



Recycling, Resource Productivity and Circular Economy Performance in the EU

Zvonimira Sverko Grdic*^{ID}, Marinela Krstinic Nizic^{ID}

University of Rijeka, Faculty of Tourism and Hospitality Management, Opatija 51410, Croatia

Corresponding Author Email: zgrdic@fthm.hr

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ABSTRACT

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This paper examines cross-country associations between resource productivity, municipal waste recycling, packaging waste recycling, GDP per capita, and circular material use across European Union (EU) member states, with the aim of identifying the factors most strongly associated with circular economy (CE) performance. The analysis uses Eurostat data for 27 EU member states for 2023. Descriptive statistics, Pearson correlation analysis, and multiple ordinary least squares (OLS) regression with robust standard errors are applied, with the circular material use rate (CMU) as the dependent variable. The results show that resource productivity is the strongest positive statistical predictor of circular material use. Municipal and packaging waste recycling rates do not retain statistically significant independent relationships with CMU after controlling for the other explanatory variables, while GDP per capita shows a significant negative conditional association. The findings highlight substantial differences in CE performance across EU member states and indicate that economic development alone does not necessarily translate into higher circular material use. From a policy perspective, the results suggest that improving the efficiency of material use deserves particular attention alongside continued investment in recycling systems.

1. INTRODUCTION

Growing pressure on natural resources and increasing waste generation have strengthened the need for economic models that use materials more efficiently and reduce dependence on primary resources. In this context, the circular economy (CE) has become an important component of the European Union's sustainability agenda. The CE has emerged as a strategic priority in response to these challenges. It aims to reduce dependence on primary raw materials, improve resource productivity, and achieve long-term sustainable economic development [1]. The linear economic model, which is still the most widely used today, is based on a "take-make-dispose" approach, while the CE seeks to keep products, materials, and resources in use for as long as possible through recycling, reuse, and waste reduction [2]. The European Union is taking various strategic documents such as the CE Action Plan and the European Green Deal. It regards the CE not only as an environmental protection policy, but also as a key instrument for strengthening competitiveness, innovation, economic resilience, and resource efficiency [3]. However, despite a common legislative framework and shared strategic objectives, there are still significant differences between the member states of the European Union in terms of the success of the CE, resource productivity, and the efficiency of recycling systems [4].

Previous research has examined the relationship between the CE, economic growth, technological innovation, and

environmental sustainability [5, 6], while few authors have investigated and explained differences in the intensity of the use of the CE among the member states of the European Union.

The purpose of this research is to examine which factors are associated with the intensity of CE implementation, i.e., to assess the relationships between resource productivity, municipal waste recycling, packaging waste recycling, economic development and circular material use. The authors use secondary Eurostat data for 2023, which they analyze with descriptive statistics, Pearson correlation analysis, and ordinary least squares (OLS) regression, using the circular material use rate (CMU) as the main indicator of the success of the CE.

The contribution of this study is not methodological complexity per se, but the simultaneous comparison of the relative associations of key resource-efficiency, recycling and economic-development indicators with circular material use across all EU-27 member states. By estimating these factors jointly, the analysis distinguishes simple bivariate relationships from their conditional associations with CMU and provides an updated assessment of which factors retain statistical relevance when competing explanations are considered simultaneously.

2. LITERATURE REVIEW

The CE has emerged as an alternative to the traditional

linear “take-make-dispose” model by seeking to maintain the value of products, materials and resources within the economy for as long as possible. Rather than being limited to waste management and recycling, CE represents a systemic approach involving the reduction, reuse, recovery and recirculation of materials across production and consumption systems. Ghisellini et al. [7] conceptualized the CE as a strategy for overcoming the limitations of the linear economic model through the closing of material and energy loops, while Geissdoerfer et al. [8] positioned CE as a sustainability-oriented paradigm that combines economic prosperity with environmental quality. Similarly, Kirchherr et al. [9], based on an analysis of 114 CE definitions, emphasized reducing, reusing, recycling and recovering materials within a systemic transition involving multiple actors and levels. These conceptual foundations are consistent with subsequent literature emphasizing product life extension, material recovery, stakeholder cooperation and institutional change as essential components of circularity [2, 10-14].

At the European Union level, CE has become an important mechanism for reducing dependence on primary raw materials, increasing resource efficiency and supporting climate-neutral development [3, 15]. However, member states differ substantially in their CE performance [4, 16-19]. These differences suggest that circularity cannot be explained by a single dimension of economic development but reflects the interaction of resource efficiency, material recovery, waste-management capacity and broader structural conditions. Existing empirical studies therefore increasingly use indicators such as resource productivity, recycling rates and circular material use to evaluate differences in CE performance [5, 6, 20-24].

