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# Municipal waste recycling in the EU: a multi-method analysis of determinants and country profiles (2005–2023)

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**Introduction:** Municipal waste recycling plays a central role in European Union's (EU) transition to a circular economy and in meeting long-term sustainability goals. Identifying key macro-level drivers of recycling outcomes remains essential for effective policy development.

**Methods:** The study aimed to examine the macro-level determinants of municipal waste recycling in EU countries over the period 2005–2023, and to identify country groupings based on shared characteristics. The dependent variable was the municipal waste recycling rate, while independent variables included real gross domestic product (GDP) *per capita*, urban population size, environmental tax revenues, government expenditures on environmental protection, government budget allocations for R&D (GBARD) directed at environmental objectives, and private investment in circular economy sectors. The analysis employed multiple linear regression with backward elimination to identify statistically significant predictors of recycling performance. Temporal patterns were assessed using a simple linear trend analysis. Ward's hierarchical clustering based on five-year averages was conducted to group countries with similar characteristics.

**Results:** Recycling rates varied substantially across countries and time, with the EU average reaching 33.29%. A positive and statistically significant trend was observed over time; however, only a small group of countries exceeded the EU's 2025 target (55%). Regression analysis revealed that higher recycling rates were statistically associated with real GDP, environmental tax revenues, private investment in circular economy sectors, and GBARD (% GDP). Interestingly, urban population size and government expenditures on environmental protection (% GDP) were negatively associated with recycling rates, possibly reflecting structural pressures in densely populated areas and inefficiencies in public spending. GBARD expressed as a share of total GBARD also showed a negative relationship, possibly reflecting time lags between research funding and observable effects. One of the more advanced clusters included Germany, France, Italy, and Spain, which combined high recycling rates with strong economic and investment profiles. The least performing cluster, comprising Bulgaria, Estonia, Lithuania, Croatia, Poland, Malta, and Cyprus, was characterized by low recycling outcomes alongside less favorable economic and institutional conditions.

**Discussion:** The findings underscore the need for differentiated fiscal and investment strategies, improved efficiency in public spending, and tailored support for countries facing demographic or infrastructural challenges.

KEYWORDS

**municipal waste recycling, circular economy, European Union, macro-level determinants, multiple linear regression, hierarchical clustering, environmental policy, country-level analysis**

# 1 Introduction

Municipal waste generation has risen steadily across Europe, placing increasing pressure on waste management systems and threatening the EU's broader climate and resource efficiency goals (Castillo-Giménez et al., 2019; EEA, 2024). Municipal waste recycling remains central to the EU's ambitions for a circular economy and sustainable resource management (Banjerdpaiboon and Limleamthong, 2023). Despite clear policy directives such as the Waste Framework Directive and Circular Economy Action Plan, substantial divergences persist among member states in recycling performance (EEA, 2024; Georgescu et al., 2025; Holmen et al., 2025). These disparities highlight the need to better understand macro-level conditions that enable efficient recycling systems. Identifying the structural determinants of recycling—spanning economic, institutional, fiscal, and demographic domains—is directly relevant to EU policymakers striving to close performance gaps and meet sustainability targets. The study period of 2005–2023 is particularly apt, as it encompasses both the enactment of critical EU policies and a phase of accelerating circular economy efforts across Europe (Banjerdpaiboon and Limleamthong, 2023; Holmen et al., 2025). This study addresses the question of which macro-level variables are most strongly associated with municipal waste recycling performance across EU member states. The analysis integrates economic factors (GDP *per capita* and private investment), institutional factors (government environmental expenditures and R&D directed at environmental objectives), fiscal instruments (environmental taxes), and demographic characteristics (urban population size). By situating these variables within a unified analytical framework, the study provides a systematic approach to understanding how structural conditions may shape recycling outcomes over time and across national contexts.

Although a growing body of literature has examined specific determinants of recycling, integrated analyses that jointly consider fiscal, institutional, economic, and demographic domains remain limited. This gap constrains the ability to understand how these factors interact and jointly influence recycling performance at the macro level. By addressing this shortcoming, the present study makes a unique contribution by developing a comparative, EU-wide analysis that integrates multiple explanatory domains over a long observation period. In doing so, it provides new insights into the structural conditions underpinning recycling performance and offers a more holistic basis for evidence-based policymaking in the EU.

# 2 Literature review

A growing body of research has sought to identify the macro-level factors that contribute to municipal waste recycling performance, recognizing that recycling outcomes are shaped by a complex interplay of economic, institutional, fiscal, and demographic conditions (Saidani et al., 2019; Önder, 2018; Soukiazis and Proença, 2020; Hondroyiannis et al., 2024; Holmen et al., 2025). Municipal waste recycling represents a key indicator of progress toward circular economy principles and sustainable resource management, reflecting both the effectiveness of waste treatment systems and the degree of societal commitment to reducing environmental pressures (EEA, 2024; García-Valderrama et al., 2024). Despite its recognized importance, there is still a lack of integrated analyses that jointly consider the multiple drivers of recycling performance within a unified analytical framework. This section therefore situates the present study within this research gap by outlining the theoretical relevance of the selected explanatory variables and their expected associations with municipal waste recycling outcomes.

Recent empirical research increasingly underscored the relevance of macroeconomic and fiscal determinants in shaping municipal waste recycling performance across European countries. Among these, environmental tax revenues have emerged as an important policy tool aimed at internalizing environmental externalities, promoting sustainable development and fostering a circular economy (Xu et al., 2023; Su et al., 2023; Yang et al., 2024). These taxes, levied on environmentally damaging activities, generate revenue that can be reinvested in environmental protection and waste management initiatives, thereby creating a virtuous cycle of ecological and economic benefits (Liu et al., 2021). A well-designed environmental tax is often described as Pigouvian, targeting pollution at its source and reflecting the true social cost of waste generation through price mechanisms that align private incentives with social costs (Cheng et al., 2022; Pigou, 1920; Fullerton and Metcalf, 2001). Such tax revenues may subsidize recycling programs, improve waste collection and sorting facilities, and raise public awareness, which in turn can increase individual recycling participation (Viscusi et al., 2011). Empirical research has consistently shown that environmental taxation correlates positively with recycling outcomes in the EU, as demonstrated by Gabor et al. (2023) and further reinforced by Kostakis and Tsagarakis (2022), who also extended this link to circularity indicators. Building on this evidence, Imran et al. (2024) highlighted that such taxes not only encouraged cleaner production but also supported investments in recycling infrastructure. By contrast, Tantau et al. (2018) observed a negative association that lost significance once country-specific heterogeneity was accounted for, emphasizing the role of contextual mechanisms in shaping outcomes. Taken together, these insights underscore the relevance of environmental taxes as a potential explanatory variable in the present study, supporting their inclusion in the analytical framework to better understand patterns of municipal recycling performance in Europe.

