

SUSTAINABILITY UNDER PRESSURE: THE CONTRIBUTION OF CIRCULAR ECONOMY TO RESILIENT GROWTH IN THE EU

Dicky Satria Ramadhan^{1*}, Istiqomah²

¹²Economics and Development Studies, Universitas Jenderal Soedirman, Indonesia

*Email corresponding author: dicky.satria@unsoed.ac.id

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Abstract

This paper analyzes greenhouse gas emissions from production activities in 27 European Union nations between 2014 and 2023 to determine the extent to which circular economy indicators contribute to global sustainability and resilience. Using a quantitative approach, this research employs a fixed effects panel regression model that incorporates four key indicators: such as the employment rate within circular economy sectors, the extent of circular material use, the per capita generation of municipal waste, and the recycling rate of municipal waste serve as critical components in understanding circularity outcomes. The findings reveal that both persons employed in circular economy sectors and circular material use rate significantly reduce GHG emissions, indicating that labor and material circularity are effective tools for decarbonization. In contrast, generation of municipal waste per capita and recycling rates of municipal waste do not exhibit significant effects, suggesting the need for more integrated and systemic waste management approaches.

Keywords: circular economy, climate, environmental sustainability, european union, greenhouse gas emissions, recycling

INTRODUCTION

The European Union is currently facing significant challenges in addressing environmental disruptions caused by climate change while promoting sustainable practices on a global level. A major initiative launched by the EU is the European Green Deal (EGD), aimed at achieving carbon neutrality by 2050 and transitioning energy use the energy supply chain away from fossil energy toward renewables. Introduced in December 2019, the EGD is a comprehensive strategy designed to make Europe a carbon-neutral continent by 2050. This initiative responds to the urgent challenges posed by the climate crisis and the need for sustainability across all sectors of the economy. The EGD encompasses a wide range of policies and initiatives to reduce greenhouse gas (GHG) emissions, improve energy efficiency, and foster innovation in environmentally friendly technologies (Ricciolini et al., 2024; Schepelmann, 2022; Tutak et al., 2021).

A core objective of the EGD is to cut GHG emissions < 55% by the year 2030, in comparison to 1990 benchmarks. To reach this target, the EU proposes a combination of measures, including the reinforcement of the Emissions Trading System, the expansion of renewable energy use, and the widespread application of circular economy practices within industrial activities (Montanarella, 2020; Perissi & Jones, 2022).

The Circular Economy Action Plan (CEAP) is a significantly initiative adopted by the European Union, beginning with the first policy package in 2015 and followed by updates in 2020. The primary objective of CEAP is to expedite Europe's transformation process toward a circular economy framework, emphasizing waste reduction and the enhancement of material reuse and recycling. CEAP encompasses a series of strategic measures aimed at promoting more efficient resource use, optimizing product life cycles, and minimizing the environmental impact of consumption and production (Kirchherr et al., 2018; LEVICKY et al., 2021; Santeramo, 2022).

One of the key aspects of CEAP is its emphasis on sustainable product design, known as ecodesign. This strategy requires manufacturers to consider sustainability spanning the entire product life cycle from sourcing raw materials to end-user application and eventual disposal. The goal is to reduce waste and enhance the recycling potential of materials, thereby minimizing the use of primary resources (Fitch-Roy et al., 2019; Santeramo, 2022). Additionally, CEAP includes regulations aimed at reducing plastic waste and single-use products, which are major contributors to environmental pollution (Siregar et al., 2023; Stankevičius et al., 2020).

CEAP aims to foster sustainable economic growth by promoting innovation in the business sector. It is foreseen that the circular economy transition will generate a significantly number of new job roles and business models that are more aligned with sustainability. A report from the European Environment Agency indicates that implementing a circular economy could boost the EU's Gross Domestic Product (GDP) and yield long-term economic benefits (Goyal et al., 2016; Leeuwen et al., 2018).

Although the European Union has launched the European Green Deal and Circular Economy Action Plan, significant challenges persist in reducing emissions from production activities. The European Environment Agency (EEA) reports that while progress has been made in regulating greenhouse gas emissions, the industrial sector still contributes substantially to overall emissions. By 2022, roughly 20% of overall greenhouse gas emissions were attributed to the industrial sector in the EU, highlighting the necessity for further action to mitigate the impacts of production activities (Almughni et al., 2024; Zuhro et al., 2025).