Resource productivity and circular material use. Resource productivity captures the economic value generated per unit of material consumed and therefore reflects how efficiently an economy transforms material inputs into economic output [25, 26]. Within a CE, greater resource productivity is theoretically associated with lower dependence on virgin materials, more efficient material use and stronger incentives to preserve the economic value of resources through reuse and recirculation [27]. Previous EU evidence identifies resource productivity as an important component of CE performance and sustainable economic development [5, 19, 23, 26]. The mechanism is therefore based on material efficiency: economies that generate more value from a given quantity of material inputs should, all else being equal, have stronger conditions for maintaining materials within productive use rather than replacing them with primary resources. Accordingly:

H1: There is a positive relationship between the CMU and resource productivity.

Recycling and circular material use. Recycling constitutes one of the principal mechanisms through which materials that would otherwise become waste are returned to economic activity. Efficient waste-management and recycling systems increase the availability of secondary raw materials, reduce disposal and contribute to closing material loops [4, 6, 16, 28]. Municipal waste recycling captures the ability of national waste-management systems to recover materials from heterogeneous household and similar waste streams, while packaging recycling reflects material recovery from a major and comparatively standardized waste stream. Higher recycling performance should therefore increase the quantity of secondary materials potentially available for reintegration into production and consequently be positively associated with

circular material use [6, 12, 16, 21].

At the same time, these relationships require cautious interpretation because municipal and packaging recycling indicators are conceptually related to the recycled material flows underlying CMU. Their expected positive relationships with CMU may therefore reflect both substantive differences in recycling capacity and, to some extent, the accounting relationship among the indicators. Nevertheless, the material-loop mechanism provides a theoretical basis for expecting positive cross-country associations. Accordingly:

H2: A positive cross-country association is expected between the CMU and the municipal waste recycling rate, while acknowledging the conceptual overlap between these indicators.

H3: A positive cross-country association is expected between the CMU and the packaging waste recycling rate, while acknowledging the conceptual overlap between these indicators.

Economic development and circular material use. Economic development may facilitate the transition towards circularity by increasing the financial, technological and institutional capacity required for investment in recycling infrastructure, eco-innovation and resource-efficient production [29-31]. Several cross-country studies report that more economically advanced EU member states tend to achieve stronger CE performance [18, 19], while CE indicators have also been positively associated with economic growth and sustainable development [5, 12, 20, 21, 24]. From this perspective, higher GDP per capita may provide greater capacity to finance technologies, infrastructure and organizational changes necessary for material recovery and circular production.

However, economic development does not automatically generate circularity. Institutional quality, regulatory frameworks, technological innovation and the efficiency of resource management may be more directly related to CE performance than national income itself [4, 30]. GDP per capita is therefore treated in the present analysis as a broader structural factor rather than a direct measure of CE performance. Based on the investment-capacity mechanism and the predominantly positive association reported in previous cross-country literature, the following hypothesis is proposed:

H4: There is a positive relationship between the CMU and gross domestic product per capita.

Taken together, these mechanisms suggest that circular material use reflects different but interconnected dimensions of CE development: resource productivity represents the efficiency with which material inputs generate economic value; recycling represents the recovery and reintegration of secondary materials; and GDP per capita captures the broader economic capacity that may facilitate investment in circular infrastructure and technologies. Previous research has extensively examined relationships between CE indicators, economic growth and sustainability [5, 6, 20, 21]. Busu [5] and Pineiro-Villaverde and García-Álvarez [26], for example, employ longitudinal approaches to analyze broader relationships between CE performance, resourced productivity and economic development. The present study addresses a narrower comparative question by examining resource productivity, municipal waste recycling, packaging waste recycling and GDP per capita simultaneously in relation to CMU across the EU-27. Its contribution therefore lies in distinguishing their bivariate relationships from their

conditional associations and in assessing which factors retain statistical relevance when considered within the same empirical framework.

3. METHODOLOGY

Based on secondary indicators obtained from Eurostat for 2023, this research analyses the level of development of CE implementation in the EU member states. The analysis includes a comparison of differences between member states in 2023. This, in turn, facilitates the identification of factors associated with higher levels of CE performance. The statistical analyses were performed using IBM SPSS Statistics.

