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Empirical Analysis of Circular Economy in EU Countries for Environment Protection in Context of Resources Material and Waste Management

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Abstract The circular economy is crucial for EU countries, addressing environmental challenges and resource limitations. Transitioning to this model aims to disconnect economic growth from resource consumption, reducing degradation and fostering sustainability. Circular principles like waste reduction and resource efficiency benefit the environment and economy. They also ensure resilience against resource scarcity, which is crucial for long-term viability. This study examines the impact of the real gross domestic product (GDP) per capita, municipal waste generated, renewable energy sources, research and experimental development, and material footprint on resource productivity in EU countries (as a variable that measures the impact rate of the circular economy and environmental protection). Data proceedings in this study are time series indicators, with an annual frequency of 2000 – 2022. The statistical approach in the panel data model is used to find statistical significance, direct on-driven fixed factors, etc. Factors such as the previous value of resource productivity (which has the highest elasticity), real gross domestic product per capita, and municipal waste generation demonstrate a positive and statistically significant influence on the circular economy in the EU. Conversely, the material footprint factor shows a positive and statistically significant impact. The model indicates that all variables have maintained a stable territorial impact on resource productivity within each EU country. EU countries should advance to circular economy policies toward climate change requirements and environmental protection, focusing on waste management and minimizing waste generation.

Keywords Circular Economy, Environment Protection, Resources Productivity, Waste Management

1. Introduction

According to the European Commission [1], the circular economy is an economic approach focused on minimizing waste and maximizing resource efficiency. It involves reusing, repairing, refurbishing, and recycling products and materials to create a closed-loop system to reduce resource consumption and environmental impact while promoting sustainable growth. The circular economy is a system aimed at preserving the value of products, materials, and resources while minimizing waste generation. It involves reusing, repairing, remanufacturing, or recycling products.

The circular economy is approached with various European Union (EU) countries' priorities, such as green recovery, climate mitigation, energy savings, biodiversity protection, and sustainable development. The EU has set clear recycling targets and a comprehensive plan for modern waste management, including targets for recycling municipal and packaging waste, reducing landfills, and tackling food waste and marine litter. Transitioning to a circular economy is vital as the current linear consumption pattern is unsustainable, leading to overconsumption of natural resources. Georgescu et al. [2] explore the pursuit of sustainable economic growth through governmental initiatives aimed at economic, social, and environmental benefits. It shows the circular economy model concept, which prioritizes the effects of effective waste management. Various sectors contribute to the circular economy's sustainable and environmental outcomes correlated to research and development expenditure, municipal waste generation per capita, and the recycling rate of municipal waste. By 2050, the world will consume as if there were three Earths, necessitating a shift to a regenerative growth model. The circular economy focuses on maintaining the value of products, materials, and resources while minimizing waste generation, which is essential for achieving climate neutrality and halting biodiversity loss. Embracing circular practices will reduce pressure on natural resources, promote sustainable growth and job creation, and mitigate the environmental impacts of human economic activities.

Directive 2008/98/EC [3] outlines a waste hierarchy, prioritizing prevention, reuse, recycling, recovery, and disposal to enforce the 'polluter-pays principle' and extend producer responsibility. This directive distinguishes waste and by-products and mandates waste management without environmental harm. Producers or waste holders must obtain permits for treatment or handling, with national authorities required to establish waste management plans. It imposes minimum requirements for extended producer responsibility schemes, strengthening waste prevention rules. Member States of the EU must support sustainable production and consumption, promote resource-efficient products, reduce food waste, and curb hazardous substances. By 2025, at least 55% of municipal waste must be recycled, rising to 65% by 2035.

There are many reasons in favor of a circular economy compared with a linear or traditional economy, so promoting a circular economy includes [3, 4, 6]:

Resource efficiency: A circular economy aims to maximize the use of resources by keeping them in circulation as long as possible, thus minimizing resource extraction and waste generation.

Environmental sustainability: By reducing resource consumption, minimizing waste, and promoting recycling and reuse, a circular economy helps mitigate environmental degradation, conserve natural resources, and reduce pollution. It offers a pathway towards long-term sustainability by promoting a regenerative approach to economic development, ensuring the well-being of present and future generations.

Economic benefits: Transitioning to a circular economy can stimulate economic growth by developing new business opportunities, fostering innovation in resource management and recycling technologies, and reducing costs associated with waste disposal and resource extraction.

Cost savings: This leads to significant cost savings for businesses and households by optimizing resource use, reducing waste disposal costs, and promoting energy efficiency.

Climate change mitigation: Reducing the demand for pure materials and energy-intensive production processes, a circular economy can help mitigate greenhouse gas emissions and contribute to global efforts to combat climate change.

Biodiversity conservation: Contributing to biodiversity conservation by minimizing habitat destruction, reducing pollution, and promoting sustainable land and resource management practices.

Resilience to supply chain disruptions: A circular economy can enhance resilience to supply chain disruptions caused by factors such as natural disasters or geopolitical conflicts by diversifying supply chains, promoting local production, and reducing dependence on finite resources.

Social benefits: Promoting social inclusivity by creating job opportunities, improving access to affordable goods and services, and fostering community engagement through sharing platforms and repairing initiatives.

Innovation: Encouraging innovation in product design, manufacturing processes, and business models, driving technological advancements and improving industry competitiveness.

Nevertheless, there are some disadvantages to implementing and functionality of circular economy:

Implementation costs: Transitioning to a circular economy often requires significant upfront investments in new infrastructure, technologies, and processes, which can financially burden businesses and governments.

Complexity: The circular economy involves a shift from linear production and consumption patterns to more circular and sustainable models, which can be complex and challenging to implement across various sectors and industries.

Behavioral change: Achieving a circular economy requires changes in consumer behavior, including habits related to consumption, disposal, and recycling, which may be difficult to incentivize and sustain.

Market barriers: Existing market structures and regulations may restrict the adoption of circular practices, such as limited access to secondary materials, insufficient recycling infrastructure, and a lack of incentives for circular business models.

