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The Contribution of the Circular Economy to Reducing Environmental Pollution in European Union Countries : An Econometric studyfor the Period (2000–2024)

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Abstract:

The study aimed to analyze and measure the impact of the circular economy on carbon dioxide emissions in the European Union countries during the period 2000–2024. The results showed that the recycling rate contributes to reducing emissions in the short term by decreasing reliance on primary resources. However, this effect reverses in the long term, as the recycling sector itself is linked to high energy consumption and an increase in the volume of waste generated. The results also indicated that the consumption of raw materials is one of the most significant contributors to emissions, both in the short and long term, it is considered a reflection of the industrial nature of the European economy. Strict environmental policies also play a role in reducing emissions over time.

Keywords: Circular economy, Recycling, Raw materials, Carbon dioxide emissions
JEL Classification :C22؛Q58؛ Q56؛ Q53؛

1. Introduction:

In recent decades, the world has witnessed a significant escalation in environmental challenges as a result of rapid economic expansion and growth, coupled with intensive consumption patterns of natural resources within a linear economic model based on the extraction-production-consumption-disposal sequence (European Commission, 2015; Korhonen, Honkasalo, &Seppälä, 2018). This model has exacerbated environmental pressures, particularly through increased pollution levels, depletion of natural resources, and the acceleration of climate change. In this context, a study by Kirchherr, Reike, &Hekkert (2017); Geissdoerfer, Savaget, Bocken, &Hultink (2017) indicates that the linear economy is one of the most prominent drivers of environmental degradation, and that a shift towards alternative production and consumption models has become a strategic necessity for achieving sustainability.

In the face of these challenges, the concept of the circular economy has emerged as one of the most important alternative models. It is based on redesigning economic systems to extend the life cycle of resources through reuse, recycling, and waste reduction. A study by Ghormare, Fatima, Grover, Phutela, and Kandpal (2024); and Henriques, Figueiredo, and Nunes (2023) demonstrated that the circular economy is not limited to waste management; it encompasses a structural transformation in production and consumption patterns aimed at achieving resource efficiency and minimizing environmental impact.

In this context, the European Union is one of the leading entities in adopting the circular economy model, as it has worked since the middle of the last decade to integrate this approach into its environmental and economic policies within an integrated strategic framework aimed at achieving sustainability and enhancing the efficiency of resource use (Silvestri, Spigarelli, & Tassinari, 2020; Mazur-Wierzbicka, 2021). This was clearly embodied in the launch of the Circular Economy Action Plan, which focused on reducing waste generation, improving resource use efficiency, and promoting recycling across various production sectors (Xu & Wang, 2025; Busu & Trica, 2019). The European Union is working to increase the contribution of recycled materials to the inputs of the production process by 2050 (European Commission, 2020).

Based on the above, this study aims to provide an econometric analysis of the relationship between the development of the circular economy and the level of reliance on raw materials, on the one hand, and levels of environmental pollution, on the other, in the European Union countries. This analysis will allow for an assessment of the effectiveness of this model in reducing environmental pressures and promoting resource efficiency. The following research question arises:

To what extent does the development of the circular economy affect levels of environmental pollution in the European Union countries, given the changing degree of reliance on raw materials?

Several sub-questions stem from this main question, the most important of which are:

- What are the most prominent circular economy indicators adopted in the European Union?
- To what extent does the circular economy contribute to reducing environmental pollution as the level of raw material consumption changes?
- Does the impact of circular economy indicators on environmental pollution differ between the short and long term?

Research Hypotheses:

Based on theoretical literature and previous studies, the following main hypothesis can be formulated:

The development of the circular economy contributes to reducing levels of environmental pollution in the European Union countries, and this impact increases as reliance on raw materials decreases.

To expand the study, we examine the following sub-hypotheses:

- The most prominent circular economy indicators adopted in the European Union are the percentage of recycled waste out of total waste, and the percentage of recycled waste used in the production process out of total inputs.
- The development of the circular economy contributes to reducing levels of environmental pollution, and this effect is enhanced with a decrease in the consumption of raw materials.
- The impact of circular economy indicators on levels of environmental pollution differs between the short and long term, with this impact being stronger and more stable in the long term.

Importance of the Research:

The importance of this research stems from its focus on a modern and strategic topic within the framework of sustainable economics at the EU and global levels. It integrates economic and environmental dimensions within an econometric framework, and its significance lies in its attempt to assess the effectiveness of the circular economy as a mechanism for reducing environmental pollution. This is achieved by providing econometric evidence that supports or evaluates the efficiency of European policies in transitioning to a low-emission economy.

The research also highlights the impact of raw material consumption on exacerbating environmental pressures, emphasizing the importance of rationalizing resource use and promoting reliance on recycled inputs. Furthermore, this work contributes to enriching the applied literature and opens future research avenues for expanding econometric studies related to the circular economy and the green economy, particularly in diverse international contexts.

Research Objectives:

This research aims to analyze the relationship between circular economy indicators and environmental pollution levels in European Union countries, while quantifying the impact of both raw material consumption and recycling rates on the environment. It also seeks to develop a standard model that can estimate this relationship in both the short and long term, allowing for an understanding of the temporal dynamics of the circular economy's impact on environmental pollution. Furthermore, the research aims to draw practical conclusions and recommendations that will support the effectiveness of environmental policies and promote the transition towards a more sustainable and resource-efficient economic model.