Equally important are government expenditures on environmental protection, which reflect the degree of governmental prioritization of sustainability in budgetary allocations, particularly in supporting infrastructure and shaping household behavior towards waste management (Finnveden et al., 2013). These expenditures can directly fund the development of robust recycling infrastructure, including advanced material recovery facilities and efficient collection systems, while also supporting public awareness campaigns that foster pro-environmental behaviors (Chierrito-Arruda et al., 2018). Their efficacy is often amplified when combined with external incentives, such as monetary rewards or social influence, which are well-established predictors of recycling participation (Hornik et al., 1995; Nikiema and Asiedu, 2022). Evidence from both European and non-European contexts highlights the relevance of public environmental expenditures. In China, such spending promoted drop-off recycling and low-carbon practices (Li et al., 2025), while in the EU studies consistently reported positive effects, with Gabor et al. (2023) identifying government expenditure on environmental protection as a significant determinant of recycling rates, Jarczok-Guzy et al. (2024) confirming similar associations across member states, and Niu (2024) linking this spending to broader outcomes in environmental, social, and governance (ESG) performance, including recycling. Importantly, these effects are shaped by the design and implementation of waste management policies, which mediate public engagement and compliance (Moeini et al., 2023). This highlights the need for governments to strategically allocate resources not only to infrastructure but also to awareness campaigns, ensuring broader participation (Nepal et al., 2023). In this context, the present study aims to explore how such government spending patterns may interact with other fiscal and macroeconomic factors to shape recycling outcomes across European countries.

The level of economic development, measured by real GDP *per capita*, is also a well-established structural determinant of recycling capacity, as higher levels of economic development are typically linked to increased environmental awareness, better waste management systems, and higher investments in sustainable infrastructure (Blagoeva et al., 2023). Empirical studies consistently confirm this relationship. Gabor et al. (2023) reported a strong positive association between GDP *per capita* and recycling performance in the EU, a finding echoed by Georgescu et al. (2022) across 25 European countries and by Holmen et al. (2025) in their analysis of 27 countries from 2000 to 2019. This points to economic wealth as a key factor in recycling and circular performance (Kostakis and Tsagarakis, 2022). Evidence beyond Europe aligns with this pattern, as economic affluence has also been linked to stronger engagement in recycling and sustainable consumption (Li et al., 2025). This supports the view that economic prosperity facilitates the adoption of advanced waste management technologies and broader public participation, although the relationship is complex since higher incomes are also associated with increased waste generation. Such dynamics highlight the need for comprehensive waste management strategies that extend beyond economic growth alone (Tisserant et al., 2017). Accordingly, the present study includes GDP *per capita* as one of the explanatory variables to examine its association with municipal waste recycling performance across European countries.

Although private investment in the circular economy has received relatively less attention as a stand-alone variable, available evidence suggests its essential role. Its importance is growing as governments and international bodies increasingly rely on private capital to accelerate the transition from linear to circular models, helping to bridge the high upfront costs often associated with this shift (Dumée, 2021; Marek and Krejza, 2024; Georgescu et al., 2025). Although further empirical research is needed, theoretical frameworks suggest a robust positive correlation between private investment and recycling performance (Georgescu et al., 2025), as increased private sector engagement can lead to higher recycling rates through improved infrastructure and market development (Dinda, 2020). Empirical evidence supports this expectation, with Schlosser et al. (2021) showing that private investments in recycling infrastructure can raise recycling rates by fostering more efficient product designs and closed-loop systems. Similarly, Hysa et al. (2020) found that private funding in circular initiatives was linked to higher recycling rates and stronger economic growth. A recent EU-wide panel study also confirmed a significant positive correlation between private investment and recycling rates (Georgescu et al., 2025). Private sector involvement often brings efficiencies, economies of scale, and access to cutting-edge technologies that can strengthen recycling infrastructure and operations (Zanoletti et al., 2021). Nevertheless, the mechanisms and conditions under which private investment most effectively promotes circularity and recycling remain insufficiently understood and call for further academic scrutiny (Dinda, 2020). In light of these considerations, this study incorporates private investment in the circular economy as a key explanatory variable to advance understanding of its potential contribution to municipal waste recycling outcomes across Europe.

Urban population size, as a demographic factor, has also been shown to influence recycling system performance, although its effect appears to be context-dependent. Studies indicate that while urbanization and population growth contribute to higher waste generation, effective community participation in waste management, including recycling, can mitigate these effects (Santoso and Farizal, 2019). This perspective is further supported by observations that public participation is critical for the success of waste recovery activities, highlighting the dual challenge of motivating participation while sustaining involvement (Oh and Hettiarachchi, 2020). In the European context, Osinska (2024) found that population density significantly affected municipal waste management efficiency, while Huang et al. (2020) reported population growth as a key driver of rising recycling volumes in China. Additional evidence points to the complexity of demographic dynamics. Kostakis and Tsagarakis (2022) added further nuance by showing that recycling and circularity rates in the EU were positively affected by fertility rate, possibly reflecting greater engagement among younger families, and that urbanization exhibited a nonlinear positive effect. These findings indicate that while larger populations generate more waste, they also provide a larger pool of participants for recycling programs if effectively mobilized through supportive policies and accessible infrastructure (Pratarelli, 2010; Thomas and Sharp, 2013). This underscores the importance of community participation in waste management, as active individual involvement is crucial for addressing waste management challenges (Brotosusilo and Nabila, 2020). Altogether, these considerations support the inclusion of population-related variables in the present study's

analytical framework, to better capture their potential role in shaping recycling performance across European countries.

Expenditures on research and development, particularly those classified under the government budget allocations for R&D (GBARD) directed towards environmental objectives, represent an important pillar in fostering recycling efforts. Such investments support the development of advanced recycling technologies, optimize material recovery processes, and create new markets for recycled products, thereby enhancing overall circularity (Murakami et al., 2014). Sustained investment in R&D infrastructure is crucial for overcoming current limitations in waste management, such as outdated machinery and facilities, which hinder effective waste collection and treatment (Markina et al., 2024). These challenges are further compounded by the prevalence of informal recycling sectors, which, despite their significant contribution to material recovery, often operate without formal recognition or integration into national waste management strategies (Wilson et al., 2005). In fact, public R&D investment is widely recognized as a driver of green innovation (Guo et al., 2018; Shi and Zhou, 2024), improving waste sorting, treatment, and reuse while also making infrastructure more efficient and accessible (Corrado et al., 2022; Daoud et al., 2025). A wide range of empirical studies reported positive relationships between R&D expenditures and recycling performance, sometimes extending to broader economic outcomes (Osinska, 2024; Tantau et al., 2018; Georgescu et al., 2022). This positive link was confirmed as well in analyses focusing on EU countries (Georgescu et al., 2025; López-Portillo et al., 2021). In addition, Kostakis and Tsagarakis (2022) further identified R&D spending as a statistically significant predictor of both recycling and circularity rates. Altogether, these insights justify the consideration of GBARD directed at environmental objectives as an explanatory variable in this study, to better capture their relevance for municipal recycling performance in the EU.