Supply chain complexity: Implementing circular practices across global supply chains can be complex, requiring coordination among multiple stakeholders and overcoming logistical challenges related to reverse logistics and material tracking.

Risk of greenwashing: Some businesses may engage in greenwashing, misleading consumers with false claims of environmental sustainability without implementing meaningful circular practices.

Social equity: Ensuring equitable access to the benefits of the circular economy, such as job opportunities and affordable goods and services, requires addressing social disparities and ensuring inclusivity in policy and implementation.

Policy and regulatory challenges: Implementing effective policies and regulations to support the circular economy, such as extended producer responsibility schemes and recycling targets, may face political resistance and require coordination among multiple levels of government.

The perspective of the circular economy in the coming decades entails a transformative shift towards sustainable and regenerative economic models, driven by increased awareness of environmental challenges and the imperative for resource efficiency. This transition involves:

Acceleration of transition: There's likely to be a significant acceleration in the transition towards a circular economy as awareness of environmental challenges grows and as governments, businesses, and consumers increasingly prioritize sustainability.

Policy support: Governments are expected to play a crucial role in driving the transition to a circular economy through the implementation of supportive policies and regulations, such as extended producer responsibility schemes, recycling targets, and incentives for circular business models.

Technological advancements: Technological advancements will continue to play a pivotal role in enabling circular practices, with innovations in areas such as recycling technologies, material science, renewable energy, and digitalization facilitating more efficient resource use and waste management.

Business opportunities: The circular economy presents significant business opportunities across various sectors, including recycling, remanufacturing, renewable energy, sustainable agriculture, and digital platforms for sharing and reuse.

Circular design: There will be a growing emphasis on circular design principles, with businesses increasingly focusing on designing products and packaging that are durable, repairable, recyclable, and made from renewable or recycled materials.

The shift in consumer behavior: Changing consumer preferences and behavior towards more sustainable and circular consumption patterns will drive demand for eco-friendly products, reuse and sharing platforms, and services that promote resource efficiency.

Circular cities: Cities will play a key role as hubs of innovation and experimentation in implementing circular practices, with initiatives focused on circular procurement, waste reduction, sustainable transportation, and the development of circular urban infrastructure.

International collaboration: There will be increased international collaboration and partnerships to address global challenges such as plastic pollution, electronic waste, and depletion of resources.

Resilience and sustainability: Embracing circular economy principles will enhance the resilience and sustainability of economies, supply chains, and communities by reducing dependence on finite resources, minimizing environmental impact, and creating more inclusive and equitable societies.

This study aims to measure the degree of influence of some economic and technical factors, natural resources, waste management, etc., in the circular economy and environmental protection. The conclusions of this study can be used to initiate and coordinate more policies to advance the circular economy concept. Although environmental protection is a current issue, and for its connection with economic growth and resource use, there is still a scientific gap in academic debates and political makers.

2. Circular Economy Indicators and their Factors in EU

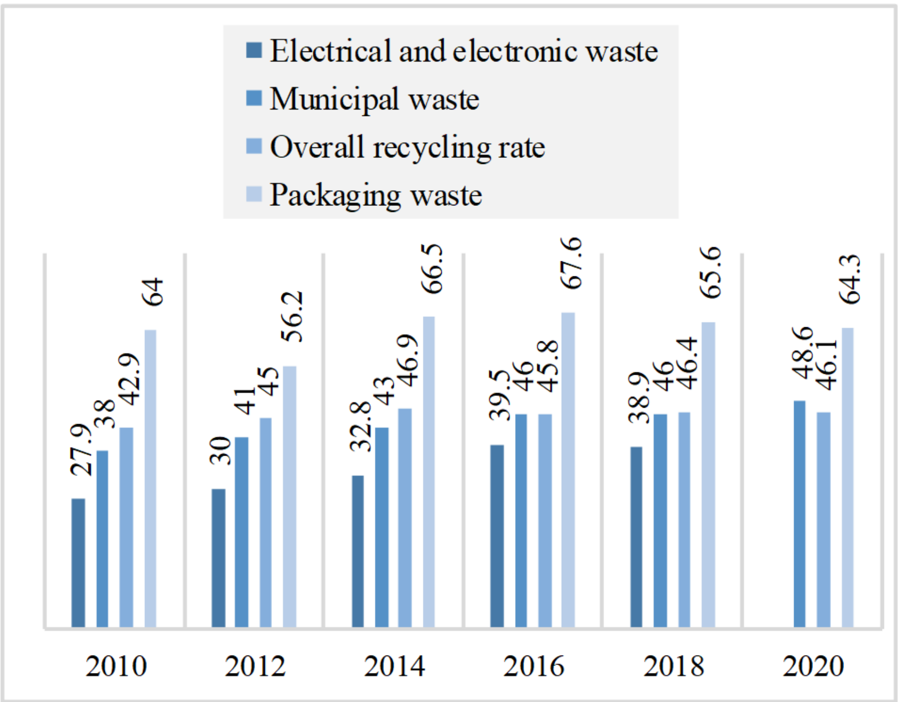
The European Union countries have an increase in their waste recycling rate, driven by binding EU recycling targets, signaling advancement toward a circular economy. However, recent progress has slowed and, in some cases, reversed, with packaging waste recycling declining over the past five years. In 2021, most waste was still disposed of through incineration or landfills. Achieving circularity in Europe and reducing environmental impacts necessitate ongoing ambitious waste management policies to encourage recycling and deter waste disposal in landfills and incinerators. The EU faces challenges due to rising demand for primary resources, affecting material self-sufficiency and the environment. Recycling is crucial for preserving valuable resources and mitigating environmental impacts. Recycling rates in the EU, including municipal, packaging, and e-waste, have been slowly increasing, driven by EU targets and legislation. However, recent years have seen stagnation and even reversals in recycling rates, highlighting the need for continued efforts to promote recycling and move towards a circular economy.