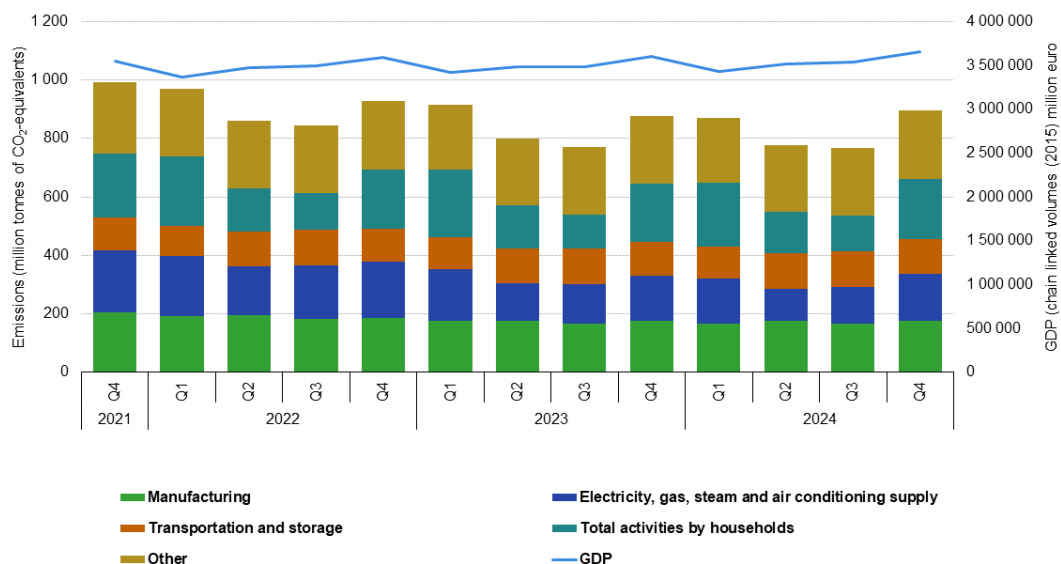


Figure 1. Greenhouse gas emissions by the economy and GDP, Q4 2021 - Q4 2024

Source: Eurostat, 2025

Based on Figure 1, the European Union continues to face significant challenges in reducing greenhouse gas (GHG) emissions across various economic sectors, despite relatively stable Gross Domestic Product (GDP) growth. From the fourth quarter of 2021 to the fourth quarter of 2024, total GHG emissions fluctuate without showing a consistent, drastic decline, remaining close to 900 million

tons of CO₂ equivalent per quarter. The household sector (which includes all activities by households) and the energy supply sector (covering electricity, gas, steam, and air conditioning) are major contributors to total emissions, followed by manufacturing and transportation. Notably, despite a general increase in GDP (illustrated by the blue line), there is a lack of strong decoupling between economic growth and emissions reductions, indicating that the EU's economic growth remains heavily reliant on carbon-intensive activities.

The Circular Material Use Rate (CMUR) in the European Union has stagnated at around 12 to 13 percent, pointing to the critical demand for strengthening the performance and results of circular economy measures for better environmental outcomes, particularly in terms of emission reduction. Despite launching forward-thinking policies such as the EGD and the CEAP, the EU aims to move beyond the linear economy toward a more sustainable alternative, the actual impact on emission reduction from production activities remains significantly below expectations.

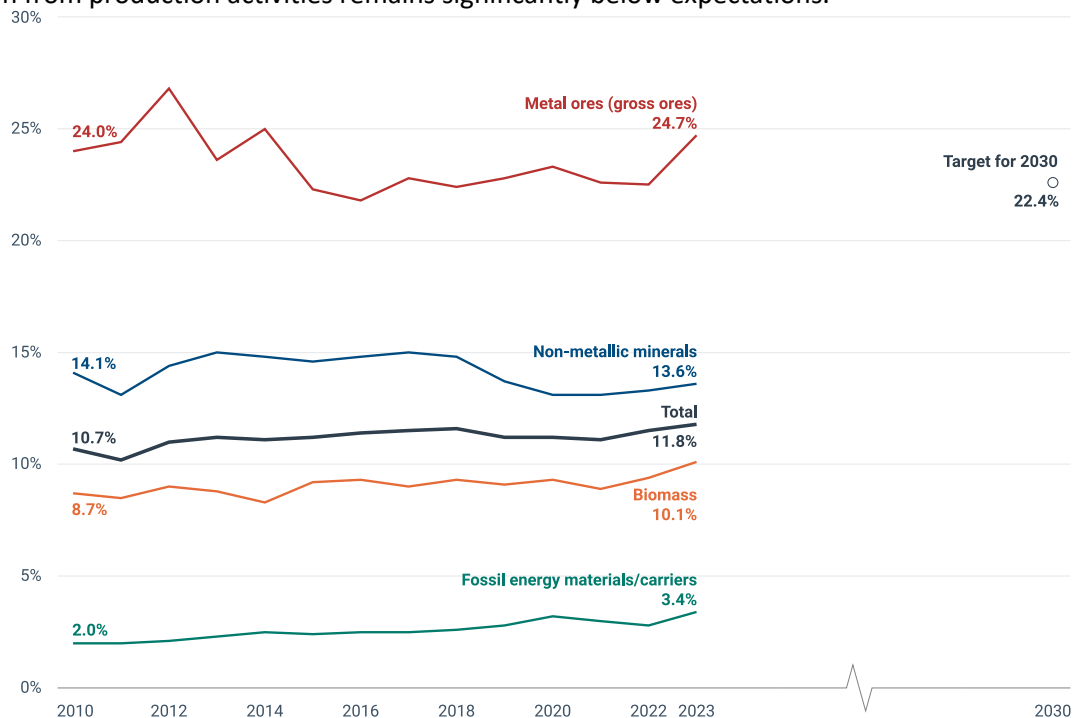


Figure 2. Circular material use rate in the EU and breakdown by material group between 2010 and 2023

Source: European Environment Agency, 2024

Figure 2 illustrates the Circular Material Use Rate (CMUR) problem in the EU, highlighting the significant challenges in achieving a circular economy. As of 2023, the EU's total CMUR stands at just 11.8 percent, which is well below the target of 22.4 percent by 2030. This indicates that nearly 90 percent of materials used in the EU still originate from primary resources rather than from recycling or reuse. The material composition reveals a clear imbalance. For instance, the use of secondary materials for metal ores is relatively high at 24.7 percent, while other sectors, such as fossil energy materials/carriers, are much lower at only 3.4 percent. Additionally, non-metallic minerals, which have significant development potential (such as concrete and ceramics), account for only 13.6 percent, and biomass, despite showing an upward trend, reaches just 10.1 percent.