One of the main indicators of CE development is the CMU, which is analyzed in the paper as a dependent variable. It measures the share of secondary raw materials reintroduced into production processes in relation to total material consumption. Higher values of this indicator reflect a higher degree of circularity within the economy. The empirical model includes four independent variables:

- resource productivity (RP_EURkg);
- municipal waste recycling rate (REC_MUN_%);
- packaging waste recycling rate (REC_PACK_%);
- gross domestic product per capita expressed in purchasing power standards (GDPpc_PPS).

All variables were obtained from the Eurostat database for the reference year 2023. The CMU was obtained from the Eurostat material flow accounts dataset (env_ac_cur), while resource productivity was obtained from the Resource Productivity dataset (env_ac_rp). The municipal waste recycling rate was obtained from the CE indicator dataset (cei_wm011), and the packaging waste recycling rate from the corresponding CE indicator dataset (cei_wm020). Gross domestic product per capita (GDPpc_PPS)—GDP per capita expressed in purchasing power standards relative to the EU-27 average (EU-27 = 100), used as an indicator of the relative level of economic development (Eurostat dataset code: nama_10_pc).

The resource productivity indicator is used as a measure of the economic efficiency of material use. Recycling rates reflect the level of development of the waste management system and the ability to close material loops. The gross domestic product per capita indicator is included as a control variable because it can be used to assess the level of economic development in the member states.

An important methodological consideration concerns the construction of the selected indicators. The CMU is derived from economy-wide material flows and incorporates recycled materials returned to the economy. Consequently, municipal and packaging waste recycling indicators are conceptually related to the recycled waste flows underlying CMU, which may generate a degree of part-whole or mechanical correlation. In addition, resource productivity is defined as GDP relative to domestic material consumption (DMC), while material consumption also enters the accounting framework underlying CMU. Therefore, the observed associations between these indicators and CMU cannot be interpreted as relationships among fully independent constructs. The results are consequently interpreted with caution as cross-country statistical associations.

The empirical analysis was conducted in three stages. First, descriptive statistics were calculated to examine the distribution of variables and were related to differences

between the member states of the European Union. Next, Pearson correlation analysis was performed to assess the direction and strength of the relationships between the variables. The statistical significance of the correlation coefficients was assessed using a t-test, with the significance level set at 5%.

In the third stage, a multiple OLS regression model was estimated to assess the simultaneous associations of resource productivity, municipal waste recycling, packaging waste recycling and GDP per capita with the CMU. All four explanatory variables were entered simultaneously into the model. Standardized beta coefficients were reported to enable a direct comparison of the relative importance of statistical predictors measured in different units. Variance inflation factors (VIF) were also examined to assess potential multicollinearity among the explanatory variables.

Given the relatively small cross-sectional sample, heteroskedasticity-robust HC3 standard errors were additionally calculated as a robustness check. Model diagnostics included inspection of residual plots, tests for heteroskedasticity, and influence statistics. Residual normality was assessed using standard diagnostic statistics and graphical inspection. Cook's distance, leverage values, studentized residuals, and DFBETAs were examined to identify potentially influential observations.

The general regression model is specified as follows:

$$CMU_i = \beta_0 + \beta_1 RP_i + \beta_2 REC_MUN_i + \beta_3 REC_PACK_i + \beta_4 GDPpc_i + \varepsilon_i$$

where,

CMU represents the circular material use rate;

RP denotes resource productivity;

REC_MUN denotes the municipal waste recycling rate;

REC_PACK denotes the packaging waste recycling rate;

GDPpc represents GDP per capita in purchasing power standards;

β_0 is the intercept;

β_1 – β_4 are regression coefficients; and

ε_i is the error term.

The hypotheses developed in the literature review were tested using the empirical model specified.

4. RESEARCH RESULTS

To provide a longer-term context for the 2023 cross-sectional analysis, developments in the CMU were first examined over the period 2010–2024. Table 1 presents the corresponding country-level values and calculated compound annual growth rate (CAGR) indicators. These long-term trends are used only as descriptive background and are not incorporated into the subsequent correlation and regression analyses, which are based exclusively on 2023 data.