All EU countries except Sweden have witnessed an increase in their municipal waste recycling rates since 2004, reflecting notable improvements in waste management. Particularly impressive gains have been observed in countries such as Slovakia, Lithuania, Slovenia, and Latvia, where recycling rates have surged by over 40% points. However, there remains a significant disparity in municipal waste recycling performance across countries. In 2021, recycling rates varied widely, from 68% in Germany to 11% in Romania. Nine countries, including Germany, Austria, and Slovenia, achieved recycling rates exceeding 50%, while four countries: Cyprus, Malta, Turkey, and Romania, recycled less than 20% of their municipal waste. Despite progress in some nations, others with lower recycling rates have shown minimal improvement over the past 15 years. Additionally, 18 EU countries were identified as at risk because of failing to meet the recycling target of 55% for municipal waste set in the Waste Framework Directive by 2025 [4].

Recycling rates across Europe for packaging waste, electrical and electronic equipment waste, and municipal waste are crucial sources of secondary and critical raw materials and have been gradually increasing. This trend indicates a positive movement towards embracing waste as a valuable resource and advancing towards a circular economy. Despite this progress, the overall recycling rate, calculated as the ratio between total waste generated (excluding minerals) and the quantity managed through recycling has remained below fifty percent of total waste generation over the available data period. Specifically, in 2016, the recycling rate stood at 48%. Recent years have shown notable progress in managing three key waste streams: packaging, municipal waste, and electrical and electronic waste. However, despite this advancement, their recycling rates still fall below the halfway mark of the waste generated, except for packaging, which reached a recycling rate of 66% in 2018. Figure 1 shows recycling rates in the EU from 2010 to 2020.

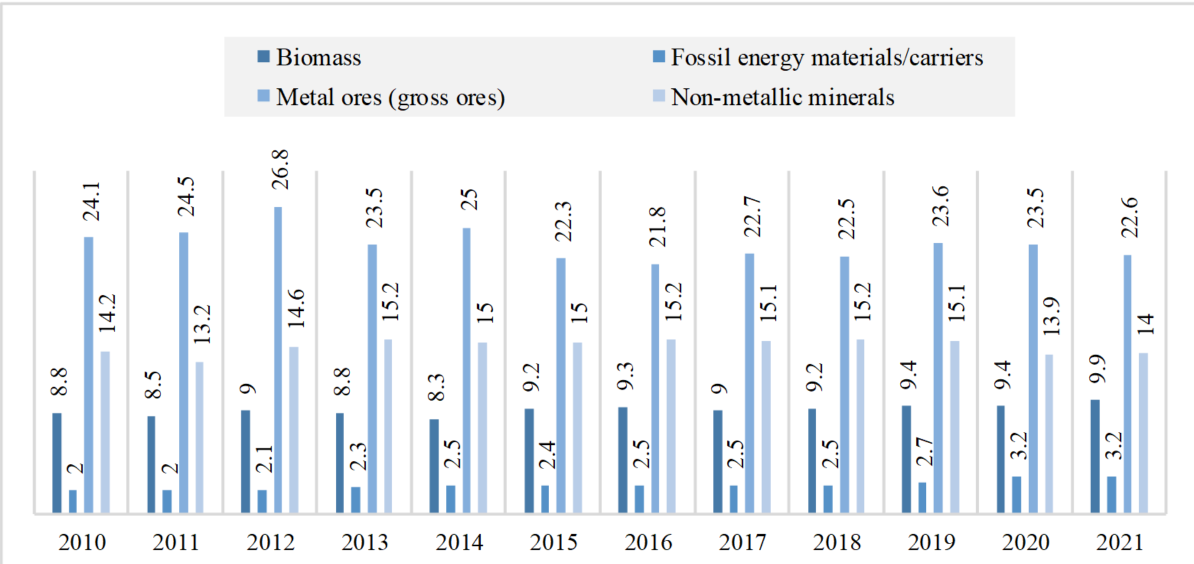
The circular material use rate (CMUR), figure 2, measures the proportion of recycled waste in the total material used in the economy. While the EU's CMUR has seen a slight increase from 10.8% in 2010 to 12.8% in 2020, it remains relatively low. This increase is primarily due to reductions in domestic material consumption while recycling rates have remained stable. Non-metallic minerals, constituting over 50% of total material consumption, have seen significant decreases, impacting the overall CMUR negatively. Different material groups exhibit varying CMURs, with metal ores surpassing 25% in 2020 and fossil fuels lagging at only 3%. This disparity reflects differences in recyclability and usage patterns. Despite fluctuations, CMURs increased for all material groups between 2010 and 2020. EU shows notable differences in consumption footprints per capita.

Resource productivity is a key measure of material usage, defined as the ratio of gross domestic product (GDP) to domestic material consumption. In developed countries, resource productivity typically increases over time. This upward trend is driven by efficiency improvements resulting from innovation, a shift in economic structures towards more service-oriented industries, and the outsourcing of extraction activities. Table 1 below shows the circular economy indicators in EU countries.



Source: European Environment Agency, Indicators 2010-2021.

Figure 1. Recycling rates in EU by waste stream, 2010-2020



Source: European Environment Agency, Indicators 2010-2021.