This condition indicates that although circular economy policies have been implemented through the CEAP and the EGD, their impact on increasing the use of secondary materials remains limited. A key factor contributing to this is the low recycling rate across various industrial sectors. As Haas et al., (2015) found, recycled materials in the EU currently account for only about 13 percent of total material use, which is insufficient to meet the needs and expectations outlined in the circular economy policy. This indicates that the industrial sector continues to rely heavily on primary raw materials, exacerbating ecological footprints and carbon emissions (Dewick et al., 2020). Furthermore,

Sumter et al., (2020) highlight that, despite advancements in recycling technologies, inadequate implementation and a lack of incentives for companies to adopt circular economy practices remain significant barriers.

Stakeholder familiarity and insight into the operational and strategic dimensions of circular economy principles, including industry and society, still need improvement. Sumter et al., (2020) highlighted that without adequate knowledge of sustainable design and practices, initiatives to implement a circular economy will not reach their full potential. Dewick et al., (2020) also emphasized that the successful transition to a circular economy relies heavily on cross-disciplinary collaboration and the integration of academic knowledge with practical applications.

Several studies indicate that many circular economy principles have yet to be comprehensively adopted by all EU member nations, resulting in limited progress in waste reduction (Bressanelli et al., 2018; Kirchherr et al., 2018). Major barriers to the success of CEAP include inadequate recycling infrastructure, inconsistent regulations, and low awareness among citizens and companies regarding the importance of this transition (Bressanelli et al., 2018; Milios, 2017).

If these issues are not structurally addressed, without adequate intervention, the EU economic system's sustainability and resilience could remain vulnerable. As a key player in global climate governance, the EU could lose its international leadership role if it fails to showcase the tangible impact of transitioning to a circular economy on reducing production emissions. Therefore, this study was conducted to examine the connections between the circular economy and greenhouse gas (GHG) emission reduction. The findings of this study can help fill the knowledge gap and strengthen the foundation for global sustainability-oriented policies.

LITERATURE REVIEW AND HYPOTHESIS FORMULATION

Employment in circular economy sectors is significantly correlated with a reduction in greenhouse gas emissions. The circular economy framework promotes practices such as recycling, reuse, and sustainable resource management, which lead to lower emissions across various industries. Recent empirical analyses indicate that regions implementing circular economy innovations experience notable declines in greenhouse gas emissions, particularly within sectors reliant on recycling and material recovery. Chen, (2022) emphasizes that the spatial impacts of the circular economy extend beyond urban centers to economically disadvantaged areas, highlighting its potential to drive effective emission reductions. Additionally, findings by Erdiaw-Kwasie et al., (2023) corroborate this assertion, providing evidence of substantial correlations across multiple economies where green employment strategies are deployed, resulting in statistically significant negative impacts on emissions.

The evidence indicates that organizations adopting circular economy principles not only contribute to environmental sustainability but also stimulate job creation in green sectors. The manufacturing industry's implementation of circular practices has been shown to promote environmentally friendly economic growth while reducing waste and emissions (Siregar et al., 2023). Additionally, the use of extended input-output models demonstrates that adopting circular economy strategies significantly decreases carbon emissions during various stages of production and process management (Retegi et al., 2023). Moreover, the steel manufacturing industry exemplifies how recycling initiatives can thrive under circular principles, resulting in lower resource consumption and reduced emissions (Nechifor et al., 2020). Based on this description, we can formulate the following research hypothesis:

H₁: "Persons employed in circular economy sectors has a significant impact on greenhouse gas emissions."

The essence of the circular economy is to maximize material use by promoting reuse, recycling, and recovery, thereby minimizing resource extraction and waste generation. Evidence from

Erdiaw-Kwasie et al., (2023) indicates that improvements in circular material utilization correlate with a decrease in greenhouse gas emissions across multiple economies, confirming the significance of this relationship. Andrade et al., (2023) explain that the steel industry, which has adopted circular economy practices, has successfully reduced its greenhouse gas emissions to 0.93 tCO₂ per ton of steel produced, emissions are reduced to roughly 50% of the global average of 1.83 tCO₂ per ton. A result largely credited to the implementation of scrap-based methods and semi-integrated plant systems, demonstrating that effective material use can lead to significant emission reductions. Research conducted by Retegi et al., (2023) supports this approach by showing how circular economy strategies can mitigate emissions while potentially creating employment opportunities. Furthermore, results from Tubiello et al., (2013) highlight that identifying emission hotspots enables targeted interventions to enhance circular material use and ultimately reduce greenhouse gases, supporting the integration of circular practices in climate change mitigation. Based on this description, we can formulate the following research hypothesis:

H₂: “Circular Material Use Rate has a significant impact on greenhouse gas emissions.”