These six explanatory variables were embedded in a conceptual framework linking recycling performance to fiscal, institutional, economic, and demographic domains. Economic variables (GDP *per capita* and private investment in the circular economy) capture the financial and technological resources that enable advanced waste management. Institutional factors (government environmental protection expenditures and GBARD directed at environmental objectives) reflect public commitment to infrastructure and innovation. Fiscal instruments, represented by environmental taxes, are grounded in Pigouvian theory, which emphasizes the role of pricing mechanisms in internalizing environmental externalities. Demographic conditions, measured through urban population size, highlight the societal dimension, where population concentration generates higher waste volumes but also enlarges the pool of potential participants in recycling programs. Together, these domains provide a multidimensional lens for analyzing the macro-level conditions that shape municipal waste recycling across European countries.

# 3 Methodology

## 3.1 Aim and hypotheses

The aim of this study was to examine the macro-level determinants of municipal waste recycling in EU countries over the period 2005–2023, and to identify country groupings based on shared characteristics.

Based on the insights presented in the Literature Review, the following hypotheses were formulated to guide the empirical analysis:

- H1a: Higher environmental tax revenues (million €) are positively associated with municipal waste recycling performance across EU countries.
- H1b: Higher environmental tax revenues (% GDP) are positively associated with municipal waste recycling performance across EU countries.
- H2a: Greater government budget allocations for R&D directed at environmental objectives (% GDP) are positively associated with municipal waste recycling performance.
- H2b: Greater government budget allocations for R&D directed at environmental objectives (% GBARD) are positively associated with municipal waste recycling performance.
- H2c: Greater government budget allocations for R&D directed at environmental objectives (€ *per capita*) are positively associated with municipal waste recycling performance.
- H3a: Greater government expenditures on environmental protection (% GDP) are positively associated with municipal waste recycling performance.
- H3b: Greater government expenditures on environmental protection (million €) are positively associated with municipal waste recycling performance.
- H4a: Increased private investment in circular economy sectors (% GDP) is positively associated with municipal waste recycling performance.
- H4b: Increased private investment in circular economy sectors (million €) is positively associated with municipal waste recycling performance.
- H5: A larger urban population (inhabitant) is positively associated with municipal waste recycling performance.
- H6: Higher real GDP *per capita* (€ *per capita*) is positively associated with municipal waste recycling performance.

## 3.2 Data structure and sources

The study was based on a panel dataset comprising 12 indicators retrieved from publicly accessible Eurostat and World Bank databases. While the raw datasets contained a total of 11,606 observations across all available years and countries, the scope of the empirical analysis was restricted to EU member states and the period 2005–2023. This resulted in 5,880 usable observations, with each of the 12 indicators contributing 490 annual data points. All variables were measured on an annual basis, consistent with the reporting frequency of Eurostat and World Bank databases (Table 1).

Several variables were analyzed in multiple units to capture both absolute and relative dimensions, which provides a more nuanced understanding of their association with recycling performance. Different operationalizations often reveal complementary aspects of the same phenomenon, reducing the risk that important relationships remain hidden due to a single choice of measurement. This approach therefore enhances the robustness

TABLE 1 Data structure.

| Indicator | Unit | Justification | Database | References |
|---|---|---|---|---|
| Recycling rate of municipal waste | % | Key policy target of the EU's circular economy strategy and a widely recognized indicator of progress in sustainable waste management | Eurostat (2025f) | EEA (2024) |
| Environmental tax revenues | million € | Widely used fiscal instrument designed to internalize environmental externalities and incentivize sustainable behavior. Considered an important driver of circular economy transitions in EU policy frameworks | Eurostat (2025c) | Gabor et al. (2023), Kostakis and Tsagarakis (2022), Imran et al. (2024) |
| | % GDP | | | |
| GBARD directed at environmental objectives | % GDP | Indicator of public commitment to environmental research and innovation, supporting technological advances in waste management and long-term improvements in recycling performance | Eurostat (2025a) | Osinska (2024), Tantau et al. (2018), Georgescu et al. (2025), López-Portillo et al. (2021) |
| | % GBARD | | | |
| | € *per capita* | | | |
| Government expenditures on environmental protection | % GDP | Expression of governmental prioritization of sustainability through budget allocations, encompassing support for environmental initiatives such as waste management systems and recycling infrastructure | Eurostat (2025b) | Li et al. (2025), Gabor et al. (2023), Jarczok-Guzy et al. (2024) |
| | million € | | | |
| Private investment in circular economy sectors | % GDP | Source of financial resources that bridges funding gaps in circular transitions, fostering recycling infrastructure, market development, and technological innovation | Eurostat (2025d) | Georgescu et al. (2025), Hysa et al. (2020), Schlosser et al. (2021) |
| | million € | | | |
| Urban population size | inhabitant | Demographic factor shaping waste generation and management needs, with potential to influence recycling performance through population density, participation, and infrastructure demand | World Bank (2025) | Osinska (2024), Kostakis and Tsagarakis, (2022) |
| Real GDP | € *per capita* | Indicator of economic development linked to institutional capacity, infrastructure investment, and societal awareness, often associated with higher recycling performance | Eurostat (2025e) | Gabor et al. (2023), Georgescu et al. (2022), Holmen et al. (2025) |

of the findings and ensures that they remain informative for countries with diverse economic structures and policy priorities.

The dataset included economic, fiscal, institutional, and demographic indicators, providing a comprehensive basis for examining the determinants of recycling performance. All variables were carefully harmonized across countries and over time to ensure full comparability of measurement units and consistency of definitions. Missing data were addressed by excluding the entire year for that country from the dataset whenever information for any indicator was unavailable in that country. This approach ensured that the final dataset used in the analysis was a fully balanced panel without missing observations. Outlier detection during preliminary data screening did not reveal any extreme distortions that could compromise the robustness of the results. Likewise, no pronounced heteroskedasticity or influential outliers were identified, and the correlation matrix of parameter estimates provided no substantial evidence of multicollinearity.

## 3.3 Analytical framework

The methodological approach consisted of three main steps: exploratory analysis, trend evaluation using simple linear regression, and multiple linear regression. In addition, hierarchical cluster analysis was applied to identify convergence patterns among countries.

1. Descriptive analysis and distribution–In the initial phase, a descriptive and distributional analysis was conducted using boxplots, histograms, and density plots. These visualizations revealed substantial heterogeneity in recycling rates across countries and over time, providing an initial framework for subsequent analytical procedures.
2. Trend analysis–In order to capture temporal dynamics, a simple linear regression was applied, with the calendar year as the independent variable and the recycling rate as the dependent variable. The model indicated a positive and statistically significant trend ($\beta = 1.112$; $p < 0.0001$). However, the coefficient of determination reached only $R^2 = 0.120$, which underscored the need to extend the model by incorporating additional explanatory variables.
3. Multiple linear regression–The core of the analytical procedure involved multiple linear regression (MLR), which was used to examine the simultaneous associations between the recycling rate (dependent variable) and a set of macro-level factors (independent variables): environmental tax revenues (million €), environmental tax revenues (% GDP), GBARD directed at environmental objectives (% GDP), GBARD directed at environmental objectives (% GBARD), GBARD directed at environmental objectives (€ *per capita*), government expenditures on environmental protection (% GDP), government expenditures on environmental protection (million €), private investment in circular economy sectors (% GDP), private investment in circular economy sectors (million €), urban population (inhabitant), real GDP (€ *per capita*).