Figure 2. Circular material use rate in EU, 2010-2021

Table 1. Circular economy indicators in EU

Indicator	*Description*	*Mean*	*St. Deviation*	*Time series*
Resource productivity (% of GDP)	Total amount of materials directly used by an economy (measured as domestic material consumption) in relation to GDP	2.03	0.22	2010-2022
Circular Material Use Rate (in %)	Biomass	9.07	0.43	2010-2021
	Fossil energy materials/carriers	2.49	0.40	2010-2021
	Metal ores (gross ores)	23.58	1.39	2010-2021
	Non-metallic minerals	14.64	0.66	2010-2020
Waste generation (in 2010 value is 100)	Waste generation includes all materials discarded, whether or not they are later recycled or disposed of in a landfill.	103.57	4.08	2010-2022
Residual waste per capita (kg per capita)	Incineration (including energy recovery)	302.67	15.81	2010-2020
	Landfill and another disposal	2155.67	191.38	2010-2020
Recycling rates (in %)	Electrical and electronic waste	33.82	5.21	2010-2020
	Municipal waste	43.77	3.87	2010-2020
	Overall recycling rate	45.52	1.43	2010-2020
	Packaging waste	64.03	4.07	2010-2020
Material Footprint (in million tons of raw material equivalent)	Biomass	1410288.79	38240.75	2010-2020
	Fossil energy materials/carriers	1402435.00	98419.73	2010-2020
	Metal ores (gross ores)	610056.81	28939.06	2010-2020
	Non-metallic minerals	2924868.92	171870.92	2010-2020

Source: Author's summary and data from European Environment Agency, Indicators 2010-2021.

Resource productivity, measured as the ratio of gross domestic product (GDP) to domestic material consumption, is a key indicator of material efficiency. A study in the United States found that there are both long-term and short-term relationships between GDP per capita and renewable energy consumption and resource productivity [5]. An increasing ratio over time suggests decoupling economic growth from resource consumption. Developed countries typically exhibit rising resource productivity due to efficiency gains from innovation, structural shifts towards services, and outsourced extraction activities. Monitoring the circular economy's contribution to resource productivity requires comprehensive analysis considering various causal factors. In the EU, resource productivity increased steadily, by an average of 2.03% in 2010-2022. This indicates that for every kilogram of domestically used materials, two euros of economic activity are generated.

Circular material use rates involve biomass, fossil energy materials/carriers, metal ores (gross ores), and non-metallic minerals. The EU's circular economy action plan targets a doubling of its circular material use rate over the next decade to alleviate pressure on natural resources. This entails augmenting recycled waste volumes or minimizing material consumption to curtail primary resource extraction and its adverse environmental and climate consequences. This indicator has an average of about 11.34% for the last decade, with a large value for metal ores and less for fossil energy materials/carriers. Additionally, enhancing circular material utilization would lessen the EU's dependency on primary resources, including imported materials, thereby bolstering its strategic autonomy.

Between 2010 and 2022, there was a 3.57% increase in total waste generation across the EU countries. In particular, major mineral wastes, primarily originating from the mining and construction sectors, constitute a significant portion of the total waste volume, which can skew interpretation of trends. These trends indicate that the EU is falling short of its waste generation reduction targets.

Residual waste per capita (kg per capita) includes incineration (including energy recovery) and landfill and other disposal. Data reveals that the EU has averaged over 2,000 kg of waste per capita through landfilling or incineration, maintaining stability over the past decade. The EU aims to limit municipal waste landfilling to 10% by 2035, necessitating increased separate waste collection by citizens. Implementing financial incentives and investing in new technologies are crucial to diverting waste from landfills and incinerators, and promoting circular waste treatment methods.

Recycling rates involve electrical and electronic waste, municipal waste, overall recycling rate, and packaging waste. Recycling rates for municipal waste, packaging waste, and electrical and electronic equipment waste are gradually increasing in the EU, signifying progress towards utilizing waste as a resource and achieving a circular economy. However, overall, in the last decade, the recycling rate has remained below half of the total waste generation. Recent years have seen substantial progress in recycling rates for key waste streams such as packaging.

The material footprint indicator relies on domestic extraction of materials and estimates of raw material equivalents for imports and exports. Material footprint (in a million tons of raw material equivalent) involves biomass, fossil energy materials/carriers, metal ores (gross ores), and non-metallic minerals. From 2010 to 2020, the EU's material footprint remained relatively stable, decreasing by 7% from 2010 to 2016, then increasing by 5% until 2019, followed by a 5% decline in 2020 due to the COVID-19 pandemic's economic slowdown. Non-metallic minerals constitute the largest portion of the footprint (50%), driving overall trends. Despite their significant weight, they have a lower impact on the environment compared to metals and fossil fuels.

3. Literature Review

From a macroeconomic perspective, a circular economy makes a difference in economic growth by utilizing natural resources and inputs. Ideally, resource extraction should be slower than resource consumption, and waste production should not exceed the environment's capacity to absorb and process it. Natural resource use and material consumption have exponentially increased in the past two decades [6]. Therefore, a circular economy operates as a regenerative system, minimizing resource input and waste through durable design, maintenance, repair, reuse, sharing, remanufacturing, refurbishing, and recycling. The principles and mechanisms of a circular economy emphasize a restorative and regenerative nature. They aim to eliminate waste through superior design and renewable energy while distinguishing between consumable and durable components. Based on the circular economy, products are designed for disassembly and reuse, shifting from end-of-life to restoration. Four sources of value creation are highlighted: minimizing material usage, maximizing consecutive cycles and time in each cycle, diversifying reuse across the value chain, and maintaining uncontaminated material streams. These principles drive material productivity and offer long-term advantages over traditional linear business models [7].

The Ellen MacArthur Foundation [8] outlines three fundamental principles for a circular economy: 1) design out waste and pollution, 2) use and reuse products and materials, and 3) regenerate natural systems. The first principle underscores the importance of considering environmental impacts during the design phase to reduce the use of pure raw materials and minimize waste generation. The second principle focuses on prolonging the life cycle of products and materials through strategies such as reuse, repair, and remanufacturing. The third principle emphasizes not only avoiding environmental harm but also actively improving the environment by returning valuable nutrients to ecosystems. Implementing a circular economy presents the opportunity to achieve sustainable and inclusive blue growth [8, 9].