The generation of municipal waste per capita significantly impacts greenhouse gas emissions. Municipal solid waste (MSW) is a crucial factor in climate change, as its anaerobic decomposition in landfills leads to substantial methane and carbon dioxide emissions. Zhang et al., (2019) show that landfills contribute to about 5% of total GHG emissions on a global scale, a figure that may rise as urban populations and waste generation continue to increase. The correlation between rising municipal waste generation and greenhouse gas emissions is particularly evident in regions where waste management systems primarily rely on landfilling, as noted by (Smol et al., 2020). In highly developed nations with advanced recycling and waste-to-energy systems, the negative effects of per capita waste generation are often mitigated, underscoring the critical need for effective waste management practices. Research conducted by Zhang et al., (2024) indicate that countries experiencing rapid urbanization and population growth are witnessing a significant increase in municipal waste, which subsequently exacerbates their greenhouse gas emissions. For instance, research by Grdić et al., (2020) reveals a correlation between municipal waste production, recycling rates, and greenhouse gas output in European countries. Furthermore, Haider, (2024) analysis of Canadian provinces shows that per capita waste generation is a key factor influencing greenhouse gas emissions, highlighting an important area for intervention through improved waste management practices. The findings of this research will enhance our understanding of the relationship between municipal waste generation and its climate impact, guiding policies aimed at reducing greenhouse gas emissions through innovative waste management strategies. Based on this description, we can formulate the following research hypothesis:

H₃: “The generation of municipal waste per capita has a significant effect on greenhouse gas emissions.”

The recycling rate of municipal waste does not significantly affect greenhouse gas emissions. While recycling offers potential benefits, including reductions in energy consumption and emissions from the production of raw materials, some evidence suggests that this relationship may not be as strong as previously assumed. Lee et al., (2016) observed that although technological advancements in waste management have contributed to reduced environmental impacts, actual recycling rates have not resulted in significant reductions in greenhouse gas emissions in the U.S. Additionally, they noted that factors such as solid waste generation rates and recycling rates have not consistently declined, indicating complex interactions that affect overall emissions. The study by Deus et al., (2017) highlights the variability in emissions reduction based on specific waste management practices. It reveals that while recycling can contribute to lower emissions, the effects depend on the context in which waste is managed (Deus et al., 2017). Bayar et al., (2021) emphasize that a combined approach of waste recycling and renewable energy usage is essential for effectively addressing CO₂ emissions.

However, they acknowledge that recycling alone, without a significant focus on renewable energy deployment, may not achieve the expected reductions in greenhouse gases. Furthermore, some recycling technologies can result in net positive emissions when considering their full life-cycle impacts, particularly in specific contexts, as demonstrated in research on recycling approaches, including wind turbine blades (Sproul et al., 2024). Based on this description, we can formulate the following research hypothesis:

H₄: “The recycling rate of municipal waste does not have a significant effect on greenhouse gas emissions.”

RESEARCH METHODS

A panel data regression model is employed in this quantitative study to investigate the relationship between circular economy indicators and global sustainability and resilience across the EU. The empirical analysis spans 27 member states from 2014 - 2023, allowing for a multidimensional investigation across both spatial (cross-country) and temporal (yearly) dimensions. The choice of panel data analysis provides robust insights by controlling for unobserved heterogeneity and enabling the detection of dynamic patterns in environmental performance across countries.

The dependent variable used to represent global sustainability and resilience is the volume of greenhouse gas emissions from production activities (measured in million tonnes of CO₂ equivalents), as it directly reflects the environmental burden imposed by economic activity. The independent variables consist of four key proxies for circular economy performance: (1) Persons employed in circular economy sectors, indicating labor engagement in sustainable industries; (2) Circular Material Use Rate (percent of total material use), reflecting the proportion of secondary raw materials reused in the economy; (3) Generation of municipal waste per capita (in kilograms), capturing waste intensity relative to population; and (4) Recycling rate of municipal waste (percent), measuring the efficiency of waste recovery systems.

To model the relationships, a log-linear panel regression is estimated as follows:

$$GHG_{it} = \alpha_0 + \beta_1 CE_Employment_{it} + \beta_2 CMUR_{it} + \beta_3 Waste_{it} + \beta_4 Recycling_{it} + \varepsilon_{it} \quad (1)$$

Keterangan:

α	: Constant
$\beta_1 \dots \beta_5$	: Koefisien Regresi
GHG	: Greenhouse gas emissions from production activities (million tonnes of CO ₂)
$CE_Employment$	: Persons employed in circular economy sectors (person)
$CMUR$	: Circular Material Use Rate (percent of total material use)
$Waste$	: Generation of municipal waste per capita (kilograms)
$Recycling$	: Recycling rate of municipal waste (percent)
ε	: Error term
it	: country -i , year -t

Before interpretation, several diagnostic tests are performed to assess the validity of classical linear regression assumptions. These tests include checks for multicollinearity (using the Variance Inflation Factor), heteroskedasticity (via the Breusch-Pagan test), and normality of residuals (utilizing the Jarque-Bera test). All data are sourced from authoritative organizations, including Eurostat and the European Environment Agency (EEA), ensuring consistency and comparability across countries and years.

RESULTS AND DISCUSSION

The estimation of a panel data regression model was employed to assess the impact of circular economy indicators on global sustainability and resilience, using greenhouse gas emissions from production activities as a proxy, across 27 EU member states from 2014 - 2023. The analysis utilized three modeling approaches: Pooled OLS, Fixed Effect Model (FEM), and Random Effect Model (REM) to identify the best model specification that fits the data characteristics. Model selection was based on the Chow test and Hausman test, while model validity was assessed through several diagnostic tests, including multicollinearity, heteroscedasticity, and residual normality.