Methodology and Tools:

The descriptive approach was employed to present the conceptual and theoretical framework of the circular economy and environmental pollution. This involved reviewing the fundamental concepts, objectives, and indicators of the circular economy, as well as relevant European policies. The study also described the reality and trends of environmental pollution in EU countries during the study period.

The analytical approach was used to analyze the relationship between circular economy indicators and manifestations of environmental pollution, interpreting temporal trends. The research relies on quantitative measurement by assessing the relationship between independent and dependent variables.

Previous studies:

- The study by Garzás& Ruiz-Fuensanta (2025), titled "Analysing the expansion of the circular economy in the European Union: How important is the regional context?", by employing a multilevel model and spatial econometric methods to analyze the factors influencing the expansion of the circular economy within the regions of the European Union, considering both regional and national factors. The results show that the expansion of circular economy activities in the EU is primarily dependent on regional factors, with local knowledge playing a significant role in supporting the growth of circular economy-related activities, while national-level public policies are not sufficiently effective in stimulating this expansion. It is also widely agreed that progress towards adopting the circular economy model in the

EU requires cooperation and integration across different levels of governance. However, most applied studies tend to adopt a national perspective, neglecting the pivotal role of provinces.

- Xu & Wang (2025) study, "Do circular innovations and carrying capacity of natural environment enhance circular economy in the European Union? Evidence from simulation and machine learning methods." This study aims to analyze the impact of circular innovations and the carrying capacity of the natural environment on the development of the circular economy in 27 EU member states, using panel data from 2010 to 2022 and employing simulation and machine learning techniques. The results show that circular innovations and resource productivity play a pivotal role in promoting circular practices, while the carrying capacity of the natural environment and per capita output have a negative impact on these practices. More specifically, the carrying capacity of the natural environment reflects potential constraints that may hinder the adoption of circular economy practices. The study recommends developing innovation in recycling technologies and reuse processes to promote the adoption of the circular economy and emphasizes the importance of reducing reliance on primary natural resources and increasing the use of recycled resources within the EU.In conclusion, this study provides important insights into the dynamics of the circular economy and sustainability in EU member states.
- A study by Chen, Elheddad, Sharma, & Lau (2025), titled "Impact of Financial Development on the Circular Economy: Empirical Evidence from the European Union", the study aimed to analyze the relationship between financial development—measured by domestic credit to the private sector as a percentage of GDP—and per capita municipal waste generation levels in 28 European countries during the period 2000–2020. The study employed an advanced econometric methodology, including fixed-effects models, instrumental variables (IV) analysis, and panel quantile regression, to test whether the availability of finance supports or hinders the performance of the circular economy. Per capita municipal waste generation was used as an inverse measure of the circular economy. Considering it reflects the inefficient use of resources and the continued dominance of the linear economic model. The results show a positive and significant relationship between financial development and waste generation, suggesting that credit expansion, in the absence of effective environmental guidance, may reinforce waste-generating consumption patterns.The study underscores the need to align financial sector growth with sustainability goals by developing green finance instruments and strengthening regulatory frameworks that incentivize environmentally responsible behavior. This study also contributes to the emerging literature on the intersection of finance, environmental strategy, and the transition to a circular economy.
- A study by Gorokhova, Kozlova, Laguta, Skrashchuk, and Kaminskyi (2024), titled "The Role of the Circular Economy in Advancing Environmentally Sustainable Industrial Production," examines the factors that promote the application of the circular economy in environmentally sustainable industrial production, resource efficiency use, and the reduction of environmental damage. The study found that implementing these approaches in the Netherlands resulted in a 30% reduction in required primary resources and a 25% reduction in industrial waste. Circular economy models were also used in China to reduce carbon dioxide emissions in heavy industries by 20%. Japan managed to recycle 80% of its plastic waste, and Germany implemented regeneration technologies in the construction sector to reduce the use of natural resources by 35%. The study concluded that the circular economy faces challenges, including high implementation costs and weak legislation.

2. Theoretical Framework of the Study

1.2 Conceptual Framework of the Circular Economy

This section addresses the theoretical concept of the circular economy as an alternative development model to the traditional linear economy, and reviews its principles, objectives, and indicators.

1.1.2 The Concept of the Circular Economy and its Historical Development:

The term 'circular economy' was coined in 1990 by Pearce and Turner in their book, "Economics of Natural and Environmental Resources".

The circular economy is a modern economic model that aims to reduce resource consumption and minimize waste generation by extending the product lifecycle through mechanisms of reuse, repair, and recycling. This model is based on keeping materials within the economic cycle for as long as possible, thus contributing in achieving greater resource efficiency and reducing environmental pressures (European Parliament, 2023), the circular economy is based on the principle of closingloops of resource flow by reintegrating products and their components into the production process instead of discarding them. This allows for a shift from a linear economic model to a more sustainable and efficient circular model (Bato&Kašťáková, 2025; Kirchherr, Yang, Schulze-Spüntrup, Heerink, & Hartley, 2023). Recent literature also indicates that the circular economy contributes to enhancing sustainability by maximizing resource use efficiency and reducing waste. Its effectiveness depends on developing recycling practices and improving resource productivity, thus supporting the transition towards more sustainable production and consumption patterns (Nowak-Marchewka, Osmólska, & Stoma, 2025; Zhang, Hu, Fan, & Yu, 2022; Morseletto, 2020).

2.1.2. Principles and Objectives of the Circular Economy

- The circular economy is based on a set of principles, including the following (Ellen MacArthur Foundation, The Circular Economy and the Promise of Glass in Concrete, 2016; McKinsey & Company, 2015):
- Conserving and enhancing natural capital by managing finite stocks and balancing renewable resource flows;
- Improving resource yield by recycling products and components for maximum benefit
- Enhancing system effectiveness by identifying negative externalities.