The European Commission plans to establish sustainability principles and regulations to improve various aspects of product design and lifecycle management. These include enhancing durability, reusability, upgradability, and reparability, reducing hazardous chemicals, and improving energy and resource efficiency. Additionally, they aim to increase recycled content, promote remanufacturing and high-quality recycling, decrease carbon and environmental footprints, combat single-use and premature obsolescence, and prohibit the destruction of unsold durable goods. The initiative also encourages product-as-a-service models and digitalization of product information. The focus was on addressing product groups like electronics, textiles, furniture, and high-impact intermediary products such as steel, cement, and chemicals based on their environmental impact and circularity potential.

Circularity plays a crucial role in transforming industries towards climate-neutrality and long-term competitiveness. It can lead to significant material savings across value chains, create additional value, and open up economic opportunities. This includes exploring options to promote circular practices within industrial processes, fostering industrial symbiosis through a reporting and certification system, supporting the sustainable bio-based sector, leveraging digital technologies for resource tracking, and encouraging the adoption of green technologies [10].

European Environment Agency [11] shows that over the past 50 years, there has been an unprecedented increase in global material demand, leading to doubled goods production, tripled material extraction, and quadrupled economic development measured by GDP. This growth has contributed significantly to biodiversity loss, water stress, and climate change drivers. Global material use is projected to nearly double by 2060, accompanied by a substantial increase in greenhouse gas emissions. The circular economy aims to mitigate these trends by recycling materials, reusing products, and extending their lifespans, yielding both economic and environmental benefits. Achieving a circular economy requires systemic changes across the value chain, including product design, technology, business models, consumer behavior, education, etc. [12]. The EU launched its circular economy package in 2015 to address sustainability challenges and establish concrete measures spanning consumption, production, waste management, and secondary raw material markets [13]. Transformation towards a circular economy demands action at various levels and collaboration among stakeholders, with an emphasis on experimentation, policy integration, and cross-sectoral coordination.

The circular economy presents an important opportunity to reduce greenhouse gas emissions by improving material efficiency, yet it's often overlooked in national climate policies due to its cross-sectoral nature and the difficulty of quantifying its impacts. Integrating circular economy actions into climate policies could unlock additional emission reductions. Currently, circular economy measures are only included in a small fraction of reported climate policies in Europe, primarily focusing on the waste sector with limited quantification of emission impacts. However, since waste contributes to about 3% of total greenhouse gas emissions, better utilization of waste resources can have broader emission-reduction effects. The circular economy is integrated better with climate policies if countries can take some crucial steps, including coordinating between countries, using models to identify impactful actions, integrating circular economy policies into climate mitigation reporting, evaluating the need for additional legislative proposals, monitoring policy progress, and continuously refining and developing integration strategies [14, 15].

In the EU, there are still challenges in waste management. The waste prevention programs in the EU primarily emphasize sustainable consumption models, promoting reuse and repair activities, and conducting awareness campaigns. However, there is a lack of concrete evidence linking these measures to reductions in waste generation or socio-economic trends. Despite nearly a decade of waste prevention programs, establishing a direct impact on waste generation remains challenging. Greater emphasis is needed on waste prevention efforts across all types of waste, requiring strong implementation of circular economy principles [16]. This entails designing durable and repairable products, as well as shifting towards less material-intensive production and consumption habits.

The connections between international trade and the circular economy should focus on policy interactions at both multilateral and regional levels. Specific policies to promote the circular economy, such as extended producer responsibility and environmental labeling schemes, are analyzed alongside trade agreements. To enhance synergy between trade and circular economy goals is suggested actions at national and international levels while highlighting areas for further research to address knowledge gaps [17].

Nowadays, technology is changing how businesses operate in every industry. Each country is figuring out how to adapt to these changes, recognizing that technology drives economic growth. It is essential to measure how well the circular economy is working. We need to build systems with clear signs that show how much progress we're making at different levels: within individual businesses, across industries, in cities and regions, and at the national level [18].

Another aspect of the circular economy analysis is the impact on the labor force. Sulich and Soloducho-Pelc [19] reveal the creation of green jobs in EU countries, finding that green jobs are most prevalent in the environmental goods and services sector. Globalization processes impact the labor market through changes in macroeconomic conditions, demand patterns, production processes, business, and competitiveness [20, 21]. Many economic models provide important analytical frameworks for examining the impact of resource efficiency policies on labor markets and employment. Thus, the circular economy can affect the labor markets, including the creation of novel employment opportunities, the redefinition of job roles, the disappearance of some jobs, and other effects [22].

The gross investment in tangible goods within the circular economy sector can vary widely depending on geographical location and industry focus [23]. Nishitani et al. [24] argue that the added value of circular economy and production factor costs are also statistically significant; the same findings are concluded in other studies [25, 26, 27]. While, municipal waste is one of the most important components of all the common waste generated by the population [28, 29].

4. Research Methodology

This study assesses the effect of circular economy in EU countries represented by the variable “resource productivity”. There are many reasons for that:

Firstly, resource productivity measures the output or value generated per unit of input or resource used. By tracking resource productivity within a circular economy framework, we can assess how efficiently resources are utilized to create value. Higher resource productivity indicates that more value is being generated with fewer resources, reflecting improved efficiency and reduced waste.

Secondly, resource productivity serves as a valuable economic indicator within the circular economy context. By monitoring resource productivity metrics, policymakers, businesses, and stakeholders can evaluate the effectiveness of circular economy initiatives and identify areas for improvement.

Thirdly, resource productivity measurement enables the evaluation of environmental impacts associated with resource use and consumption. A higher resource productivity implies reduced resource extraction, energy consumption, and waste generation, leading to lower environmental burdens such as greenhouse gas emissions, pollution, and habitat destruction. It helps assess progress toward environmental sustainability goals and identify opportunities for resource efficiency and conservation.

Fourthly, resource productivity metrics encourage innovation and inform decision-making processes across various sectors. Businesses are incentivized to develop and adopt technologies, processes, and business models that enhance resource efficiency and productivity. Governments can use resource productivity data to adapt incentives and policies or regulations that promote the transition towards a circular economy. Consumers also benefit from increased transparency regarding the environmental performance of products and services, enabling more informed purchasing decisions.