Regression Model Selection

The selection of the regression model is carried out with testing stages including the chow test, hausman test, and LM test as presented in the following Table.

Table 1. Chow Test

Effects Test	Statistic	d.f.	Prob.
Cross-section F	83.289332	(26,205)	0.0000
Cross-section Chi-square	577.693956	26	0.0000

Source: Secondary Data Processing, 2025

The test results, as shown in Table 1, report a Cross-section F-statistic of 83.289 degrees of freedom (26, 205) and a p-value of 0.0000, the test statistics strongly suggest significance. The cross-section Chi-square test, yielding 577.694 with 26 degrees of freedom and the same p-value, also confirms this. Therefore, the null hypothesis is rejected at the 5% level of confidence. This indicates that the intercepts vary significantly across countries, and thus, individual heterogeneity is present and should be controlled in the estimation process. These results confirm that the Fixed Effects Model (FEM) is statistically more appropriate than the Pooled OLS model for this panel dataset.

Table 2. Hausman Test

Test Summary	Chi-Sq. Statistic	Chi-Sq. d.f.	Prob.
Cross-section random	18.625809	4	0.0009

Source: Secondary Data Processing, 2025

In Table 2, the Hausman test yields a Chi-square statistic of 18.626 with 4 degrees of freedom and a p-value equal to 0.0009. This value is significantly < 0.05 level, indicating that the null hypothesis should be rejected, suggesting that the unobserved individual effects are indeed correlated with one or more independent variables in the model. Therefore, based on the outcome of the Hausman test, the FEM is confirmed as the more appropriate estimation technique for this study. This finding aligns with the results of the Chow test, and together they indicate that controlling for country-specific heterogeneity is essential to avoid biased and inconsistent coefficient estimates. Consequently, the analysis proceeds with the Fixed Effects Model to examine the impact of circular economy indicators on greenhouse gas emissions in the European Union from 2014 to 2023.

Classical Assumption Testing

Before interpreting the regression results, it is essential to verify the validity of the underlying classical linear regression assumptions. This ensures that the model produces unbiased, consistent, and efficient estimators. Accordingly, this study conducted several diagnostic tests to examine the presence of multicollinearity, heteroskedasticity, and non-normality of residuals. Violations of these assumptions may undermine the reliability of the estimated coefficients.

First, the Pearson correlation matrix is examined to detect multicollinearity among the explanatory variables. A correlation coefficient exceeding 0.80 is often considered indicative of a potential multicollinearity problem. The following presents the results of the multicollinearity analysis.

Table 3. Multicollinearity Test

	CE_Employment	CMUR	Waste	Recycling
CE_Employment	1.000000	0.303131	0.012911	0.287021
CMUR	0.303131	1.000000	0.127680	0.487300
Waste	0.012911	0.127680	1.000000	0.315966
Recycling	0.287021	0.487300	0.315966	1.000000

Source: Secondary Data Processing, 2025

The correlation analysis results indicated that all pairwise correlation coefficients among the four independent variables were significantly below the critical threshold of 0.80. Most correlations were moderate to low, suggesting no strong linear dependence between the variables. This finding further supports the VIF results, confirming that the model does not suffer from multicollinearity.

Second, to evaluate whether the variance of the residuals is constant across observations (homoskedasticity), the study employs the Glejser test. This test involves regressing the absolute residuals from the main regression model on each independent variable. A statistically significant relationship ($p\text{-value} < 0.05$) indicates the presence of heteroskedasticity, which could result in inefficient parameter estimates and incorrect standard errors if not addressed.

Table 4. Heteroskedasticity Test

Dependent Variable	: Res_Abs		
Method	: Panel Least Squares		
Cross-section included	: 27		
Total panel (unbalanced) observations	: 236		
Variable	Coefficient	t-Statistic	Prob.
Constant	250.6393	0.739483	0.4605
CE_Employment	0.001346	0.751660	0.4531
CMUR	13.92821	0.950035	0.3432
Waste	-0.106994	-0.352477	0.7248
Recycling	-1.126256	-0.190864	0.8488

Source: Secondary Data Processing, 2025

The Glejser test, as summarized in Table 4, indicates a lack of statistical significance for all independent variables, given that their $p\text{-values} > 0.05$. This result suggests no detectable relationship between the regressors and the absolute residual terms. Therefore, we can conclude that the regression model does not suffer from heteroskedasticity, and the assumption of homoskedasticity is satisfied.

Third, the assumption of normal distribution of residuals is evaluated using the Jarque-Bera test, which combines measures of skewness and kurtosis to assess deviation from normality. A non-significant result ($p\text{-value} > 0.05$) supports the normality assumption, which is especially important for small-sample inference and for ensuring the validity of t- and F-tests in the regression model.