Regarding the objectives of adopting the circular economy, it is based on a conceptual framework that aims to maximize the economic and environmental value of resources throughout their life cycle. This is achieved by conserving natural, physical, and human capital, and improving resource utilization efficiency within production systems (Ellen MacArthur Foundation, 2013). This model focuses on extending product lifespans and enhancing their reusability, repairability, and recycling, thus preserving their functional value for as long as possible. The circular economy is also based on redesigning resource flows according to the logic of closed-loop systems, where products and their components are recovered after the end of their life cycle and reintegrated into the production process instead of being disposed of as waste. This contributes to reducing material losses and limiting waste generation, and supports the transition from a linear economic model to a more efficient and sustainable circular model (Stahel, 2016).

2.1.3. Circular Economy Indicators:

Based on the principle that "what cannot be measured cannot be managed," the need arose to develop indicators to measure the effectiveness of circular economy policies and to generate a deep and integrated understanding across different levels of implementation. These indicators aim to achieve two main objectives: one forward-looking to provide guidance and course correction, and the other retrospective to provide feedback, measure and evaluate performance, and establish accountability. According to recent literature, developing indicators to measure the circular economyhas become essential to support policymaking. These indicators are used not only to track progress and measure performance but also to guide decision-makers, correct future course, evaluate results, and ensure retrospective accountability (UNECE, 2024; OECD, Monitoring Progress towards a Resource-Efficient and Circular Economy, 2024). Recent literature, particularly OECD reports and EU platforms, indicates that measuring the performance of the circular economy relies on a set of indicators covering resource productivity, circular activities, waste generation, energy, and emissions. These indicators include GDP per unit of materials, recycling rates, waste per capita, and the share of renewable energy (IMF, 2022; OECD, 2024; SUMMA, 2017).

Table 1: Circular economy performance indicators:

indicator	Domain
GDP per kilogram of domestic material consumption	Resource Productivity
Recycling Rate Environmental Innovation Index (indicator of green investment, innovation, patents, etc.).	Circular Activities
Waste per unit of GDP. Municipal Waste per capita.	Waste Generation
Share of Renewable Energy Greenhouse Gas Emissions per unit of GDP.	Energy and Greenhouse Gas Emissions

Source: Prepared by the two researchers based on (SUMMA, 2017; OECD, 2024)

The performance indicators of the circular economy vary between GDP indicators, the recycling rate, the innovation index, and others, whose performance is measured in different domains, including resource productivity, circular activities, and waste generation.

2.2. Environmental Pollution:

This section focuses on the theoretical framework of environmental pollution as one of the most significant global challenges.

1.2.2. The Concept and Dimensions of Environmental Pollution:

With the increasing global interest in environmental protection and achieving sustainable development, the need has arisen to define the concept of environmental pollution precisely in a way that allows for its legal regulation and the measurement of its various impacts. Environmental pollution is one of the most prominent challenges facing contemporary economic and social systems, given its direct link to human health and the integrity of ecosystems. In this context, various national and international legislations have sought to develop comprehensive definitions of this concept. At the European level, the European Union defines environmental pollution as the direct or indirect introduction of substances or energy into the air, water, or land, which may have adverse effects on human health or damaging biological resources, ecosystems, or physical property (EP and Council, Directive 2008/50/EC on ambient air quality and cleaner air for Europe, 2008). Pollution is also defined as "the direct or indirect introduction, as a result of human activity, of substances, vibrations, heat, or noise into the air, water, or soil, which may be harmful to human health or environmental quality" (EP and Council, 2010). These definitions reflect the comprehensive nature of environmental impact and its extension to various elements of the natural and economic environment.

2.2.2. Types of Environmental Pollution:

There are several types of environmental pollution that vary depending on the affected environment. These include (FAO & UNEP, 2021; UN-Water, Water Quality Policy Brief, 2011):

- **Water Pollution**: This refers to the introduction of substances, microorganisms, or energy into the aquatic environment (oceans, seas, rivers), whether directly or indirectly, as a result of human activities. This leads to damage to water quality, rendering it unsuitable for various uses, especially human consumption.
- **Land Pollution**: This refers to the deterioration of soil properties due to the accumulation of pollutants resulting from industrial and agricultural activities and waste disposal. This leads to an imbalance in the soil's ecosystem, reduces its productivity, and threatens the health of living organisms.

The United Nations Environment Programme (UNEP) report also adds key dimensions to pollution, including air pollution, marine and coastal pollution, and pollution from chemicals and waste. This classification reflects the modern holistic approach to pollution within the framework of international environmental policies (UNEMG, 2025). In addition to traditional types, modern forms of environmental pollution also include radioactive pollution, which refers to the dispersal of materials orIonizing radiation in the environment has harmful effects on human health and living organisms, particularly as a result of nuclear and medical activities (UNSCEAR, 2022). Noise pollution, which is characterized by continuous or excessive exposure to loud sounds resulting from urban and industrial activities, negatively impacts human mental and auditory health (EPC, Directive 2002/49/EC relating to the assessment and management of environmental noise, 2002). Light pollution refers to the excessive or unregulated use of artificial lighting, which disrupts nighttime ecosystems and affects human health and circadian rhythms (DarkSky International, 2026).

