability. This is mostly related to the private investments in CE when prioritizing economic gains at the expense of environmental and social considerations. To mitigate this issue, it is recommended to encourage private investors to have a long-term strategic plans integrated with sustainability principles. This can be carried out through strengthening the collaboration between academia, NGOs, and public authorities.

5. Conclusions

This study investigated the relations between the CE and the three pillars of sustainable development across 27 EU countries. Using a comprehensive dataset of CE indicators and macroeconomic measures from the European Union's statistical office, we found that the CE is closely aligned with sustainable development and can positively impact economic growth, environmental performance, and social well-being.

The findings can be useful for public authorities and policymakers to improve the circular economy landscape in their respective countries.

The limitation of our research is related to the temporal scope, as our panel data covers the timeframe of the 2012–2020 period. This limitation may be an obstacle to capturing the long-term effects of circular economy practices on selected macroeconomic indicators. The findings may not take potential changes or trends in circular economy adoption into account, which could limit the generalizability of the findings beyond the study period.

Future research might require longer-term data to provide a more comprehensive understanding of these dynamics. It is recommended to identify how the Circular Economy Action Plan in the EU has affected the transition towards circularity and conduct a before-and-after comparison. In addition, it is recommended to test other dependent variables from economic, social, and environmental pillars to reveal broader synergies between the CE and sustainable development.

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Appendix A

Table A1. Definitions of the selected variables according to EUROSTAT database.

Variables	Definitions
Resource productivity (cei_pc030) (RP)	The indicator is defined as the gross domestic product (GDP) divided by domestic material consumption (DMC). DMC measures the total amount of materials directly used by an economy. It is defined as the annual quantity of raw materials extracted from the domestic territory of the local economy, plus all physical imports minus all physical exports. It is important to note that the term 'consumption', as used in DMC, denotes apparent consumption and not final consumption. DMC does not include upstream flows related to imports and exports of raw materials and products originating outside of the local economy.
Recycling rate of all waste excluding major mineral waste (cei_wm010) (RRW) (RRW)	The indicator is calculated as recycled waste (RCV_R) divided by total waste treated excluding major mineral wastes (TRT), multiplied by 100. It is expressed in percent (%) as both terms are measured in the same unit, namely tonnes.
Circular material use rate (cei_srm030) (CMU)	The indicator measures the share of material recycled and fed back into the economy—thus saving extraction of primary raw materials - in overall material use. The circular material use, also known as circularity rate is defined as the ratio of the circular use of materials to the overall material use.
Trade in recyclable raw materials (cei_srm020) (TRRM)	The indicator measures the quantities recyclable waste and scrap as well as other secondary raw materials (by-products) that are shipped between the EU Members States (intra-EU) and across the EU borders (extra-EU). The indicator includes the following variables: • Intra-EU trade of selected recyclable raw materials (measured as the Imports from EU countries). • Imports from non-EU countries and exports to non-EU countries of selected recyclable raw materials (as regards extra-EU trade).
Private investment and gross added value related to circular economy sectors (cei_cie012) (PI/GAV)	The indicator includes "Gross investment in tangible goods" and "Value added at factor costs" in the following three sectors: the recycling sector, repair and reuse sector and rental and leasing sector.
Persons employed in circular economy sectors (cei_cie011) (CEEMP)	The indicator measures "Number of persons employed" in the following three sectors: the recycling sector, repair and reuse sector and rental and leasing sector. Jobs are expressed in number of persons employed and as a percentage of total employment.
Energy Productivity (EP)	The indicator measures the amount of economic output that is produced per unit of gross available energy. The gross available energy represents the quantity of energy products necessary to satisfy all demand of entities in the geographical area under consideration.
Environmental Tax (ET)	the indicator is presented as the proportion of environmental tax revenues in Gross Domestic Product (GDP). This allows a comparison of environmental taxation between Member States taking into account the size of the different national economies.