The sample consists of panel data from European Union - 27 countries: The EU countries are: Austria, Belgium, Bulgaria, Croatia, 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 below shows the analyzed data, with a time series of 2000 – 2022 (with annual frequency), based on official publications of the Eurostat.

Table 2. Variables used in the model.

Variables	*Description*	*Unit of measure*	*Source*
RP	Resource Productivity [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 (the annual quantity of raw materials extracted from the domestic territory of the local economy, plus all physical imports minus all physical exports).]	Euro per kilogram	Eurostat
GDP	Real gross domestic product (GDP) per capita [The indicator is calculated as the ratio of real GDP to the average population of a specific year.]	Euro per capita	
MWG	Municipal waste generated [It covers waste from households, including bulky waste, similar waste from commerce and trade, office buildings, institutions and small businesses, as well as yard and garden waste, street sweepings, the contents of litter containers, and market cleansing waste if managed as household waste.]	Thousand tons	
ERS	Renewable energy sources [Shares of energy from renewable sources over total energy supply.]	Percentage	
RD	Gross domestic expenditure on research and development [Research and experimental development (R&D) comprise creative and systematic work undertaken in order to increase the stock of knowledge.]	Percentage of gross domestic product (GDP)	
MF	Material Footprint [The indicator quantifies the worldwide demand for material extractions (biomass, metal ores, non-metallic minerals and fossil energy materials/carriers) triggered by consumption and investment by households, governments and businesses in the EU. Raw material consumption indicator is a measure of material footprints.]	Tons per capita	

Source: Author’s summary.

The multiple linear regression model for panel data is used to perform the parameter's estimations, as explained below:

$$RP_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 MWG_{it} + \beta_3 ERS_{it} + \\ + \beta_4 RD_{it} + \beta_5 MF_{it} + \varepsilon_{it} \quad (1)$$

This is a linear model form for panel data, where:

CO_{2it} = the dependent variable;

GDP_{it}, MWG_{it}, ERS_{it}, RD_{it}, MF_{it} = the independent variables for *i*-countries and *t*-times respectively;

β_i = the model parameters, or coefficients of independent variables in the model, for $i = 1, 2, ..., 13$ (the change of the dependent variable ΔCO_{2it} is explained by these coefficients β_i, in "*ceteris paribus*").

ε_{it} = the error term is the only variable that is not predicted and it must be stochastic.

The multiple linear regression model for panel data is conducted in this study following basic assumptions of the Gauss-Markov Theorem [30]:

First condition: the model must be of linear form related to the parameters β_i.

Second condition: the mathematical expectation of the error term must be $E(\varepsilon_{it}) = 0$.

Third condition: the model must have the error variance constant, i.e., $V(\varepsilon_{it}) = E(\varepsilon_{it}^2)=\sigma$.

Fourth condition: the model must not be correlated between error, $Cov(\varepsilon_{it}; \varepsilon_{jt})= 0, i \neq j$.

Fifth condition: the model must not have multicollinearity, i.e., $Cov(x_{it}; x_{jt}) = 0, i \neq j$.

The parameter estimations are tested according to the fixed and random effects. Following identifying unit and time effects via the LR test, one should assess whether these impacts are fixed or result from coincidence. Within this context, the Hausman test is commonly conducted to choose among estimators. One of the most emphasized differences between fixed and random effects models is the correlation between unit impacts and independent variables. Random effects can be put forward as a more appropriate model if no such correlation exists. Hausman statistic is calculated from formula [31]:

$$H = \left(\hat{\beta}^{RE} - \hat{\beta}^{FE}\right)^T \left[Var\left(\hat{\beta}^{RE}\right) - Var\left(\hat{\beta}^{FE}\right)\right]^{-1} \left(\hat{\beta}^{RE} - \hat{\beta}^{FE}\right) \quad (2)$$

Where $\hat{\beta}^{RE}$ are coefficients of the random effects model, $\hat{\beta}^{FE}$ are coefficients of the fixed effects, $\left(\hat{\beta}^{RE} - \hat{\beta}^{FE}\right)^T$ is the transpose matrix of $\left(\hat{\beta}^{RE} - \hat{\beta}^{FE}\right)$, $Var\left(\hat{\beta}^{RE}\right)$ is variance of $\hat{\beta}^{RE}$, $Var\left(\hat{\beta}^{FE}\right)$ is variance of $\hat{\beta}^{FE}$ and $\left[Var\left(\hat{\beta}^{RE}\right) - Var\left(\hat{\beta}^{FE}\right)\right]^{-1}$ is the inverse matrix of the variance differences.

In the Hausman test, H_0 = No correlation exists between explanatory variables and unit effects. After applying the Hausman test, the null hypothesis is accepted as related to the time. This implies that a random effect estimator is a better fit for the analysis of the phenomena in question, but the test figures out evidence to the contrary related to cross-sections, which implies the fixed effect estimator by country.

5. Empirical Analysis and Findings

Descriptive statistics of standard deviation, correlation, and mean values of the model's parameters are given in Table 3 below. According to the correlation coefficient, the independent variables are not strongly correlated (this fact provides non-multicollinearity), while the direction of correlation with the dependent variable and statistical significance follows the logic explained by studies of this field with similar indicators in different regions.

Table 3. Descriptive statistics and correlation.

	Correlation matrix						*Descriptive statistics*	
	RP	*GDP*	*MWG*	*ERS*	*RD*	*MF*	*Mean*	*St. Deviation*
RP	1.0000						1.76	1.05
GDP	0.7779*	1.0000					2.59E+04	1.69E+04
MWG	0.4353*	0.0778	1.0000				7.04E+06	1.01E+07
ERS	-0.3497*	-0.0830	-0.1714	1.0000			21.30	11.61
RD	0.3432*	0.4609*	0.2776*	0.3762*	1.0000		1.63	0.88
MF	-0.2376*	0.2828*	-0.3097*	0.4915*	0.3097*	1.0000	18.13	7.71

Note: "*" $p < 0.05$ (statistical significance).