The initial model was refined using backward elimination, whereby statistically non-significant variables were systematically

removed. The final specification retained only variables that were statistically significant at the α = 0.05 level. The optimized model achieved an $R^2$ of 0.5745, indicating a relatively high proportion of explained variability.

The verification of regression assumptions (model diagnostics) included the following procedures:

- assessment of normality and homoscedasticity of residuals using residual plots;
- evaluation of multicollinearity through the correlation matrix and variance inflation factors (VIF), with no extreme values detected;
- identification of influential observations based on Cook's distance and Bonferroni-adjusted thresholds.

Despite the high negative correlation between urban population size and environmental tax revenues (r = −0.931), both variables were retained in the final model because they capture distinct domains—demographic structure and fiscal policy—making them theoretically relevant and empirically valuable for assessing recycling performance.

4. Cluster Analysis–To group countries by structural characteristics, Ward's hierarchical clustering method was applied to column-standardized values (z-scores) of five-year averages for the period 2019–2023 (Kaufman and Rousseeuw, 2009; Everitt et al., 2011). Ward's method minimizes the within-cluster sum of squares and is defined over the Euclidean distance metric, which was explicitly used in this study (Rokach and Maimon, 2005). The clustering input included the explanatory variables that proved statistically significant in the regression analysis, namely real GDP (€ *per capita*), urban population size (inhabitants), environmental tax revenues (million €), private investment in circular economy sectors (% GDP), government expenditures on environmental protection (% GDP), and government budget allocations for R&D (GBARD) directed at environmental objectives (% GDP). Recycling rate (%) was used only for profiling the resulting clusters, not for computing distances.

The selection of the period 2019–2023 was motivated by three considerations: first, to reduce short-term volatility, including distortions linked to the COVID-19 pandemic; second, to capture the most recent structural conditions shaped by the implementation of major EU circular economy policies; and third, to enhance robustness by smoothing out annual shocks. This five-year averaging approach is consistent with established practices in comparative country profiling (Everitt et al., 2011).

Cluster validation was performed using cophenetic correlation and silhouette scores across alternative values of k, with k = 5 yielding the highest average silhouette and therefore retained. Silhouette scores were calculated as an internal validation measure to assess cluster coherence and separation (Rousseeuw, 1987). Additional robustness checks with Manhattan distance and average linkage confirmed the stability of the core cluster structure. The resulting clusters exhibited distinct profiles in terms of recycling performance, economic development, and institutional capacity, offering a framework for differentiated policy support and knowledge transfer across EU member states.

# 4 Results

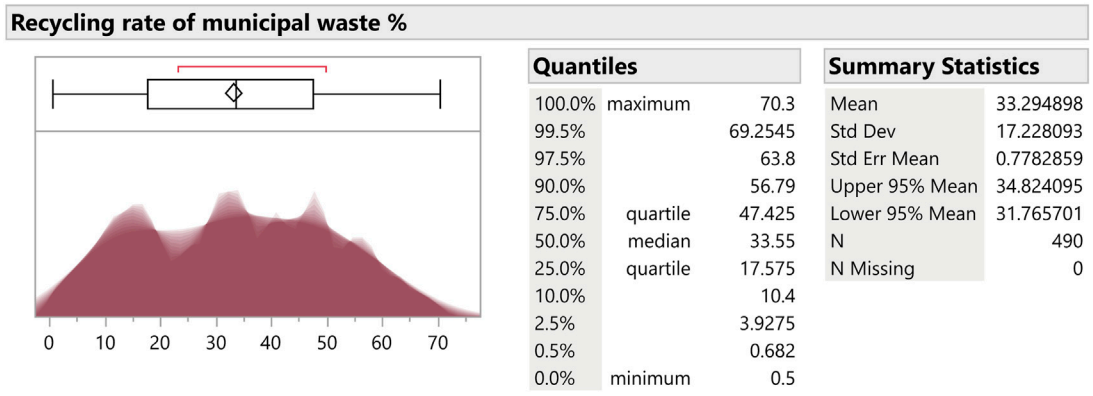
## 4.1 Country-level analysis of recycling rates

The analysis of recycling rates in European countries for the period 2005 to 2023, covering 490 observations derived from annual data for 27 EU member states, revealed substantial variation in recycling levels across countries (Figure 1). The average recycling rate was 33.29%, accompanied by a relatively high standard deviation of 17.23%. The median value (33.55%) was very close to the mean, indicating an approximately symmetrical distribution. However, the density plot also suggested a slightly multimodal distribution, with pronounced concentrations in the 20%–30% and 40%–50% intervals. This pattern may reflect the presence of two dominant groups of countries—those with lower and those with higher levels of recycling system development.

The minimum observed recycling rate was 0.5%, reflecting extremely low levels of recycling in certain cases, most likely corresponding to the early years of the observed period or to less developed countries. In contrast, the maximum value of 70.3% indicated that some countries had already achieved highly advanced levels of recycling, aligning closely with the European Union's circular economy objectives. The 95% confidence interval for the mean ranged from 31.77% to 34.82%, further supporting the reliability of the average estimate.

To assess the trend in municipal waste recycling rates across European countries, a simple linear regression was applied, with calendar year (TIME_PERIOD) as the independent variable and the recycling rate, expressed as a percentage, as the dependent variable (Figure 2). The results of the regression model indicated a positive and statistically significant trend ($p < 0.0001$), with the slope of the regression line estimated at 1.112. This suggests that, on average, recycling rates increased by approximately 1.11 percentage points per year over the period 2005 to 2023.

Although the positive trend indicated progress in recycling, the coefficient of determination ($R^2 = 0.120$) suggested that only approximately 12% of the variation in recycling rates could be attributed to the time variable. This indicates that recycling progress cannot be understood through time alone but must be viewed in the context of institutional capacity, the pace of infrastructure development, and the allocation of resources to waste management. Improvements in infrastructure or policy often involve delays, with their effects becoming visible only gradually in recycling outcomes. In other words, such factors often require time before becoming visible in recycling performance. This pointed to the presence of additional influential determinants—such as legislation, private investment in the circular economy, environmental expenditures, or GDP—that warranted further investigation through more comprehensive modelling. In 2023, the regression line reached approximately 42%, indicating that, if the current trajectory were to continue, the EU target of 55% by 2025 would likely remain out of reach in the absence of additional policy interventions. The dispersion of data points around the regression line also revealed




**Quantiles**

| | | |
|---|---|---|
| 100.0% | maximum | 70.3 |
| 99.5% | | 69.2545 |
| 97.5% | | 63.8 |
| 90.0% | | 56.79 |
| 75.0% | quartile | 47.425 |
| 50.0% | median | 33.55 |
| 25.0% | quartile | 17.575 |
| 10.0% | | 10.4 |
| 2.5% | | 3.9275 |
| 0.5% | | 0.682 |
| 0.0% | minimum | 0.5 |

**Summary Statistics**

| | |
|---|---|
| Mean | 33.294898 |
| Std Dev | 17.228093 |
| Std Err Mean | 0.7782859 |
| Upper 95% Mean | 34.824095 |
| Lower 95% Mean | 31.765701 |
| N | 490 |
| N Missing | 0 |

FIGURE 1
Descriptive analysis and distribution of municipal waste recycling rates in the EU (2005–2023).