2.2. 3. Indicators for Measuring Environmental Pollution:

Pollution Indicators and Measurement Methods

Air Quality Measurements: Air quality measurements are among the most important indicators of environmental pollution. They are used to assess pollutant levels in the atmosphere, especially in industrial areas and areas of heavy transportation. These measurements include determining the concentrations of pollutants such as particulate matter (PM), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO), with the aim of comparing these levels to established standards for protecting human health and the environment (EPC, 2008).

Water-Related Measurements: Monitoring water quality requires laboratory analyses and sampling to determine pollution levels in various water sources, including drinking water, groundwater, and wastewater. Water quality is assessed based on the presence of chemical and biological pollutants that affect its suitability for human use and environmental impact (UN-Water, 2011).

Noise measurement: Noise pollution is linked to human activities such as transportation, industry, and construction. It is measured through environmental noise levels. Studies indicate that continuous exposure to high noise levels leads to negative health effects such as sleep disorders, cardiovascular diseases, and psychological effects (EPC, 2002).

Human well-being depends directly on biodiversity. Therefore, it is essential to measure, plan, and reduce any activity that may alter the ecological balance. All human activities impact ecosystems, and some cause irreversible environmental damage.

3.2. The Relationship Between the Circular Economy and Environmental Pollution

This section explains how the shift towards a circular economy impacts the reduction of environmental pollution, through theoretical analysis and previous empirical studies.

3.2.1 Mechanisms of Circular Economy Impact on the Environment

• **The Role of Recycling in Reducing Emissions and Waste:** Recycling plays a pivotal role in reducing environmental emissions by decreasing the need to extract and consume primary raw materials, which are often associated with energy-intensive extraction and high emissions. For example, data from the European Environment Agency indicates that the recycling rate in the European Union was approximately 11.8% in 2023, and improving this rate is a priority of European environmental policy (EEA E., 2025). In an economic context, the circular economy seeks to break the traditional link between economic growth and resource consumption through strategies known as the R-strategies (Refuse, Rethink, Reduce, Reuse, Recycle). This is because half of all greenhouse gas emissions and more than 90% of biodiversity loss and water scarcity result from resource extraction and its processing (EC E., 2020).

• **Resource Efficiency in Reducing Environmental Pressure**: Resource efficiency is a fundamental dimension of the circular economy. It aims to achieve higher productivity levels using fewer inputs, thereby reducing pressure on natural resources and mitigating negative environmental impacts. This role is particularly evident when relying on secondary materials instead of primary ones. This leads to a reduction in extraction processes and the associated energy consumption and pollutant emissions. Furthermore, each stage of production requires energy inputs, making the shift towards recycling and improved resource efficiency a strategic environmental choice. In this context, the European Investment Bank (EIB) report indicates that widespread adoption of the circular economy model could contribute to reducing greenhouse gas emissions by approximately 9.3 billion tons by 2050 across several key sectors (EIB, 2024, p. 3).

2.3.2. European Circular Economy Policies

• **The European Circular Economy Strategy**: The European Commission launched its first Circular Economy Action Plan in 2015, which was updated in March 2020. This plan aims to make the European economy more competitive, in line with the goals of achieving carbon neutrality by 2050 (EC E, 2020, p. 3). According to the Commission, the transition to a circular economy contributes to haltingBiodiversity loss and achieving emissions neutrality by reducing pressure on natural resources by around 2050 (EC E., 2020, p. 1).

• **EU environmental initiatives towards carbon neutrality:** Prominent initiatives include the European Green Deal, which is closely linked to the circular economy, the emissions trading system, and legislative measures such as the review of waste and product directivesand the promotion of by-products. According to an analysis by the Institute for European Environmental Policy, there are 35 actions in the 2020 Circular Economy Plan covering products, waste, and materials that contribute to climate goals (Watkins & Meysner, 2022, p. 17).

3. Standard Study:

In this research paper, we attempt to highlight the role of the circular economy in reducing environmental pollution. The study focuses on the recycling rate variable, which represents the circular economy, and the variable of raw material consumption volume, which represents the traditional economy, as independent variables. Carbon dioxide emissions, representing environmental pollution, are the dependent variable. The study is conducted in European Union countries that have adopted strategies for waste utilization and recycling. We employ the Autoregressive Distributed Lag (ARDL) methodology due to its numerous advantages and because it is the most recent method enabling us to study the relationship between the dependent variable and the independent variables in both the long and short term.

3.1. Presentation of the Proposed Standard Model:

In this study, carbon dioxide emissions are the dependent variable, denoted by CO2 (or LCO2 with a logarithm). The independent variables are:

RR: the recycling rate, taken with a logarithm of LRR, which represents the percentage of waste recycled or reintroduced into the production process out of the total waste.

RMC: Raw material consumption volume, expressed as the logarithm LRMC, representing the volume of raw materials used in the production process during a year.

Applying this to an annual series from 2000 to 2023, the ARDL model, as proposed by Pesaran, Shin, and Smith (2001), is formulated using the logarithm of the original values:

$$\Delta LCO2_t = C + \rho LCO2_{t-1} + \theta LRR_{t-1} + \varphi LRMC_{t-1} + \sum_{j=1}^{p} \alpha_j \Delta CO2_{t-j} + \sum_{j=0}^{q} \beta_j \, \Delta LRR_{t-j} + \sum_{j=0}^{T} \tau_j \, \Delta LRMC_{t-j} + \varepsilon_t$$

Where $\boldsymbol{\rho}$ ،$\boldsymbol{\theta}$ ،$\boldsymbol{\varphi}$ represent the long-run coefficients, $\boldsymbol{\tau_j}$،$\boldsymbol{\beta_j}$، $\boldsymbol{\alpha_j}$represent the short-run coefficients, and ،$\boldsymbol{T, q, p}$ represent the time lags of the variables.