Source: Authors' calculations in E-views 12.

The analysis would be complete if we analyzed the correlations of the independent variables impacted by the independent variables in a multi-variable regression model. Table 4 below shows the tested model results for each variable of the model.

Table 4. Pool data model (*Dependent variable RP*)

Independent variables:	*Coefficient*	*Prob. (t-stat.)*
β_0	0.1182	0.0003*
RP_{it-1}	0.9284	0.0000*
GDP_{it}	4.28E-06	0.0002*
MWG_{it}	1.82E-09	0.0455*
ERS_{it}	-0.00024	0.7651
RD_{it}	0.0115	0.2836
MF_{it}	-0.0063	0.0000*
AR(1)	-0.2345	0.0013*
Adjusted R^2	*0.9886*	
Prob. (F-stat.)	*2289.63*	*0000**

Note: "*" $p < 0.05$ (statistical significance) and AR (1) is error lag = 1 to reject autocorrelation from the model.

Source: Authors' calculations in E-views 12.

As you can see, in Table 4, the model is statistically significant (5% significance level) and has a high coefficient of determination of 98.86%. So, 98.86% of the variation in resource productivity is explained by the progress of the values of the factors (independent variables) included in this model. Some factors have a positive and some negative impact on resource productivity. Those who have a positive and statistically significant impact (with a statistical significance level of 5%) are:

Resource Productivity of a year ago (RP_{it-1}): If the resource productivity value from a year ago increases by one time, it will increase the current resource productivity by 0.92 times. This generally happens as the productivity of an economy does not fluctuate in the short term but in the long term. Thus, an economy that has a satisfactory level of efficiency in the use of resources in the creation of GDP is very likely to carry the efficiency of one year to the following years. The reason is that the efficiency of the use of resources (resource productivity) is related to the level of technology and the level of practices and policies that an economy uses in production. The circular economy involves various interconnected processes and systems. Changes in one part of the system can have ripple effects throughout the entire system, leading to unexpected outcomes or delays in realizing the full benefits of increased resource productivity. Even with increased resource productivity, there may be other constraints within the system, such as limited availability of certain resources or infrastructure limitations, which prevent the full realization of the potential productivity gains.

Real gross domestic product per capita (GDP): If the real gross domestic product per capita increases by 10000 euros, it will increase the resource productivity by 4.3%. The positive correlation between resource productivity and real GDP per capita suggests that improving the efficiency and effectiveness of resource use is conducive to economic growth and higher living standards. Countries that prioritize resource productivity tend to experience sustainable economic development and improved well-being for their citizens over time.

Municipal waste generated (MWG): If the municipal waste generated increases by a million thousand tons (or a billion tons), it will increase the resource productivity by 0.18%. This fact is ambiguous because, in the circular economy context, the goal typically focuses on achieving a negative correlation between resource productivity and municipal waste generated by maximizing resource efficiency, promoting reuse and recycling, and improving waste management systems. The positive correlation between increasing municipal waste generation and resource productivity underscores the potential for transforming waste into a valuable resource through innovation, technology, and policy interventions. By adopting a holistic approach to waste management that emphasizes resource recovery and circular economy principles, societies can achieve higher levels of resource productivity while minimizing environmental impacts.

Based on the econometric model of Table 4, we find that resource productivity has a negative and statistically significant correlation (with a statistical significance level of 5%) with the variable material footprint (MF). If the material footprint increases by an average of 100 tons per capita, it will decrease the resource productivity by 0.63%. The increase in the consumption of raw materials increases the material footprint and, under the conditions of a certain GDP, decreases the productivity of resources. The higher the consumption of materials for a given GDP, the lower the productivity of resources. The negative correlation between Material Footprint and Resource productivity highlights the importance of adopting sustainable consumption and production practices to achieve efficient resource use and minimize environmental degradation. Without these measures, increased consumption can lead to greater resource depletion and environmental harm, ultimately reducing overall resource productivity. Furthermore, it is meaningful, and conversely, a negative correlation would mean that as resource productivity increases (meaning more efficient use of resources), the material footprint decreases (meaning less material is required for production).

Although the model has a very high level of determination coefficient and is a statistically significant model, two independent variables do not have a statistically significant effect on resource productivity. The direction of the connection of the variable resource productivity is negative with *renewable energy sources (ERS)* and positive with *gross domestic expenditure on research and development (RD)*; logically, this is how they should be correlated, but from the econometric tests, they are statistically not significant (for two decades in the EU countries these variables have no impact on resource productivity). So, the degree of influence and the correlative states are:

Gross domestic expenditure on research and development (RD): If the research and experimental development increases by an average of 1% of GDP, it will increase the resource productivity by 1.15%. Increasing investment in research and development fosters the creation of more efficient technologies, processes, and materials, which can lead to higher resource productivity. Through research and development, industries can develop methods to reduce waste, improve resource extraction techniques, and enhance recycling processes. Innovations such as sustainable materials, energy-efficient technologies, and circular economy practices contribute to resource productivity by maximizing the value extracted from resources while minimizing waste and environmental impact.

Renewable energy sources (ERS): The share of energy from renewable sources over total energy supply is negatively correlated with resource production, but not statistically significant. The negative correlation comes from several key factors. Firstly, the resource-intensive nature of building and maintaining renewable energy infrastructure, such as solar panels and wind turbines, contributes to higher resource consumption. Despite technological advancements, the expanding demand for renewable energy may still strain resources. Trade-offs between renewable energy development and other sustainability goals, such as land use conflicts and environmental impacts, further contribute to this negative correlation. Therefore, while renewable energy is vital for sustainability, careful management of resources is essential to maximize overall productivity and minimize environmental impacts.