The results indicate that Latvia (13.19%), Croatia (9.77%), Malta (9.38%), Czechia (7.61%) and Cyprus (7.49%) recorded the highest compound annual growth rates in the CMU over the period 2010–2024. Relatively high growth rates were also recorded in Slovakia (6.58%), Bulgaria (6.39%) and Estonia (6.06%). By contrast, Finland (−11.17%), Romania (−6.83%), Luxembourg (−5.44%), Poland (−2.58%) and Spain (−2.40%) recorded negative growth rates. At the EU-27 level, CMU increased moderately from 10.7% in 2010 to 12.2% in 2024, corresponding to a CAGR of 0.94%. In terms of the actual

CMU levels achieved in 2024, the highest values were recorded in the Netherlands (32.7%), Belgium (22.7%) and Italy (21.6%). Some country-level changes are unusually large and should therefore be interpreted cautiously. For example, Finland's reported CMU declines from 10.5% in 2010 to 2.0% in 2024, while Luxembourg decreases from 23.4% to 10.7%. Such shifts may partly reflect revisions in underlying material-flow accounts, methodological adjustments, changes in statistical reporting, or potential breaks in the time series rather than purely substantive changes in CE performance.

Table 1. Compound annual growth rate (CAGR) of the circular material use rate (CMU) in European Union member states, 2010-2024, in %

Country	2010	2024	CAGR (%)
EU-27	10.7	12.2	0.94
Belgium	13.5	22.7	3.78
Bulgaria	2.1	5.0	6.39
Czechia	5.3	14.8	7.61
Denmark	8.0	9.4	1.16
Germany	11.2	14.8	2.01
Estonia	9.0	20.5	6.06
Ireland	1.9	2.0	0.37
Greece	2.5	5.2	5.37
Spain	10.4	7.4	-2.40
France	17.6	17.8	0.08
Croatia	1.6	5.9	9.77
Italy	11.3	21.6	4.74
Cyprus	2.0	5.5	7.49
Latvia	1.2	6.8	13.19
Lithuania	3.9	4.2	0.53
Luxembourg	23.4	10.7	-5.44
Hungary	5.2	7.3	2.45
Malta	5.3	18.6	9.38
Netherlands	24.8	32.7	1.99
Austria	6.8	15.2	5.91
Poland	11.1	7.7	-2.58
Portugal	1.8	3.0	3.72
Romania	3.5	1.3	-6.83
Slovenia	5.9	10.1	3.91
Slovakia	5.0	12.2	6.58
Finland	10.5	2.0	-11.17
Sweden	7.2	10.4	2.66

Source: Calculation of authors.

Before testing the proposed hypotheses, a descriptive statistical analysis was conducted to provide an overview of the distribution of the selected variables and to identify differences among the EU member states. Descriptive statistics provide a preliminary assessment of the degree of heterogeneity across countries and form the basis for the subsequent correlation and regression analyses.

The descriptive statistics reveal substantial cross-country variation among EU member states. The unweighted mean CMU is 10.69% (SD = 7.46), with national values ranging

from 1.50% to 32.00%. Resource productivity averages EUR 2.10/kg (SD = 1.33), while municipal and packaging waste recycling rates average 41.02% (SD = 15.55) and 63.58% (SD = 10.74), respectively. GDP per capita shows particularly high cross-country dispersion, with a mean of 103.67 PPS and a standard deviation of 64.79 (Table 2).

Table 2. Descriptive statistics of the variables (EU-27, 2023)

Variable	Mean	Standard Deviation	Min.	Max.
CMU (%)	10.69	7.46	1.5	32
RP (EUR/kg)	2.1	1.33	0.39	5.81
REC_MUN (%)	41.02	15.55	12.4	68.7
REC_PACK (%)	63.58	10.74	37.3	79.7
GDPpc_PPS (EU-27 = 100)	103.67	64.79	38.2	320.4

Source: Calculation of authors by Eurostat.

Note: Means and standard deviations are calculated as unweighted statistics across the 27 EU member states. Each Member State is treated as one observation. Therefore, the reported means should not be interpreted as official EU-27 aggregate values. CMU = circular material use rate.

Resource productivity also exhibits significant cross-country variation, with an average value of EUR 2.10 per kilogram. The wide gap between the minimum and maximum values indicates substantial differences in the economic efficiency of material and resource use among member states.

The municipal waste recycling rate averages 41.02%, while the packaging waste recycling rate is considerably higher, at 63.58%. These findings suggest that EU member states are generally more successful in recycling packaging waste than in managing the recycling of overall municipal waste.

The substantial dispersion in gross domestic product per capita confirms the existence of considerable economic disparities, which may be associated with differences in CE development and in the capacity to invest in recycling systems and resource management.

To examine the direction and strength of the relationships among the selected variables, a Pearson correlation analysis was performed. This analysis enables the identification of linear relationships between variables and represents an important preliminary step before estimating the regression models.