3.2. Model Estimation:

3.2.1.Test of Time Series Stationarity:

Before beginning the estimation process, the stationarity of the time series of the variables must be studied to determine their degree of integration and to ensure the applicability of the ARDL methodology. One of the most important conditions for its application is that the series be integral of order I (0) or I (1) (Pesaran, Shin, & Smith, 1999, p. 289). To test the unit root, we use the Augmented Dickey-FullerTest (ADF) and the Phillips-Perron Test (PP) (Phillips & Perron, 1988). The unit root is tested in all three models. The test model is selected fromthe three models for each series according to the method of Dolado, Jenkinson, and Sosvilla-Rivero (1990). The test results are shown in the following table:

Table 1: Unit Root Test Results for Time Series Variables

		Original Level			**1st Difference**			
Variable Decision	**Test**	**tstatistique**	**Proba**	**Decision**	**tstatistique**	**Proba**	**Decision**	**Degree of Integration**
LC02	**ADF**	-2.674	0.2547	Non-stationary	-5.271	0.0018	stationary	**I (1)**

	PP	-2.375	0.3813	Non-stationary	-7.440	0.0000	stationary	
LRR	**ADF**	-7.205	0.0000	stationary				**I (0)**
	PP	-6.466	0.0000	stationary				
LRMC	**ADF**	-1.208	0.6525	stationary	-4.781	0.0010		**I (1)**
	PP	-1.202	0.6554	stationary	-4.793	0.0010		

Source: Prepared by the two researchers based on the outputs of (Eviews 12) software

From the results shown in the table above, it is clear that all the series are stable at the first difference or stable at the level, meaning they are integral of degree zero I(0) or integral of degree one I(1). Therefore,The ARDL methodology can be applied to estimate the relationship between the dependent variable and the independent variables.

3.2.2. Cointegration Test:

To test the cointegration and the existence of a long-term relationship between the independent and dependent variables, we use the Bounds Test, as described by Pesaran, Shin, and Smith (1999). The results are shown in the following table:

Table 2: Results of the Cointegration Test Using the Bounds Test

Value of F There is a	**Upper Limit**	**Lower Limit**	**Decision**
12.728	6.747	5.55	There is cointegration

Source: Prepared by the two researchers based on the outputs of Eviews 12 software.

The table above shows that Fisher's statistic in the bounds test exceeds the upper limit of the critical value at a significance level of 0.05, confirming the existence of a cointegration relationship (a long-term equilibrium relationship) between the dependent variable and the independent variables.

3.2.3 Model Estimation and Statistical Analysis of Results:

The (1,2,4) ARDL model was developed, and the results of the long-term and short-term model estimation are summarized in the following table:

Table 3: Long-Term and Short-Term Model Estimation Results

Long-run variables			
Variables	**Estimated Parameters**	**T-value**	**Probability**
LRR	1.393	5.516	0.0004
LRMC	0.476	4.521	0.0014
Short-run variables			
Variables	**Estimated Parameters**	**T-value**	**Probability**
D(LRR)	-0.041	-0.139	0.8923
D(LRR (-1))	-1.870	-3.943	0.0034
D(LRMC)	0.792	7.291	0.0000
D(LRMC (-1))	-0.010	-0.124	0.9037
D(LRMC (-2))	0.0403	0.4579	0.6579
D(LRMC (-3))	0.405	- 4.292	- 0.0020
CointEq(-1)	-1.509	-6.831	0.0001

Source: Prepared by the researchers based on outputs from Eviews 12 software.

- The table above shows that long-run changes in the LRR (Low Recycling Rate) positively affect the dependent variable. Its long-run parameter is positive and statistically significant, with a value of 1.393 and a p-value of 0.0004, which is less than the significance level of 0.05. This means that for every 1% change in the LRR, CO_2 emissions change in the same direction by approximately 1.39% in the long run, indicating a direct relationship.

In the short term, the probability value of the variable D(LRR) was 0.8923, which is greater than the significance level of 0.05. This indicates that the current effect of the recycling rate is not significant in the short term. However, a significant effect is observed for changes occurring just one period prior to the change, where the probability value of the variable D(LRR(-1)) was approximately 0.0034, which is less than the significance level, with a coefficient of -1.870. This means that any 1% change in the recycling rate in the preceding period leads to a change in CO2 of approximately 1.87% in the short term, in the opposite direction.

- The table shows that the raw material consumption variable (LRMC) has a positive and significant long-term effect, with a parameter value of 0.476 and a probability value of 0.0014, which is less than the significance level of 0.05. This means that for every 1% change in raw material consumption, CO2 changes in the same direction by approximately 0.47% in the long term.
- In the short run, the parameter of the variable D(LRMC) shows a value of 0.792 with a probability of 0.0000, which is less than the significance level of 0.05. Therefore, any change in raw material consumption in the current period of 1% leads to a change in CO2 of approximately 0.79% in the same direction and this effect. Meanwhile, the delays of one and two periods were insignificant, with the probability values for the parameters of the variables D(LRMC(-1)) and D(LRMC(-2)) being 0.9037 and 0.6579, respectively, which are greater than the significance level of 0.05. This indicates that changes delayed by one and two periods have no statistically significant effect in the short run. However, a clear significant effect is shown for changes delayed by three periods, with the value of the parameter of the variable D(LRMC (-3)) reaching approximately -0.405 with a probability of 0.0020, which is less than the significance level. This means that any change in consuming raw materials before three periods in advance by 1% leads to a change in (CO2) of approximately 0.4% in the short term and in the opposite direction.
- The table shows that the error correction coefficient CointEq(-1) is negative and significant, with a value of 1.509 and a probability value of 0.0001, which is less than the significance level of 0.05. This indicates that any imbalance in the relationship between the variables is corrected very quickly in the long run, with equilibrium being restored more than 100% in less than one period. This points to the strength and dynamic nature of the equilibrium relationship.