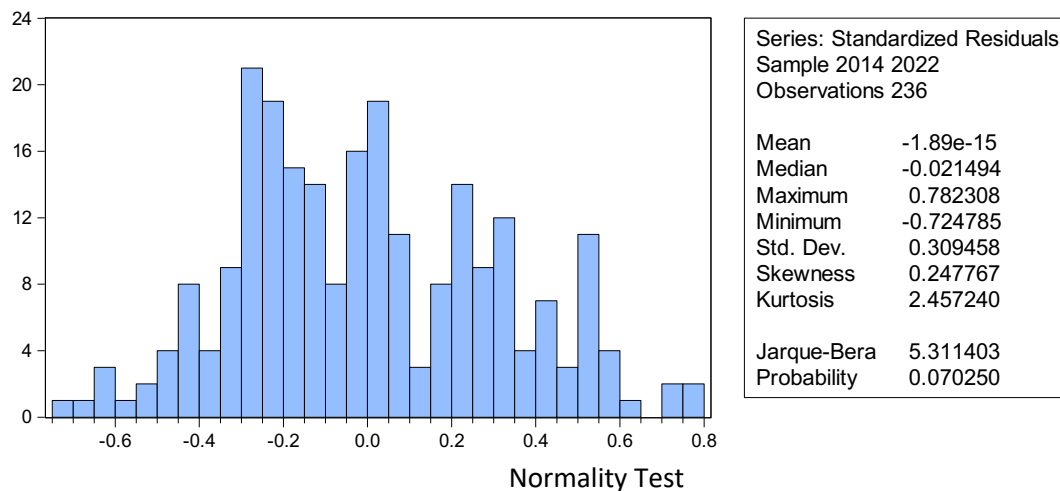


Figure 3.

Source: Secondary Data Processing, 2025

As shown in Figure 3, the histogram of standardized residuals is symmetrically bell-shaped, the residuals show no significant deviation from a normal distribution. The Jarque-Bera value of 5.311403 with a p-value of 0.070250 supports the null hypothesis, as the p-value exceeds the commonly used 0.05 threshold for significance. The residuals exhibit acceptable levels of skewness (0.247767) and kurtosis (2.457240), both of which are near the expected values for a normal distribution (i.e., skewness ≈ 0 and kurtosis ≈ 3). The mean of the residuals is effectively zero, and the distribution is fairly symmetric around the median. Based on these results, we conclude that the assumption of normality is satisfied, reinforcing the validity of the model's inferential statistics, including hypothesis testing and confidence intervals.

Panel Data Regression

Following the selection of the Fixed Effect Model as the most suitable estimation technique—based on the results of the Chow and Hausman tests—and after confirming the fulfillment of classical linear regression assumptions, the study proceeds to interpret the empirical findings. Diagnostic tests confirmed the absence of multicollinearity, heteroskedasticity, and non-normality of residuals, ensuring that the regression estimates are statistically reliable, efficient, and unbiased.

This section presents the estimation results from the FEM regression, which quantifies how essential circular economy indicators affect environmental sustainability, with greenhouse gas emissions from production serving as the proxy variable, analyzed across 27 EU member states from 2014 - 2023. The interpretation focuses on the magnitude, direction, and statistical significance of the coefficients for each explanatory variable, providing insights into how employment in circular economy sectors, circular material use, waste generation, and recycling performance affect the EU's progress toward sustainability and resilience.

Table 5. Panel Data Regression

Dependent Variable	: Greenhouse gas emissions			
Method	: Panel Least Squares			
Cross-section included	: 27			
Total panel (unbalanced) observations	: 236			
Variable	Coefficient	Std. Error	t-Statistic	Prob.
Constant	10623.04	682.6366	15.56179	0.0000***
CE_Employment	-0.009456	0.003606	-2.622622	0.0094***
CMUR	-102.2979	29.52732	-3.464519	0.0006***
Waste	-1.180620	0.611361	-1.931133	0.0548*

Recycling	-0.729050	11.88447	-0.061345	0.9511
Effect Specification				
Cross-section Fixed				
R-Squared	0.930431	F-Statistic	91.39064	
Adjusted R-Squared	0.920250	Prob(F-Statistic)	0.000000	

Significance Level: *** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.10$

Source: Secondary Data Processing, 2025

Based on the results of the data processing, the panel data regression equation is formulated as follows.

$$GHG_{it} = 10623.04_{it} - 0.009456CE_{Employment_{it}} - 102.2979CMUR_{it} - 1.180620Waste_{it} - 0.729050Recycling_{it} \dots\dots\dots (2)$$

The coefficient for the number of persons employed in circular economy sectors is -0.009456. This indicates that for every additional person employed in these sectors, greenhouse gas emissions are reduced by 0.009456 million tonnes of CO₂. The coefficient for the Circular Material Use Rate is 102.2979, indicating a negative relationship. This means that every 1 percent increase in total material use will reduce greenhouse gas emissions by 102.2979 million tonnes of CO₂. The coefficient of municipal waste generation per capita is -1.180620. This indicates that for every increase of 1 kilogram of municipal waste per capita, greenhouse gas emissions are reduced by 1.180620 million tons of CO₂. The coefficient of the recycling rate of municipal waste is -0.729050. This indicates that for every 1 percent increase in the recycling rate of municipal waste, greenhouse gas emissions will decrease by 0.729050 million tons of CO₂.

To assess the individual significance of each explanatory variable in the Fixed Effects Model, the study employs the t-test for regression coefficients. This test evaluates whether each independent variable has a statistically significant effect on the dependent variable, controlling for other variables in the model. Specifically, it examines the null hypothesis that the coefficient of a given independent variable is equal to zero, which implies no partial effect on the outcome variable.