This pool data model has successfully passed the main criteria of creating efficient models according to the Gauss-Markov theorem's main assumptions (Table 5), so the model is statistically reliable to explain the direction and strength of correlation of the variables. To analyze and evaluate the robustness of the model, fixed effects and random effects models (Table 6) were tested according to the countries (EU countries) and the time (2000 – 2022). The Hausman test favors the model with fixed effects by countries (chi-squared = 165.59 with $p < 0.01$). The same test favors the model with random effects with regard to time (chi-squared = 7.77 with $p > 0.05$).

Table 5. Analysis of the residual of the model

The test	*Null hypothesis*	*Test result*		*Decision*
		Statistic	*Prob.*	
Multicollinearity: VIF-test	H0: “model has not multicollinearity $\{Cov(\varepsilon_{it}; \varepsilon_{jt}) = 0$ and $Cov(x_{it}; x_{jt}) = 0$ for each $i \neq j\}$”	Absolute coefficient correlation < 0.5	p < 0.5	H0 is not rejected
Autocorrelation: LM-test (Breusch Pegan)	H0: “model has not autocorrelation $\{Cov(\varepsilon_{it}; \varepsilon_{it-p}) = 0$ for p = 1.	Chi-squared = 884.28	0.0872	H0 is not rejected
Heteroskedasticity: Wald-test	H0: “model has not heteroskedasticity $\{E(\varepsilon_{ti})$ = constant}”	F-statistic = 11.051	0.4804	H0 is not rejected
Normality test of ε_{ti}: Jarque-Bera-test	H0: “the residual $\{\varepsilon_{ti}\}$ of the model has normality distribution”	Chi-squared = 128.24	0.0000	H0 is rejected

Source: The table summarizes the tests once they are proceeded in EViews 12 by the authors.

Table 6. Final model - fixed effects model (by countries) and random effects model (in time)

	Fixed effects model		*Random effects model*	
Independent variables:	*Coefficient*	*Prob. (t-stat.)*	*Coefficient*	*Prob. (t-stat.)*
β_0	0.8629	0.0000*	0.1510	0.0001*
RP_{it-1}	0.1999	0.0012*	0.9106	0.0000*
GDP_{it}	2.95E-05	0.0000*	5.47E-06	0.0001*
MWG_{it}	2.10E-08	0.0089*	2.41E-09	0.0304*
ERS_{it}	-0.0014	0.7152	-0.0005	0.5925
RD_{it}	0.1033	0.0532	0.0060	0.6494
MF_{it}	-0.0268	0.0000*	-0.0073	0.0001*
Adjusted R^2	*0.9925*			
Prob. (F-stat.)	*877.49*	*0000**		

Note: “*” p < 0.05 (statistical significance) and AR (1) is error lag = 1 to reject autocorrelation from the model.

Source: Authors’ calculations in E-views 12.

Analyzing the model by time and country, the results show that the time effect is not stable; therefore, over time, variables included in the model have had a change in resource productivity (i.e., circular economy) in EU countries. This means that during the time the importance of this variable has changed (thus are used unstable policies). Meanwhile, if we analyze the same model by EU countries, the model results show that this territorial effect is stable from one country to another, in the elasticity that economic factors impact the resource productivity levels. This stable effect by country is statistically significant, as shown in the pool model (Table 4).

6. Conclusions

The circular economy aims to preserve the value of products, materials, and resources while minimizing waste generation. This is crucial for achieving climate objectivity and preventing biodiversity loss. The economy, promoting prevention, reuse, recycling, and recovery, is guided by prioritizing waste management, and extends producer responsibility. The EU countries prioritize the circular economy for green recovery and sustainability, and transitioning is essential due to unsustainable consumption. By 2050, a shift to regenerative growth, so needed to embrace circular practices, will reduce waste, promote growth, and mitigate environmental impacts. Waste in EU contributes about 3% of total greenhouse gas emissions; maximizing waste resource utilization can have broader emission-reduction effects. Better integration of the circular economy with climate policies requires coordination between countries, modeling impactful actions, incorporating circular economy policies into climate mitigation reporting, assessing the need for additional legislation, monitoring policy progress, and continuously refining integration strategies.

Packaging, electrical and electronic equipment, and municipal waste recycling rates in Europe have been increasing, signaling a shift towards viewing waste as a valuable resource and promoting a circular economy. Despite the progress, the overall recycling rate remains at 50% of total waste generation. The circular material use rate in the EU increased slightly from 10.8% in 2010 to 12.8% in 2020, mainly due to reductions in domestic material consumption. However, it remains relatively low due to the low reuse of non-metallic minerals, which account for over 50% of total material consumption. Despite the fluctuations, circular material use rates increased for all material groups in the last decade.

Resource productivity is a measure of the circular economy. In the last decade, it has increased steadily by an average of 2.03% in the EU, but not at the expected level. A problematic factor is municipal waste generated because another factor, material footprint has an important effect and remained relatively stable last years. The current two decades have seen an increase of 3.57% in waste generation across the EU countries, particularly major mineral wastes, primarily originating from the mining and construction sectors. These trends indicate that the EU does not realize its waste-generation reduction targets.

According to this study's findings, based on econometric models, the circular economy is represented by resource productivity. Factors such as the previous value of resource productivity (this is the factor with the highest level of elasticity), the real gross domestic product per capita, and the municipal waste generated have a positive and statistically significant impact on the circular economy in the EU. In contrast, the factor of material footprint has a positive and statistically significant impact. The model suggests that all variables have had a stable territorial impact on resource productivity in each EU country. Meanwhile, this effect is unstable in the time dimension.

Some recommendations from this study are addressed to EU policymakers as follows. There should be more effective coordination between EU countries for implementing circular economy policies toward climate change requirements and environmental protection. Strategies may be requested to maximize environmental benefits and measure them with concrete targets for each country. EU countries should strengthen more policies to promote circular, including extending producer responsibility with a focus on waste management (efforts should be intensified to further increase recycling rates) and minimization of waste generation. Measures should be implemented to address the stability of the material footprint, particularly focusing on reducing the consumption of non-metallic minerals.

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