4.2.3 Model Validity Test:

To confirm the model's validity, we conduct diagnostic tests to verify its effectiveness and accuracy in estimating the relationship between the dependent variable and the independent variables. This is done by ensuring the stability of the error variances, that the model does not suffer from autocorrelation between errors, and that the model is stable. We use the ARCH instability of Variance test, the LM autocorrelation test, the Ramsey-Reset stability test, and the Jarque-Bera normal distribution of errors.

The test results are shown in the following table:

Table 4: Results of the Model Diagnostic Tests

Test	Statistical	Statistical Value	Probability	Decision
Unsteadiness of Variance ARCH	F-statistic	0.551	0.6563	Accept null hypothesis
Autocorrelation of Errors LM	F-statistic	1.876	0.2345	Accept null hypothesis
Model Stability Ramsey-Reset	F-statistic	1.555	0.2476	Accept null hypothesis
Distribution of Errors Jarque-Bera	Jarque-Bera	0.949	0.6219	Accept null hypothesis

Source: Prepared by the researchers based on the output of Eviews 12 software.

From the results in the table above, we observe the following:

- In the instability test for variance, the p-value is 0.6563 in F-Statistic, which is greater than 0.05. Therefore, we accept the null hypothesis that the variances of errors are equal.

- In the autocorrelation test for errors, the p-value for the LM test is 0.2345 in F-Statistic, which is greater than the significance level of 0.05. Therefore, we accept the null hypothesis that there is no autocorrelation between the errors.

- In the model stability test, the model coefficients are stable at a significance level of 0.05 because the p-value for the two-test statistics (F-statistic)is 0.2476, which is greater than 0.05. Therefore, we accept the null hypothesis.

- In the normality test, the Jarque-Bera probability value is 0.6219, which is greater than the significance level of 0.05. This confirms the null hypothesis, which states that the errors are normally distributed.

Based on the results of the previous tests, we can rely on this model to explain and estimate the effect of changes in independent variables on the dependent variable.

4. Analysis of Results:

• The results of the standard estimation indicate that the recycling rate has a positive and significant effect on long-term carbon dioxide emissions. This contradicts the prevailing theoretical view that recycling contributes to reducing emissions by decreasing the need to extract raw materials and reducing energy consumption. However, this result suggests that, within the context of the European Union countries during the study period, recycling activities may be associated with a relative increase in long-term emissions. This could be explained by the high energy intensity of some processing and reprocessing operations.

In the short term, the results showed that immediate changes in recycling rates do not have a statistically significant direct impact on carbon dioxide emissions. However, delayed values over a single period revealed a significant negative effect, indicating that an increase in recycling during the earlier period contributes to reducing emissions in the current period. This reflects a time lag between implementing recycling activities and realizing their environmental impact, a finding supported by the study by Ghisellini, Cialani, and Ulgiati (2016). Furthermore, the OECD report (2026) indicated that improving recycling rates leads to a reduction in carbon emissions in the long term by reducing pressure on natural resources. This pattern of results can be explained by the fact that the recycling process involves a series of stages (waste collection, sorting, transportation, and industrial processing), which are time-consuming and energy-intensive, thus leading to a delay in the positive environmental impact emerges, the emissions reductions becoming apparent over time, not immediately. The shift from a negative short-term impact of recycling on emissions to a positive long-term impact can be explained from the perspective of the dynamics of the circular economy in Europe. While recycling reduces emissions in the short term by decreasing direct reliance on raw materials, the circular sector itself has become a massive industrial sector, and some circular sectors still depend on fossil fuels. Recycling in Europe relies on large, modern factories that are energy-intensive and fuel-intensive (sorting, grinding, smelting, etc.…). This is confirmed in reports by the European Environment Agency (EEA), which state that chemical recycling consumes a lot of energy and causes pollution (EEA E., 2022, pp. 22-23), and indicate that processing and sorting operations consume significant energy and investment (EEA E., 2022, pp. 40-41). Therefore, the impact of recycling can be negative (EEA E., 2022, p. 58). Furthermore, the World Bank report (Kaza, Yao, Bhada-Tata, &Woerden, 2018) confirm that waste management, including recycling, may be accompanied by additional emissions due to logistics and energy consumption. This aligns with the findings of the EEA (2025) report, which indicated that the circular economy has not yet reached full efficiency. While structural improvements exist, a phase of diminishing returns is emerging, and the overall increase in waste production may negate the positive impact of recycling.

Furthermore, higher recycling rates may themselves be a consequence of increased consumption and a larger volume of waste. This means that improved recycling does not necessarily translate into long-term environmental improvement unless accompanied by a sufficient increase in clean energy and a genuine decrease in consumption rates.

These findings support the interpretation that recycling does not operate in an ideal environment but rather within a mixed waste management system. This may explain the standard results indicating a positive long-term impact, while the positive environmental impact appears only after a certain period. Recycling temporarily reduces emissions when it improves, but it becomes a neutral or even a net emission booster when it does not develop at a pace consistent with the energy transition and the requirements of a true circular economy.