Appendix B

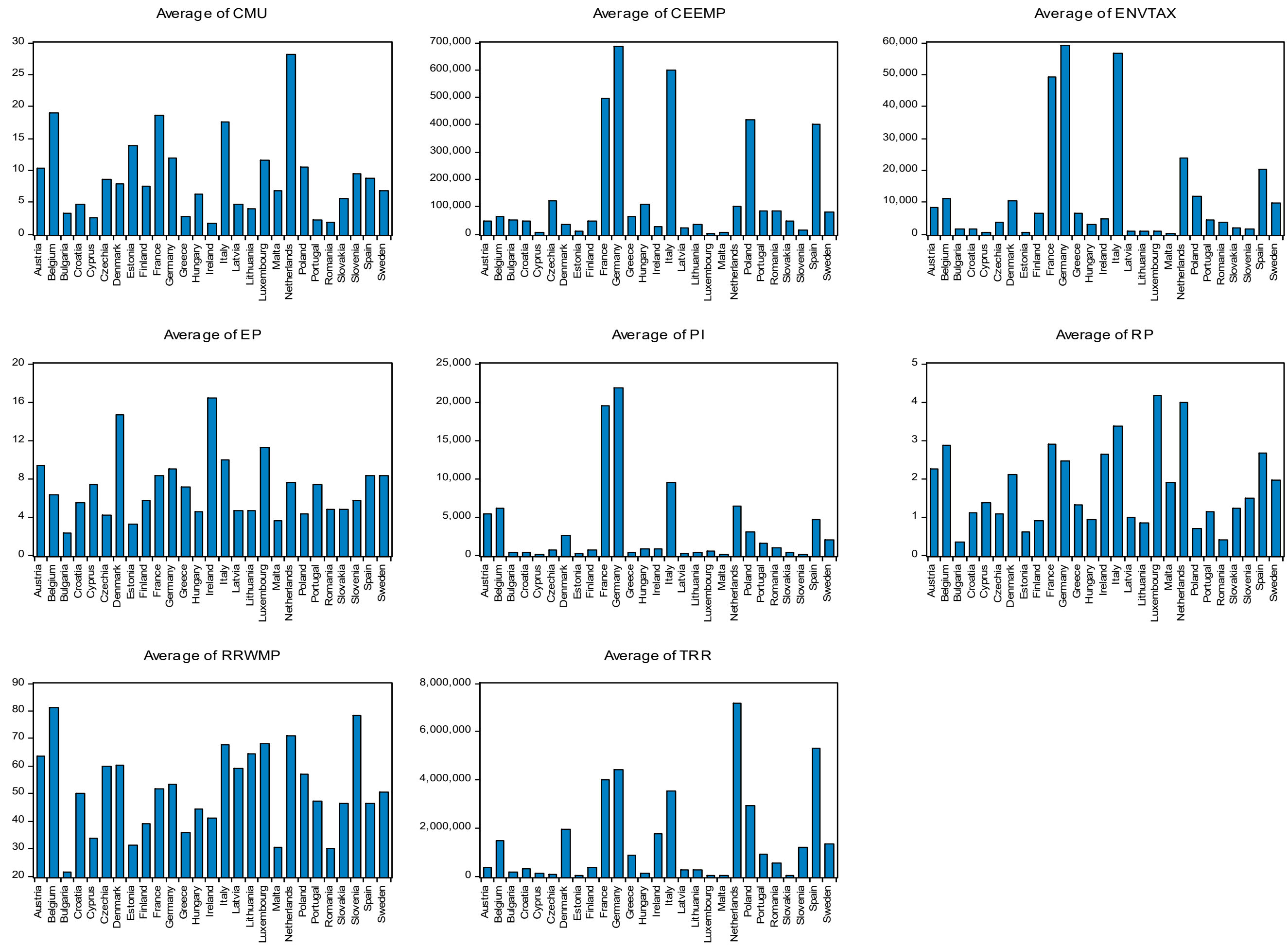

Figure A1. Additional bar charts of the CE indicators for EU countries between 2012 and 2020 on average.

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