The correlation analysis shown in Table 3 indicates that CMU is positively and significantly associated with resource productivity ($r = 0.643$, $p < 0.001$), municipal waste recycling ($r = 0.414$, $p < 0.05$), and packaging waste recycling ($r = 0.510$, $p < 0.01$). By contrast, the bivariate relationship between CMU and GDP per capita is positive but not statistically significant ($r = 0.165$, $p > 0.05$). These correlations provide a preliminary overview of the relationships among variables, while their simultaneous and relative relationships are examined in the multiple regression model.

Table 3. Correlation matrix (Pearson correlation coefficients)

Variable	CMU	RP	REC MUN	REC PACK	GDPpc
CMU	1	0.643***	0.414**	0.510***	0.165
RP	0.643***	1	0.505***	0.416**	0.703***
REC_MUN	0.414*	0.505***	1	0.635***	0.440**
REC_PACK	0.510**	0.416**	0.635***	1	0.243
GDPpc	0.165	0.703***	0.440**	0.243	1

Note: Statistical significance is denoted as follows: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. CMU = circular material use rate.

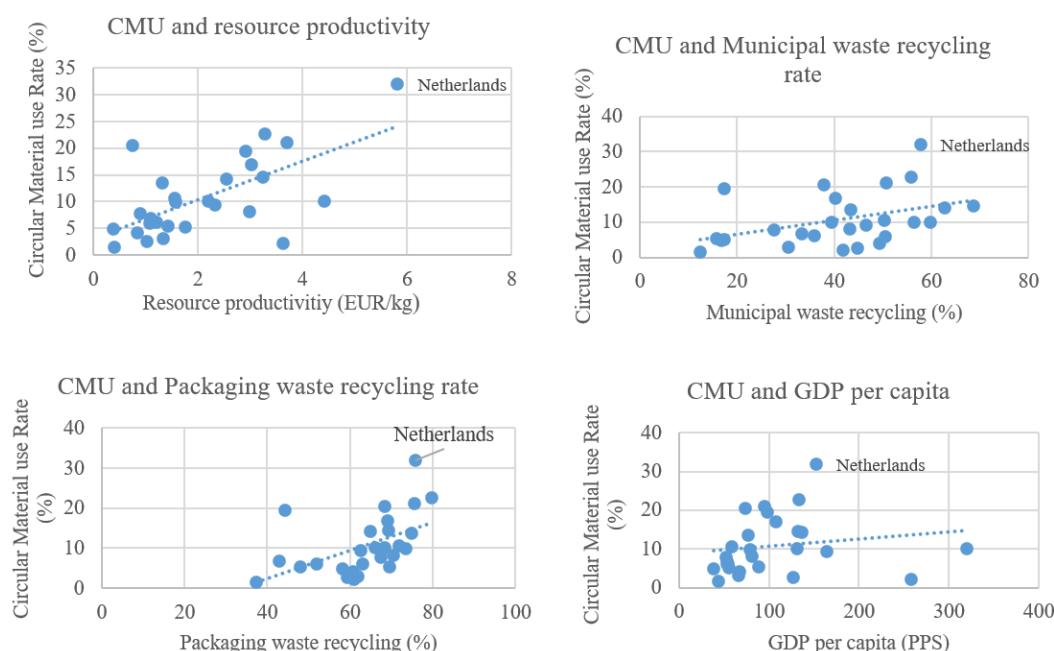


Figure 1. Scatter plots of the circular material use rate (CMU) and selected explanatory variables across European Union (EU) member states (n = 27)

Source: Authors' calculations based on Eurostat data.

Table 4. Multiple regression analysis predicting the circular material use rate (CMU)

Variable	B	HC3 Robust SE	Standardized β	t	p	VIF
Constant	-4.754	7.010	—	-0.678	0.505	—
Resource productivity	5.083	1.583	0.908	3.211	0.004	2.294
Municipal waste recycling	0.024	0.073	0.049	0.323	0.750	1.992
Packaging waste recycling	0.164	0.132	0.235	1.239	0.228	1.770
GDP per capita	-0.064	0.024	-0.552	-2.641	0.015	2.084

Note: HC3 heteroskedasticity-robust standard errors are reported. Standardized β coefficients are based on the original OLS specification.

These bivariate correlations should, however, be interpreted in light of the accounting relationships among the indicators. In particular, the positive correlations of CMU with municipal and packaging waste recycling may partly reflect the fact that recycled material flows contribute to the construction of the CMU indicator itself. Likewise, the association between CMU and resource productivity may partly reflect their common relationship with material consumption.