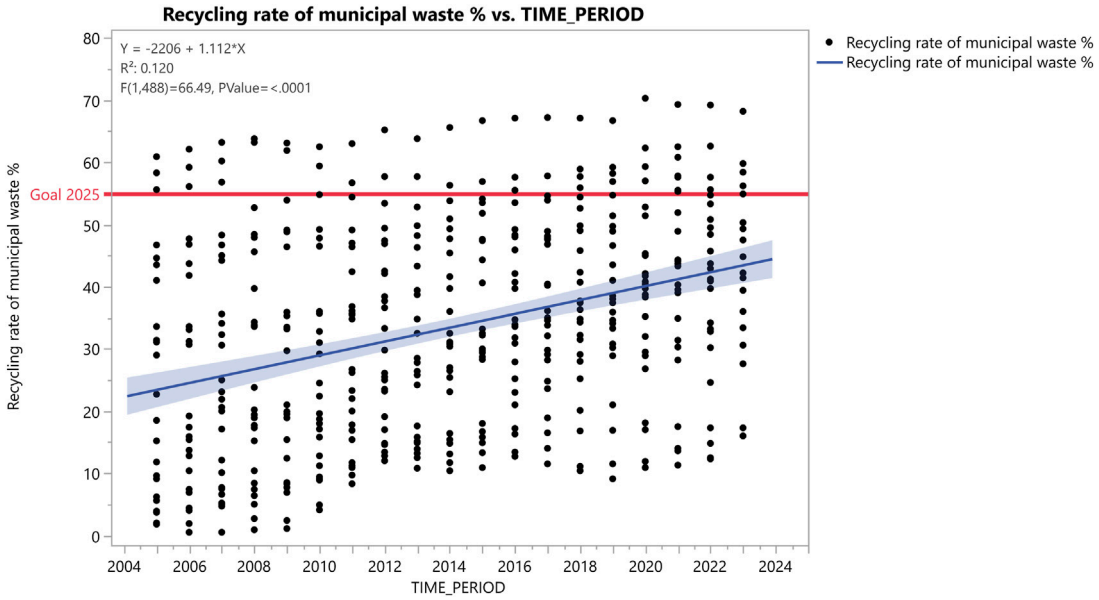



FIGURE 2
Trend in municipal waste recycling rates in the EU (2005–2023).

substantial heterogeneity across countries and over time, while some countries consistently achieved rates above 60%, others remained persistently below 30%. This observation reinforced the need for differentiated policy approaches tailored to the specific challenges and capacities of individual member states in advancing circular economy objectives.

While the analysis confirmed a statistically significant upward trend in recycling rates, the overall pace of progress appeared insufficient to meet the EU's 2025 target (EEA, 2024). This highlights that progress relies on broader structural and institutional factors beyond time, and further emphasizes the importance of targeted policy efforts, particularly in countries with below-average performance.

The inclusion of a country-level perspective allowed for the identification of notable disparities in the implementation of waste management policies across EU member states. Figure 3 illustrates considerable variation among countries, both in terms of achieved recycling rates and the dynamics of their development over the period 2005 to 2023.

Countries such as Austria, Belgium, Germany, and the Netherlands have consistently recorded above-average recycling rates, exceeding the EU's 2025 target (55%) from the outset of the observed period (EEA, 2024). Slovenia joined this group in the middle of the timeframe. In these countries, recycling performance appears to have stabilized at high levels, likely reflecting the presence of well-functioning waste separation systems, stringent environmental legislation, and strong public engagement.

In contrast, countries such as Romania, Bulgaria, Malta, Cyprus, Croatia, and Greece reported persistently low recycling rates across the entire observed period. Despite gradual improvements, their current performance remained substantially below the EU's 2025 target

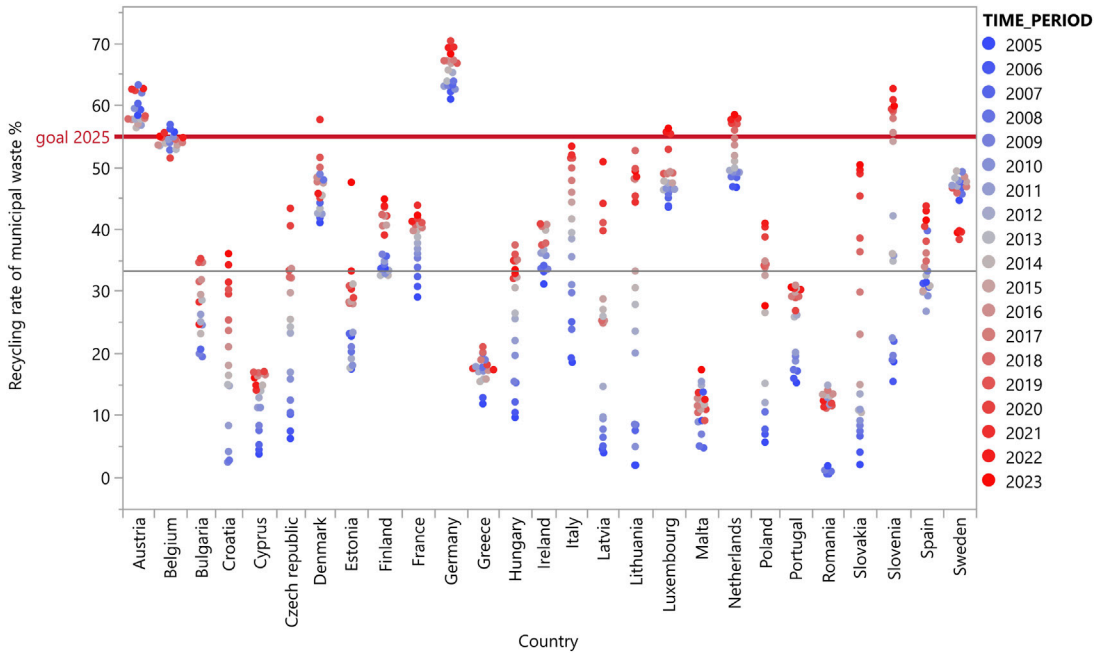



FIGURE 3
Cross-country comparison of municipal waste recycling rates in EU member states (2005–2023).

(EEA, 2024) patterns may reflect the continued presence of structural limitations, including insufficient infrastructure, constrained investment capacity, and lower levels of environmental awareness.