• The model results also show that raw material consumption has a significant positive impact on long-term CO2 emissions, which is consistent with economic and environmental literature that confirms that increased use of primary resources is linked to higher industrial activity and increased energy demand, particularly in advanced economies with complex production structures directly contribute to increased emissions levels. This is confirmed by a 2019 UN Environment report indicating that global demand for resources has more than tripled since 1970. This increase is linked to rising industrial production and urbanization, leading to a rapid rise in energy consumption and associated emissions, particularly in industrialized economies. While the report confirms the direct relationship between material consumption and emissions, it also suggests that improving resource efficiency and adopting a circular economy can decouple economic growth from emissions. Similar findings emerged in a study by Wiedmann et al. (2013).

In the short term, the results show a strong positive impact of current raw material consumption, reflecting the immediate nature of the relationship between industrial production and emissions. The immediate increase in resource demand leads to an intensification of fossil fuel-based production processes, a finding corroborated by analytical studies on the relationship between energy consumption, industrial growth, and emissions (Sadorsky, 2012). Conversely, the model's results reveal a significant negative impact of raw material consumption after a time lag (three periods). This reflects the dynamics of environmental adaptation within European economies, where the initial surge in resource consumption stimulates regulatory and technological responses that subsequently reduce emissions. This was highlighted in a study by Aghion, Dechezleprêtre, Hémous, Martin, and Reenen (2016). This delayed adverse effect is explained by the stringent environmental policies adopted by the European Union, particularly the Emissions Trading System (EU ETS), which imposes a direct cost on carbon. This incentivizes companies to improve energy efficiency and invest in green innovation and clean production technologies, leading to emissions reductions after a period of adaptation. This was further confirmed by reports from EC E. (2023) and EEA E. (2020).

The literature also confirms that environmental policies based on carbon pricing have a dual effect: increased costs in the short term and incentives for innovation and emissions reduction in the medium and long term (Porter & Linde, 1995), which supports the findings of this model. Based on this, it can be argued that the consumption of raw materials produces a dual effect: it immediately raises emissions due to intensified industrial activity, but simultaneously generates regulatory and technological pressures that drive companies to adopt cleaner production strategies, leading to reduced emissions after a short period. This reflects the "self-correcting mechanism driven by environmental policies" within the European economy.

5. Conclusion:

This study addresses with analyzingthe impact of both recycling rates and raw material consumption on carbon dioxide emissions in the European Union countries during the period 2000–2024. It employed a dynamic econometric approach that allows for differentiation between short-term and long-term effects, aiming to clarify the true role of the circular economy in reducing environmental pollution.

The results showed that the relationship between the circular economy and carbon dioxide emissions is complex and non-linear, due to the interplay of energy, industrial, and regulatory dimensions. Regarding recycling rates, despite their theoretical importance as a tool for reducing emissions, the results indicated that they do not lead to a reduction in the long term; rather, they are associated with an increase. This can be explained by the fact that a significant portion of recycling activities relies on fossil fuels. Furthermore, the expansion of this sector is often accompanied by an increase in waste volume and consumption, thus raising the overall demand for energy.

Conversely, the results revealed a positive short-term impact of recycling, as delayed changes in recycling rates contribute to a gradual reduction in emissions. This reflects its cumulative role in reducing reliance on primary raw materials and improving resource efficiency over time.

Regarding raw material consumption, the results confirmed a positive and stable long-term impact on carbon dioxide emissions, consistent with the intensive industrial nature of European economies. However, dynamic analysis also showed that the delayed effects of raw material consumption are significant and negative. This reflects the role of stringent environmental policies, particularly the European Emissions Trading System (EU ETS), in exerting regulatory pressures that drive companies to improve energy efficiency and adopt cleaner production technologies, leading to emissions reductions after a period of adjustment.

Therefore, it can be concluded that the effectiveness of the circular economy in reducing emissions is not automatic. It requires close integration with energy transition policies, strengthened regulatory frameworks, and improved resource efficiency to ensure a sustainable reduction in carbon emissions.

In light of the findings, we propose a set of practical recommendations:

- Strengthening the energy transition within the recycling sector: Working to increase the share of renewable energy in recycling processes and reducing reliance on fossil fuels, thereby enhancing the sector's positive environmental impact.
- Shifting from a remedial to a preventative approach: Focusing on reducing waste at the source by adopting eco-design principles, extending product lifecycles, and expanding repair and reuse activities.
- Optimizing raw material consumption through industrial innovation: Encouraging European companies to adopt alternative materials and low-carbon technologies, and improving energy efficiency, particularly in the most resource-intensive sectors (metal, chemical, and construction industries).
- Enhancing the effectiveness of the European Emissions Trading System (EU ETS): Expanding the system to include additional sectors and tightening emission limits, thereby strengthening economic incentives for transitioning to cleaner production.
- Improving the integration of circular economy and energy policies: Ensuring coordination between legislation related to waste management, resource efficiency, and energy transition policies, thereby achieving coherence in environmental objectives.
- Supporting research and development in the environmental field: Stimulating innovation in low-energy recycling technologies and developing industrial solutions based on the use of secondary materials, thereby enhancing resource efficiency and reducing emissions in the medium and long term.