Figure 1 presents scatter plots of CMU against each of the four explanatory variables, allowing a visual assessment of the form and strength of the bivariate relationships and the identification of potentially unusual observations.

The scatter plots generally indicate positive bivariate relationships between CMU and resource productivity, municipal waste recycling, and packaging waste recycling, whereas the relationship between CMU and GDP per capita appears considerably weaker. The plots also reveal several potentially influential observations. In particular, the Netherlands records the highest CMU value and relatively high resource productivity, warranting additional influence and sensitivity diagnostics in the regression analysis.

To further examine the simultaneous associations between the selected explanatory variables and circular material use, a multiple OLS regression model was estimated, and the results are presented in Table 4.

The multiple regression model was statistically significant ($F(4, 22) = 9.503$, $p < 0.004$) and explained 63.3% of the variance in the CMU ($R^2 = 0.633$; adjusted $R^2 = 0.567$). Resource productivity emerged as the strongest positive

statistical predictor of CMU (standardized $\beta = 0.908$, $p < 0.004$), providing support for H1. This result indicates that, after controlling for recycling rates and economic development, countries generating greater economic value per unit of material consumed tend to achieve substantially higher levels of circular material use. Municipal waste recycling had a small positive but statistically non-significant independent relationship ($\beta = 0.049$, $p = 0.750$), while packaging waste recycling also showed a positive but non-significant relationship ($\beta = 0.235$, $p = 0.228$). Although both recycling indicators were significantly correlated with CMU at the bivariate level, their relationships were no longer statistically significant when the other explanatory variables were controlled for. This result is particularly relevant given the accounting overlap between the recycling indicators and CMU. The significant bivariate associations should therefore not be interpreted as evidence that municipal or packaging recycling independently explains circular material use.

GDP per capita showed a statistically significant negative association with CMU ($\beta = -0.552$, $p = 0.015$). Since H4 proposed a positive relationship, H4 was not supported. The change from a non-significant positive bivariate correlation to a significant negative coefficient in the multivariate model suggests that the relationship between economic development and circular material use becomes different once resource productivity and recycling performance are held constant.

Influence diagnostics were examined because of the small sample size. Cook's distance identified Malta, Estonia, and Ireland as the observations with the largest overall association,

while the Netherlands showed relatively high leverage but a Cook's distance below the conventional $4/N$ threshold. The Netherlands nevertheless had a comparatively large DFBETA for the resource productivity coefficient, indicating that it affects the magnitude of the RP estimate. For this reason, an additional sensitivity analysis excluding the Netherlands was performed.

Because the Netherlands records both the highest CMU value and very high resource productivity, a sensitivity analysis was conducted by re-estimating the model after excluding this observation. Resource productivity remained positively and statistically significantly associated with CMU ($B = 4.332$, standardized $\beta = 0.784$, $p = 0.005$), although the explanatory power of the model declined from $R^2 = 0.633$ to $R^2 = 0.475$. This indicates that the positive RP–CMU association is not solely driven by the Netherlands.

Standardized beta coefficients confirm that resource productivity has the largest positive relative contribution to CMU among the statistical predictors included in the model. The VIF values ranged from 1.770 to 2.294, indicating that multicollinearity does not represent a serious concern in the estimated model.

Additional model diagnostics were conducted to assess the robustness of the regression results. The Breusch–Pagan test did not indicate evidence of heteroskedasticity ($p = 0.896$). Regarding residual normality, the Shapiro–Wilk test did not reject the assumption of normality at the 5% significance level ($p = 0.069$), although the Jarque–Bera test indicated some departure from normality ($p = 0.009$). Given the small sample size and the presence of potentially influential observations, HC3 heteroskedasticity-robust standard errors were used for statistical inference.

5. DISCUSSION

The results show that resource productivity has the strongest positive conditional association with CMU among the indicators examined, whereas the two recycling indicators are significant only at the bivariate level. An analysis of the relationship between resource productivity, the recycling rate of municipal waste, the recycling rate of packaging waste and economic development confirms that the level of circularity of the economy is most strongly associated with the efficient use of resources, while recycling indicators show positive bivariate associations but no statistically significant independent relationship in the multivariate model.

The multiple regression results confirm the central role of resource productivity in explaining differences in circular material use across EU member states. Resource productivity displays the largest positive standardized coefficient ($\beta = 0.908$, $p = 0.004$) even after controlling simultaneously for municipal waste recycling, packaging waste recycling and GDP per capita. This finding provides stronger evidence than the bivariate models that efficient material use shows the strongest positive conditional association with circular material use among the indicators included in the model, while this relationship should be interpreted in light of the shared material-consumption component of the indicators.