Countries such as Poland, the Czech Republic, Slovakia, and Portugal demonstrated notable progress in recycling rates between 2005 and 2023. Nevertheless, their performance remained below the EU's 2025 target (EEA, 2024). These trends indicate that while recent developments have moved in the right direction, further acceleration may be needed to keep pace with policy expectations.

Overall, the findings revealed substantial cross-country disparities in both the level and trajectory of recycling rates, with only a small group of countries having reached the EU's 2025 target of 55% by the end of the observed period (EEA, 2024). These results highlighted the importance of further examining the economic, structural, fiscal, and institutional factors that may be associated with national recycling performance. Accordingly, the next stage of the analysis explored how variables such as environmental expenditures, tax revenues, urbanization levels, and private investment in the circular economy were statistically associated with recycling rates across EU member states, using multiple linear regression.

## 4.2 Multiple linear regression

Multiple linear regression was employed to assess the statistical associations between the dependent variable (Y) and a set of independent variables (X) considered simultaneously. This method has been widely applied in predictive modelling, as it allows for the estimation of the dependent variable (Y) based on its statistical associations with multiple explanatory variables (Xs). Within this framework, the parameters β represent unknown coefficients to be estimated, while ε refers to the random disturbance term linked to each observation:

$$Y = \beta_0 + \beta_1 X_1 + \cdots + \beta_k X_k + \varepsilon$$

Beyond its predictive applications, multiple linear regression has also proven suitable for explanatory analysis, particularly in identifying co-occurrence patterns between outcome and explanatory variables.

In this study, the municipal waste recycling rate (%) was considered as the dependent variable (Y). The set of independent variables included: environmental tax revenues (million €), environmental tax revenues (% GDP), GBARD directed at environmental objectives (% GDP), GBARD directed at environmental objectives (% GBARD), GBARD directed at environmental objectives (€ *per capita*), government expenditures on environmental protection (% GDP), government expenditures on environmental protection (million €), private investment in circular economy sectors (% GDP), private investment in circular economy sectors (million €), urban population (inhabitant), real GDP (€ *per capita*).

### 4.2.1 Results prior to the optimization of independent variables

The analysis of eleven independent variables in relation to the dependent variable revealed several statistically strong associations. Among EU countries, the municipal waste recycling rate showed the closest links with environmental tax revenues, private investment in the circular economy, real GDP *per capita*, government expenditure on environmental protection (as a percentage of GDP), urban population, and GBARD directed at environmental objectives (% GBARD and % GDP).

**Effect Summary**

| Source | Logworth | PValue |
|---|---|---|
| Environmental tax revenues (million €) | 8.278 | 0.00000 |
| Private investment in circular economy sectors (% GDP) | 7.350 | 0.00000 |
| Real GDP (€ per capita) | 6.823 | 0.00000 |
| Government expenditures on environmental protection (% GDP) | 5.433 | 0.00000 |
| Urban population (inhabitant) | 5.056 | 0.00001 |
| GBARD directed at environmental objectives (% GBARD) | 2.144 | 0.00718 |
| GBARD directed at environmental objectives (% GDP) | 1.480 | 0.03315 |
| Government expenditures on environmental protection (million €) | 1.135 | 0.07326 |
| GBARD directed at environmental objectives (€ per capita) | 0.413 | 0.38620 |
| Private investment in circular economy sectors (million €) | 0.149 | 0.70967 |
| Environmental tax revenues (% GDP) | 0.132 | 0.73827 |

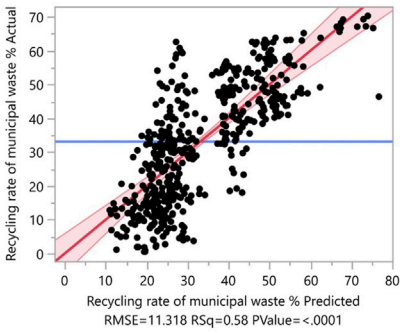



FIGURE 4
Pre-optimization regression model.

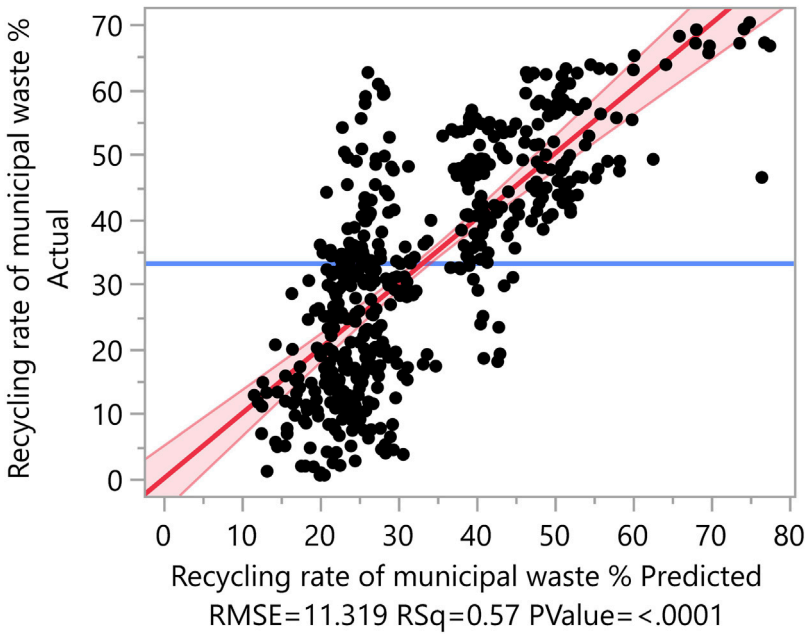



FIGURE 5
Explanatory power and statistical significance of the model after optimization.

Independent variables that were not statistically significant (highlighted with red borders) were sequentially removed from the model. The model specification was repeatedly adjusted until only statistically significant explanatory variables remained. These variables were ordered according to their statistical significance. Figure 4 presents the initial set of independent variables along with the model's explanatory power and statistical significance before optimization.

### 4.2.2 Results after the optimization of independent variables

The purpose of the regression analysis was to identify factors statistically associated with municipal waste recycling rates across European countries. The dependent variable was defined as the municipal waste recycling rate, expressed as a percentage, while the independent variables represented economic, fiscal, demographic, and institutional indicators. The model was specified as a multiple linear regression including seven explanatory variables (Figure 5).

Based on Figure 5, the coefficient of determination ($R^2$) for the regression model was 0.5745, indicating that the selected independent variables collectively captured approximately 57% of the variation in municipal waste recycling. The overall model was found to be highly statistically significant ($F(7, 482) = 92.97$; $p < 0.0001$). The mean value of the dependent variable was 33.29%, while the root mean square error (RMSE) amounted to 11.32 percentage points.

All independent variables included in the final specification of the model were statistically significant at the $\alpha = 0.05$ level (Figure 6). The results of the parameter estimates and effect tests revealed the following patterns of association with the municipal waste recycling rate.