Table 6. t-test

Variable	Coefficient	t-Statistic	t-table	Prob.
Constant	10623.04	15.56179	1.970	0.0000***
CE_Employment	-0.009456	-2.622622	1.970	0.0094***
CMUR	-102.2979	-3.464519	1.970	0.0006***
Waste	-1.180620	-1.931133	1.970	0.0548*
Recycling	-0.729050	-0.061345	1.970	0.9511

Significance Level: *** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.10$

Source: Secondary Data Processing, 2025

The t-statistic for persons employed in circular economy sectors is -2.622622, with a probability of 0.0094. This t-statistic exceeds the critical value in the t-table (-2.622622 > -1.970), and the probability is less than 0.05 (0.0094 < 0.05). These results indicate that persons employed in circular economy sectors has a significant impact on greenhouse gas emissions. The t-statistic for Circular Material Use Rate is -3.464519, with a probability of 0.0006. This t-statistic exceeds the critical value in the t-table (-3.464519 > -1.970), and the probability is less than 0.05 (0.0006 < 0.05). These results indicate that Circular Material Use Rate has a significant impact on greenhouse gas emissions.

The t-statistic for the generation of municipal waste per capita is -1.931133, with a probability of 0.0548. The t-statistic is less than the critical value from the t-table (-1.931133 < -1.970) and the probability is greater than 0.05 (0.0548 > 0.05), this indicates that the generation of municipal waste per capita does not have a significant effect on greenhouse gas emissions. The t-statistic for the

recycling rate of municipal waste is -0.061345, with a probability of 0.9511. The t-statistic is less than the critical value from the t-table ($-0.061345 < -1.970$) and the probability is greater than 0.05 ($0.9511 > 0.05$), this indicates that the recycling rate of municipal waste does not have a significant effect on greenhouse gas emissions.

To evaluate the overall explanatory power of the regression model, the study conducts an F-test that assesses the joint significance of all independent variables. The null hypothesis of the F-test posits that all slope coefficients are simultaneously equal to zero, suggesting that the model lacks explanatory relevance. A statistically significant F-statistic ($p\text{-value} < 0.05$) indicates that the independent variables, taken together, have a meaningful effect on the dependent variable. Based on Table 5, the F-statistic value is 91.39064, with a probability of 0.000000. This F-statistic exceeds the critical value from the F-table ($91.39064 > 2.696$) and the associated probability is significantly lower than the 0.05 threshold ($0.0000 < 0.05$). These results indicate that the variables of persons employed in circular economy sectors, circular material use rate, generation of municipal waste per capita, and recycling rate of municipal waste collectively impact greenhouse gas emissions.

To assess the goodness of fit of the regression model, this study examines the coefficient of determination (R^2), which indicates the proportion of variation in the dependent variable explained by the independent variables. In other words, R^2 measures the model's explanatory power. A higher R^2 value suggests that the model captures a greater share of the variability in greenhouse gas emissions from production activities, the proxy for environmental sustainability used in this analysis. The Adjusted R-Squared value is 0.920250, or 92.02 percent, indicating that 92.02 percent of the variability in greenhouse gas emissions is explained by the variables related to individuals employed in circular economy sectors, the Circular Material Use Rate, the generation of municipal waste per capita, and the recycling rate of municipal waste. The remaining 7.97 percent, or 0.07975, is attributed to other variables not included in the model.

Discussion

The concept of a circular economy (CE) has emerged as a crucial strategy for reducing greenhouse gas (GHG) emissions across various sectors in the European Union (EU). Evidence indicates a statistically significant negative relationship between employment in circular economy sectors and GHG emissions, suggesting that transitions to CE can effectively promote environmental sustainability. Research indicates that innovations and strategies associated with the circular economy significantly reduce emissions. Erdiaw-Kwasie et al., (2023) provide empirical evidence that circular technological innovations decrease GHG emissions in various economies, highlighting the effectiveness of circular economy (CE) initiatives in lowering carbon footprints. This finding aligns with Nechifor et al., (2020) who emphasize that integrating circular principles in industries like steel manufacturing can substantially reduce CO_2 emissions across supply chains, thereby promoting sustainability. The significance of circular economy practices is further underscored by Dumitraş et al., (2023) argue that adopting a CE model addresses challenges related to resource extraction and mitigates externalities such as climate change and pollution.

Additionally, regional studies validate the impact of the circular economy (CE) on greenhouse gas (GHG) emissions reduction. Retegi et al., (2023) assess the effects of CE policies on regional economies and environmental outcomes using input-output models. Their work illustrates that regions embracing CE strategies experience a decrease in GHG emissions, reinforcing the argument for increased employment in these sectors to enhance sustainability. The benefits of integrating CE practices are further demonstrated by Gracida-Alvarez et al., (2019) who discuss how systems utilizing cyclic material flows can significantly mitigate emissions. Employment within circular economy sectors has a significant negative impact on greenhouse gas emissions, as shown by multiple studies. The transition to CE practices promises not only economic benefits, such as job creation and resource efficiency, but is also crucial for curbing climate change and its associated challenges.