This finding is consistent with previous studies identifying resource productivity as an important component of circular economy performance and sustainable economic development in EU countries [5, 19, 23, 26]. More recent evidence also supports the close relationship between resource productivity

and circular material use. Islam and Afolabi [32], analysing EU-27 countries, found that higher circular material use significantly increases the likelihood of belonging to a higher resource productivity convergence club, highlighting the close connection between circularity and the efficiency of material use.

Municipal and packaging waste recycling rates are positively correlated with CMU, confirming that countries with more developed recycling systems generally tend to record higher levels of circular material use. However, their coefficients are not statistically significant in the multiple regression model once resource productivity, GDP per capita and the other recycling indicator are controlled for. This suggests that the contribution of recycling to circularity may partly overlap with broader differences in resource efficiency and other structural characteristics of EU member states. Therefore, the findings do not imply that recycling is unimportant, but rather that it does not show an independent statistically significant relationship within the present cross-sectional model.

The positive bivariate relationships identified in the present study are broadly consistent with previous research emphasizing the importance of recycling and waste-management performance in the transition towards a circular economy [6, 16, 28]. However, recent evidence indicates that recycling performance is influenced by a broader set of socioeconomic and institutional conditions. Hondroyannis et al. [33], using national and regional data from EU countries, found that economic performance, institutional quality and educational attainment significantly contribute to recycling performance, suggesting that recycling outcomes should be interpreted within a broader structural context.

An additional explanation for these relationships lies in the construction of the indicators themselves. Municipal and packaging recycling rates are not conceptually independent of CMU because recycled material flows contribute to the circular use of materials measured by CMU. Consequently, part of their bivariate association may be mechanical rather than reflecting an independent structural relationship. A similar consideration applies to resource productivity, since RP is calculated relative to domestic material consumption, which is also related to the material-flow accounting underlying CMU. Therefore, the relatively strong association between RP and CMU should not be interpreted as evidence of an entirely independent causal mechanism.

The results for GDP per capita differ notably between the bivariate and multivariate analyses. Although its bivariate correlation with CMU is weak and statistically non-significant, GDP per capita becomes a significant negative statistical predictor when resource productivity and recycling performance are simultaneously controlled for ($\beta = -0.552$, $p = 0.015$). This finding should not be interpreted as evidence that economic development reduces circularity. Rather, it indicates that, among countries with comparable levels of resource productivity and recycling performance, higher GDP per capita is not necessarily associated with higher circular material use. The change in the direction of the coefficient also reflects the substantial association between GDP per capita and resource productivity and highlights the importance of examining the explanatory variables simultaneously rather than through separate bivariate models.

The complex relationship between economic development and circularity observed in the present study also finds support in recent research. Uzuner et al. [34] showed that the

relationship between material circularity and economic performance is not necessarily straightforward, reporting that increased material circularity may generate environmental benefits without automatically translating into stronger economic performance. Similarly, Álvarez et al. [35] identified GDP per capita and resource productivity as significant factors associated with circular economy efficiency, further indicating that economic development and circularity interact through multiple structural dimensions.

The differences identified among the member states of the European Union confirm that the transition to a CE does not follow a single development pattern. While countries such as the Netherlands, Belgium and Italy achieve the highest values of circular use of materials, some countries, such as Croatia and Latvia, record among the highest growth rates during the observed period. These cross-country differences suggest that high CE performance is not exclusively associated with higher levels of economic development and that resource productivity, recycling infrastructure and material-flow management may represent important characteristics of countries achieving stronger circularity outcomes.

The substantial cross-country differences identified in the present analysis are consistent with recent comparative evidence. Islam and Afolabi [32] identified four distinct resource productivity convergence clubs among EU countries, indicating persistent differences in their development trajectories. Similarly, Álvarez et al. [35] reported marked disparities in circular economy transition efficiency across the EU-27, with Germany, Italy and the Netherlands among the countries achieving the highest efficiency scores. These findings reinforce the conclusion that EU member states follow heterogeneous pathways in their transition towards a circular economy.

In the conventional OLS sensitivity model excluding the Netherlands, resource productivity remained positively and statistically significantly associated with CMU ($B = 4.332$, standardized $\beta = 0.784$, $p = 0.005$). However, when HC3 robust standard errors were applied to this reduced-sample specification, statistical significance weakened ($p = 0.072$). This finding suggests that the magnitude and precision of the estimated RP association are sensitive to influential observations in the relatively small cross-sectional sample and should therefore be interpreted cautiously.