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7- Appendices:

7.1. Time Series Stationarity Study:

Phillips-Perron Unit Root Test on LCO2

Null Hypothesis: LCO2 has a unit root
Exogenous: Constant, Linear Trend
Bandwidth: 7 (Newey-West automatic) using Bartlett kernel

		Adj. t-Stat	Prob.*
Phillips-Perron test statistic		-2.375368	0.3813
Test critical values:	1% level	-4.416345	
	5% level	-3.622033	
	10% level	-3.248592	

Phillips-Perron Unit Root Test on LCO2

Null Hypothesis: LCO2 has a unit root
Exogenous: Constant, Linear Trend
Bandwidth: 7 (Newey-West automatic) using Bartlett kernel

		Adj. t-Stat	Prob.*
Phillips-Perron test statistic		-2.375368	0.3813
Test critical values:	1% level	-4.416345	
	5% level	-3.622033	
	10% level	-3.248592	

Augmented Dickey-Fuller Unit Root Test on D(LCO2)

Null Hypothesis: D(LCO2) has a unit root
Exogenous: Constant, Linear Trend
Lag Length: 0 (Automatic - based on SIC, maxlag=3)

		t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic		-5.271660	0.0018
Test critical values:	1% level	-4.440739	
	5% level	-3.632896	
	10% level	-3.254671	

Phillips-Perron Unit Root Test on D(LCO2)

Null Hypothesis: D(LCO2) has a unit root
Exogenous: Constant, Linear Trend
Bandwidth: 11 (Newey-West automatic) using Bartlett kernel

		Adj. t-Stat	Prob.*
Phillips-Perron test statistic		-7.440282	0.0000
Test critical values:	1% level	-4.440739	
	5% level	-3.632896	
	10% level	-3.254671	

7.2. Cointegration:

F-Bounds Test		Null Hypothesis: No levels relationship		
Test Statistic	Value	Signif.	I(0)	I(1)
		Asymptotic: n=1000		
F-statistic	12.72834	10%	4.19	5.06
k	2	5%	4.87	5.85
		2.5%	5.79	6.59
		1%	6.34	7.52
Actual Sample Size	20	Finite Sample: n=30		
		10%	4.577	5.6
		5%	5.55	6.747
		1%	7.977	9.413

7.3. Measurement Results:

ARDL Error Correction Regression
Dependent Variable: D(LCO2)
Selected Model: ARDL(1, 2, 4)
Case 5: Unrestricted Constant and Unrestricted Trend
Date: 11/14/25 Time: 03:32
Sample: 2000 2023
Included observations: 20

ECM Regression
Case 5: Unrestricted Constant and Unrestricted Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	24.72901	3.622647	6.826226	0.0001
@TREND	-0.078365	0.011364	-6.895625	0.0001
D(LRR)	-0.040763	0.292684	-0.139274	0.8923
D(LRR(-1))	-1.870664	0.474329	-3.943814	0.0034
D(LRMC)	0.792039	0.108633	7.290950	0.0000
D(LRMC(-1))	-0.010640	0.085489	-0.124455	0.9037
D(LRMC(-2))	0.040357	0.088131	0.457923	0.6579
D(LRMC(-3))	-0.405243	0.094413	-4.292228	0.0020
CointEq(-1)*	-1.509732	0.220993	-6.831587	0.0001

ARDL Long Run Form and Bounds Test
Dependent Variable: D(LCO2)
Selected Model: ARDL(1, 2, 4)
Case 5: Unrestricted Constant and Unrestricted Trend
Date: 11/13/25 Time: 23:00
Sample: 2000 2023
Included observations: 20

Conditional Error Correction Regression

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	24.72901	4.463982	5.539674	0.0004
@TREND	-0.078365	0.015260	-5.135191	0.0006
LCO2(-1)*	-1.509732	0.245929	-6.138887	0.0002
LRR(-1)	2.104094	0.503672	4.177508	0.0024
LRMC(-1)	0.719219	0.202553	3.550759	0.0062
D(LRR)	-0.040763	0.330086	-0.123493	0.9044
D(LRR(-1))	-1.870664	0.650619	-2.875208	0.0183
D(LRMC)	0.792039	0.155521	5.092804	0.0007
D(LRMC(-1))	-0.010640	0.117718	-0.090382	0.9300
D(LRMC(-2))	0.040357	0.106331	0.379542	0.7131
D(LRMC(-3))	-0.405243	0.128992	-3.141607	0.0119

* p-value incompatible with t-Bounds distribution.

Levels Equation
Case 5: Unrestricted Constant and Unrestricted Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LRR	1.393687	0.252652	5.516234	0.0004
LRMC	0.476388	0.105371	4.521070	0.0014

EC = LCO2 - (1.3937*LRR + 0.4764*LRMC)

7.4. Model Validity Tests Results:

Ramsey RESET Test
Equation: ARDL1
Omitted Variables: Squares of fitted values
Specification: LCO2 LCO2(-1) LRR LRR(-1) LRR(-2) LRMC LRMC(-1) LRMC(-2) LRMC(-3) LRMC(-4) C @TREND

	Value	df	Probability
t-statistic	1.247140	8	0.2476
F-statistic	1.555358	(1, 8)	0.2476
Likelihood ratio	3.553209	1	0.0594

Breusch-Godfrey Serial Correlation LM Test:
Null hypothesis: No serial correlation at up to 3 lags

F-statistic	1.876593	Prob. F(3,6)	0.2345
Obs*R-squared	9.681660	Prob. Chi-Square(3)	0.0215

Heteroskedasticity Test: ARCH

F-statistic	0.551141	Prob. F(3,13)	0.6563
Obs*R-squared	1.918200	Prob. Chi-Square(3)	0.5896