**Effect Summary**

| Source | Logworth | PValue |
|---|---|---|
| Real GDP (€ per capita) | 19.136 | 0.00000 |
| Environmental tax revenues (million €) | 16.253 | 0.00000 |
| Private investment in circular economy sectors (% GDP) | 9.540 | 0.00000 |
| Urban population (inhabitant) | 5.863 | 0.00000 |
| Government expenditures on environmental protection (% GDP) | 5.092 | 0.00001 |
| GBARD directed at environmental objectives (% GDP) | 4.176 | 0.00007 |
| GBARD directed at environmental objectives (% GBARD) | 2.680 | 0.00209 |

**Parameter Estimates**

| Term | Estimate | Std Error | t Ratio | Prob>\|t\| ^ | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| Intercept | 20.532461 | 2.127351 | 9.65 | <.0001* | 16.352434 | 24.712488 |
| Real GDP (€ per capita) | 0.0002863 | 0.00003 | 9.54 | <.0001* | 0.0002273 | 0.0003453 |
| Environmental tax revenues (million €) | 0.0007169 | 8.248e-5 | 8.69 | <.0001* | 0.0005549 | 0.000879 |
| Private investment in circular economy sectors (% GDP) | 9.3946569 | 1.45868 | 6.44 | <.0001* | 6.5284987 | 12.260815 |
| Urban population (inhabitant) | -3.305e-7 | 6.757e-8 | -4.89 | <.0001* | -4.632e-7 | -1.977e-7 |
| Government expenditures on environmental protection (% GDP) | -7.385078 | 1.636815 | -4.51 | <.0001* | -10.60125 | -4.168903 |
| GBARD directed at environmental objectives (% GDP) | 305.40389 | 75.91311 | 4.02 | <.0001* | 156.24238 | 454.5654 |
| GBARD directed at environmental objectives (% GBARD) | -1.260114 | 0.407239 | -3.09 | 0.0021* | -2.060297 | -0.45993 |

**Effect Tests**

| Source | Nparm | DF | Sum of Squares | F Ratio | Prob > F |
|---|---|---|---|---|---|
| Real GDP (€ per capita) | 1 | 1 | 11652.018 | 90.9446 | <.0001* |
| Urban population (inhabitant) | 1 | 1 | 3064.845 | 23.9213 | <.0001* |
| Private investment in circular economy sectors (% GDP) | 1 | 1 | 5314.540 | 41.4803 | <.0001* |
| Government expenditures on environmental protection (% GDP) | 1 | 1 | 2608.166 | 20.3569 | <.0001* |
| GBARD directed at environmental objectives (% GBARD) | 1 | 1 | 1226.718 | 9.5746 | 0.0021* |
| GBARD directed at environmental objectives (% GDP) | 1 | 1 | 2073.670 | 16.1851 | <.0001* |
| Environmental tax revenues (million €) | 1 | 1 | 9680.580 | 75.5574 | <.0001* |

FIGURE 6
Statistically significant independent variables associated with the recycling rate.

Real GDP *per capita* (€/inhabitant) was positively associated with the municipal waste recycling rate ($\beta = 0.000286$; $p < 0.0001$), indicating that countries with higher levels of economic development tended to report higher recycling performance, possibly due to more established infrastructure and greater consumer awareness. Environmental tax revenues (in million €) also exhibited a positive statistical association with the municipal waste recycling rate ($\beta = 0.000717$; $p < 0.0001$), underscoring the relevance of fiscal instruments in environmental policy frameworks. Private investment in circular economy sectors, expressed as a percentage of GDP, demonstrated a strong and statistically significant positive relationship ($\beta = 9.395$; $p < 0.0001$), highlighting the role of private-sector engagement in the development of circular economy practices. In contrast, urban population size showed a statistically significant negative association ($\beta = -3.305 \times 10^{-7}$; $p < 0.0001$), which may reflect structural challenges inherent to waste collection and management systems in more densely populated or urbanized regions. Government expenditure on environmental protection (as a share of GDP) was negatively associated with the municipal waste recycling rate ($\beta = -7.385$; $p < 0.0001$), potentially reflecting inefficiencies in the allocation or implementation of public environmental funding. Conversely, government budget allocations for R&D (GBARD) directed at environmental objectives (as a percentage of GDP) were positively associated with the municipal waste recycling rate ($\beta = 305.40$; $p < 0.0001$), suggesting that a higher prioritization of environmental objectives within national R&D budgets corresponded with improved recycling performance. Finally, GBARD directed at environmental objectives expressed as a share of total GBARD showed a statistically significant negative relationship ($\beta = -1.260$; $p = 0.0021$), which may be attributable to time lags between research investments and their observable effects on waste management performance.

The graphical analysis of residuals (Residual by Predicted Plot and Studentized Residuals) provided no indication that the model violated the fundamental assumptions of linear regression (Figure 7). The residuals appeared to be approximately symmetrically distributed around the zero axis, with no observations substantially exceeding the Bonferroni-adjusted boundaries for the 95% simultaneous confidence intervals. There was no evidence of pronounced heteroskedasticity or influential outliers. The correlation matrix of parameter estimates did not reveal any substantial evidence of multicollinearity. The strongest correlation was observed between urban population size and environmental tax revenues ($r = -0.931$). Despite this strong correlation, both variables were retained in the final model specification because they capture conceptually distinct domains—demographic structure in the case of urban population and fiscal policy in the case of environmental taxes. Their theoretical relevance and empirical contribution were considered essential for a balanced assessment of demographic and fiscal drivers of recycling performance.

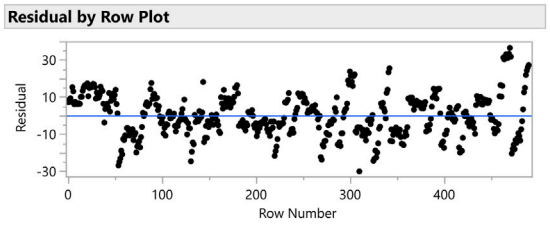



FIGURE 7
Graphical analysis of residuals.

The results of the analysis indicated that economic indicators—specifically real GDP *per capita*, environmental tax revenues, and private investment in the circular economy—were positively and statistically significantly associated with municipal waste recycling rates. In contrast, increases in urban population size and certain forms of public expenditure—notably government budget allocations for environmental research (GBARD) and general government expenditures on environmental protection—were associated with lower levels of recycling performance, which may reflect delays in the translation of policy investment into operational impact or the presence of inefficiencies in expenditure execution.

The model as a whole provides a reliable basis for formulating environmental policy aimed at increasing municipal waste recycling rates through a combination of financial incentives, private sector support and strategic government expenditures.

### 4.2.3 Hypothesis evaluation

The evaluation of the proposed hypotheses was based on the final regression model, which retained only statistically significant explanatory variables. Each hypothesis was assessed according to its estimated association with the municipal waste recycling rate across EU countries for the period 2005–2023.