From a policy perspective, the results point primarily to the importance of resource efficiency. First, European and national policies could place greater emphasis on improving resource productivity, since this indicator makes the greatest contribution to the development of a CE. At the same time, continued investment in municipal and packaging recycling systems remains important, although their independent relationships are not statistically significant after the other explanatory variables are controlled for. The results also show that CE policies should not focus solely on economic growth, but primarily on more efficient resource management, the development of innovation and strengthening the implementation of CE policies. Such an approach would enable all member states, regardless of their level of economic development, to make a more successful transition to a more sustainable development model.

Overall, this research is associated with the existing literature by providing a comparative empirical analysis of the relative importance of key CE indicators within a single analytical framework. An important contribution of the study is the simultaneous assessment of the selected explanatory

variables within a single multivariate framework. The use of standardized beta coefficients enables direct comparison of their relative contributions despite differences in measurement units. The results identify resource productivity as the strongest positive statistical predictor of circular material use among the variables included in the model. Key prerequisites for achieving the goal are increased resource productivity and the development of efficient recycling systems. Previous studies have mainly examined the relationship between CE development and economic growth, while the present analysis indicates that resource productivity shows the strongest positive association with circular material use among the variables examined. At the same time, the relationship between economic development and circularity appears more complex, suggesting that GDP per capita alone does not adequately explain cross-country differences in circular material use.

6. CONCLUSION

This study examined the associations between resource productivity, recycling performance, economic development and circular material use across the EU-27 in 2023. The multiple regression results identify resource productivity as the strongest positive statistical predictor of CMU among the variables examined. The results of the multiple regression analysis indicate that resource productivity is the strongest positive statistical predictor of circular material use among the explanatory variables examined. Although municipal and packaging waste recycling rates show positive bivariate relationships with CMU, their independent relationships are not statistically significant when all variables are considered simultaneously. GDP per capita shows a significant negative conditional association with CMU, indicating that a higher level of economic development does not in itself translate into greater circular material use. Overall, the findings underline the central importance of resource efficiency in explaining differences in CE performance across EU member states.

These results suggest that cross-country differences in circular material use are more strongly associated with resource productivity than with GDP per capita. Recycling performance also shows positive bivariate relationships with CMU, although these relationships are not statistically significant in the multivariate specification. The findings indicate that resource productivity shows the strongest positive cross-country association with circular material use among the indicators examined. The relationship between economic development and circularity appears more complex: although GDP per capita is only weakly associated with CMU at the bivariate level, its strong correlation with resource productivity suggests that economic development may be related to circularity through broader structural and resource-efficiency characteristics. Therefore, the results should not be interpreted as evidence that economic development has no role in CE performance. Rather, they indicate that GDP per capita alone does not adequately capture cross-country differences in circular material use.

This research contributes to the CE literature by showing that, within the present EU-27 cross-sectional model, resource productivity has a stronger positive association with circular material use than GDP per capita.

The research has several limitations that need to be taken into account. The analysis is based on secondary Eurostat data

for a single year (2023), which does not allow for causal inferences or examination of changes over time. In addition, the research is limited to the 27 EU member states, which makes the results difficult to generalize directly. A further limitation arises from the accounting and conceptual overlap among some of the indicators. Recycling flows contribute to the construction of CMU, while resource productivity and CMU are both related to domestic material consumption. This may introduce mechanical correlation and limits the extent to which the estimated coefficients can be interpreted as independent relationships. Future research could address this issue by incorporating indicators that are conceptually and mathematically more independent of the CMU measure. Although the selected indicators represent some of the most commonly used measures of CE performance, other potentially important explanatory variables – including institutional quality, technological innovation, regulatory frameworks, R&D investment and consumer behavior – are not included in the analysis. Given the relatively small cross-sectional sample of 27 EU member states, the results should be interpreted cautiously and primarily as evidence of conditional associations rather than causal relationships. Future research should use panel data covering longer periods and include additional institutional, technological and environmental explanatory variables. The small cross-sectional sample also makes the estimates sensitive to individual country observations. Influence and sensitivity diagnostics indicate that several countries, including the Netherlands, Malta and Estonia, affect the estimated coefficients to varying degrees. Although the principal RP association remains positive across specifications, its statistical precision weakens under the most conservative robustness specification.

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