The Circular Material Use Rate (CMUR) is crucial for assessing greenhouse gas (GHG) emissions in the European Union (EU). Numerous studies show that higher rates of circular material usage significantly reduce GHG emissions across various sectors. Erdiaw-Kwasie et al., (2023) provide evidence that innovations in circular economic practices result in substantial reductions in GHG emissions. Their analysis of 30 advanced and emerging economies reveals a notable negative correlation between the adoption of circular technologies and GHG emissions, underscoring that increased circular material usage directly contributes to this reduction. The study indicates that implementing circular principles leads to fewer emissions by reducing dependency on raw material extraction, a major source of GHG emissions. Andrade et al., (2023) emphasize the importance of recycling in the steel industry, which uses scrap as an input material. Their findings support the assertion that increased use of recycled materials correlates with lower environmental impacts, including greenhouse gas (GHG) emissions, from industrial operations. By transitioning to a circular economy model, industries can mitigate the negative consequences associated with traditional linear production methods that heavily rely on virgin materials. The integration and enhancement of Circular Material Use Rates across various sectors within the EU correlate negatively with GHG emissions. Evidence consistently shows that increasing circularity not only promotes sustainability but also serves as a critical strategy in combating climate change by significantly reducing emissions generated from traditional production practices.

An analysis of the determinants of greenhouse gas (GHG) emissions in the European Union (EU) indicates that the generation of municipal waste per capita does not have a statistically significant direct impact on aggregate GHG emissions. Several studies suggest that the relationship between municipal waste generation and GHG emissions is mediated by additional factors, such as waste composition, management strategies, and overall energy consumption, rather than the volume of waste alone. Apostu et al., (2023) provide evidence that variables such as final energy consumption and economic indicators significantly influence municipal waste generation, further suggesting that the direct effect of municipal waste generation per capita on GHG emissions is not statistically significant. This implies that when considered in isolation, waste generation is not a primary determinant of GHG emission levels in the EU. Instead, the interplay between macroeconomic factors and waste management strategies appears to govern both municipal waste generation and emission outcomes. Research by Nęcka et al., (2024) underscores that while accurate forecasting of municipal waste is essential for optimizing waste management processes, per capita generation figures do not necessarily lead to proportional changes in GHG emissions. Their findings imply that emissions are more strongly influenced by waste treatment technologies and practices such as recycling rates and energy recovery methods than by the total volume of waste produced per individual. The available empirical evidence from the EU context suggests that municipal waste generation per capita does not significantly affect GHG emissions. This is largely because waste management outcomes are determined by the composition of waste, regulatory frameworks that promote advanced waste treatment technologies, and the overall efficiency of waste processing systems. Therefore, from a policy perspective, efforts to mitigate GHG emissions may be more effectively directed toward improving waste management infrastructure and adopting superior processing technologies, rather than solely focusing on reducing per capita waste generation.

A synthesis of the available literature indicates that while recycling is widely promoted as a key element of sustainable waste management, the recycling rate of municipal waste alone does not have a statistically significant impact on greenhouse gas (GHG) emissions within the European Union (EU). Several studies suggest that recycling rates, typically measured by mass-based targets, may not adequately capture the environmental benefits associated with improved waste management practices or changes in waste composition. Anshassi et al., (2018) argue that mass-based recycling metrics often favor heavier materials and do not accurately reflect the true environmental benefits such as GHG emission avoidance achieved through recycling lighter or more energy-intensive materials. Their work emphasizes the need for recalibration toward life-cycle-based metrics, as the

environmental performance of recycling can vary significantly across different types of waste. Similarly, Lee et al., (2016) contend that while recycling contributes to resource conservation, its isolated effect on overall GHG emissions can be obscured by systemic factors such as energy consumption in waste treatment processes and variations in technology adoption. This suggests that despite improvements in municipal waste recycling, the net change in GHG emissions may not be statistically significant when evaluated in isolation. Although recycling is a critical component of a circular economy and plays an important role in resource conservation and energy efficiency, empirical evidence indicates that the recycling rate of municipal waste when viewed in isolation does not have a statistically significant effect on GHG emissions in the EU. This underscores the need for a more integrated approach that considers waste composition, treatment efficiency, and overall management practices to accurately quantify recycling's contribution to GHG mitigation.

CONCLUSION

The empirical results revealed that two circular economy indicators, persons employed in circular economy sectors and the circular material use rate (CMUR) have a statistically significant negative effect on greenhouse gas (GHG) emissions. These findings suggest that increased labor participation in circular sectors and heightened material circularity substantially contribute to reducing the environmental burden of production activities, thereby enhancing sustainability outcomes. This underscores the strategic importance of scaling up employment and innovation in the circular economy as a pathway to carbon neutrality and systemic resilience.

Conversely, the generation of municipal waste per capita and the recycling rate of municipal waste were found to have no statistically significant effect on GHG emissions within the model. This implies that isolated metrics of waste generation or mass-based recycling rates may not adequately capture the complexity of emissions dynamics, as their environmental impact depends on other factors such as waste composition, processing technologies, and lifecycle efficiencies. These results align with recent literature suggesting the need for more integrated, system-level approaches to waste management and recycling policy.

The study provides empirical evidence that selected circular economy strategies can play a critical role in supporting the EU's climate goals, particularly in reducing production-related emissions. The findings also highlight the importance of focusing not only on recycling rates but also on upstream interventions such as material reuse, design innovation, and green employment to achieve tangible sustainability gains. These insights are valuable for policymakers aiming to align economic transition strategies with environmental objectives under frameworks like the European Green Deal and the Circular Economy Action Plan.

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