H1a predicted a positive association between environmental tax revenues (million €) and municipal waste recycling. This hypothesis was supported, as the variable exhibited a positive and statistically significant relationship ($\beta = 0.000717$; $p < 0.0001$).

H1b assumed a positive association between environmental tax revenues (% GDP) and recycling performance. This hypothesis was not supported, as this operationalization did not remain in the final specification of the model due to lack of statistical significance.

H2a hypothesized that higher government budget allocations for R&D directed at environmental objectives (% GDP) would be positively associated with recycling performance. This hypothesis was supported, showing a strong positive relationship ($\beta = 305.40$; $p < 0.0001$).

H2b expected a positive association for GBARD directed at environmental objectives measured as a share of total GBARD. Contrary to expectations, this hypothesis was rejected, as the results indicated a statistically significant negative association ($\beta = -1.260$; $p = 0.0021$).

H2c predicted a positive association between GBARD *per capita* and recycling performance. This hypothesis was not supported, as the variable was removed from the model during specification due to lack of significance.

H3a assumed a positive association between government expenditure on environmental protection (% GDP) and recycling performance. This hypothesis was rejected, since the results showed a statistically significant negative relationship ($\beta = -7.385$; $p < 0.0001$).

H3b predicted a positive association for government expenditure on environmental protection measured in absolute terms (million €). This hypothesis was not supported, as the variable was excluded from the final specification due to insignificance.

H4a hypothesized a positive association between private investment in circular economy sectors (% GDP) and recycling performance. This hypothesis was supported, as the results confirmed a strong and significant positive relationship ($\beta = 9.395$; $p < 0.0001$).

H4b assumed a positive association between private investment in circular economy sectors measured in absolute terms (million €) and recycling performance. This hypothesis was not supported, as it was not retained in the final model.

H5 predicted that a larger urban population would be positively associated with recycling performance. This hypothesis was rejected, as the results showed a statistically significant negative association ($\beta = -3.305 \times 10^{-7}$; $p < 0.0001$).

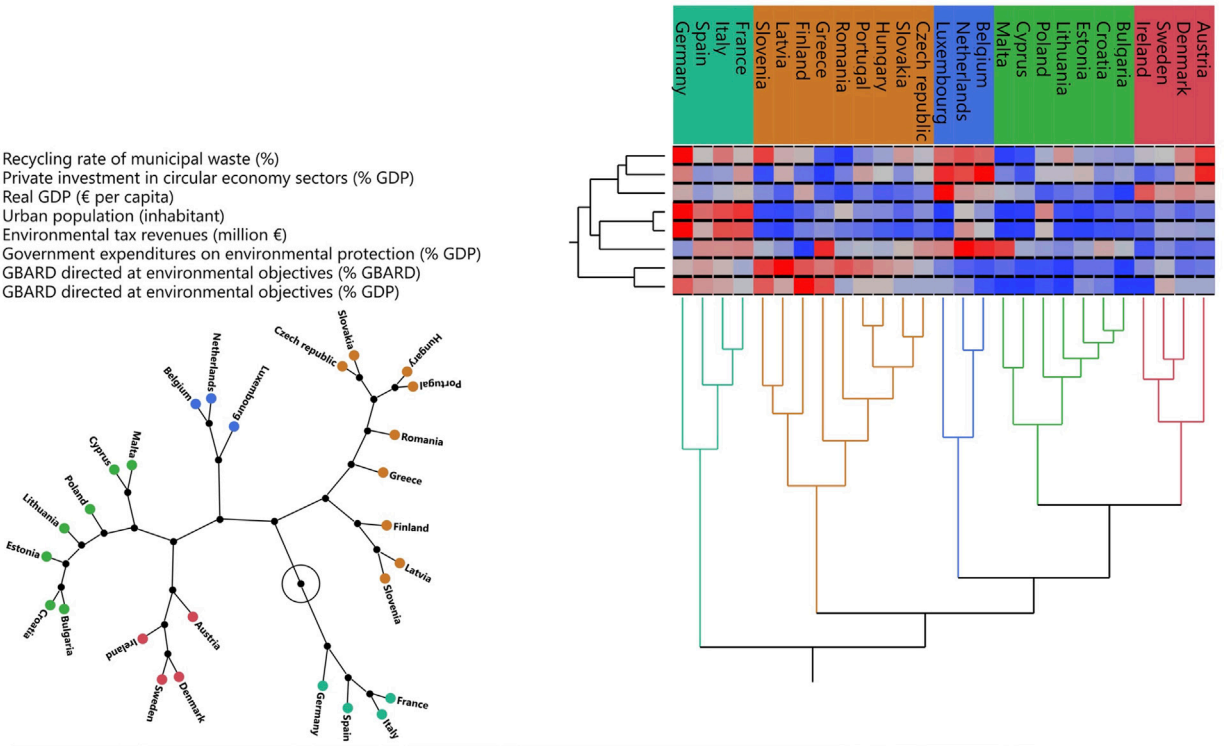
H6 hypothesized a positive association between real GDP *per capita* and recycling performance. This hypothesis was supported, as the variable was positively and significantly associated with the recycling rate ($\beta = 0.000286$; $p < 0.0001$).

Overall, the evaluation of hypotheses indicated that fiscal, economic, and R&D-related factors were consistently associated with municipal waste recycling performance, with environmental tax revenues, private investment, GDP *per capita*, and GBARD (% GDP) showing significant positive relationships. By contrast, demographic factors such as urban population size and institutional measures of government expenditure on environmental protection revealed negative or insignificant associations, suggesting structural or efficiency-related challenges in these domains. The mixed results for different operationalizations of variables, particularly in the case of GBARD and government expenditures, highlight the importance of measurement choices and point to the complex ways in which macro-level conditions shape recycling outcomes across the EU.

## 4.3 Cluster analysis

As a supplementary analytical method to the regression analysis, Ward's hierarchical cluster analysis was applied to identify relatively homogeneous groups of EU countries based on shared characteristics in selected socioeconomic and environmental indicators (Figure 8). The clustering approach served to examine the extent to which countries exhibited similar profiles in variables that had previously demonstrated statistically significant associations with municipal waste recycling rates. The analysis was conducted using average values calculated over the final 5 years of the observed period (2019–2023).

The results in Figure 8 indicated that the countries could be grouped into five distinct clusters, each characterized by varying average levels of recycling performance, and other selected indicators.




| Recycling rate of municipal waste (%) | Private investment in circular economy sectors (% GDP) | Real GDP (€ per capita) | Urban population (inhabitant) | Environmental tax revenues (million €) | Government expenditures on environmental protection (% GDP) | GBARD directed at environmental objectives (% GBARD) | GBARD directed at environmental objectives (% GDP) |
|---|---|---|---|---|---|---|---|
| 11.75 | 0.200 | 10027.5 | 517234.6 | 304 | 0.200 | 0.335 | 0.0000 |
| 17.52 | 0.297 | 14559.981 | 3721511.4 | 2820 | 0.313 | 0.743 | 0.0025 |
| 23.28 | 0.393 | 19092.463 | 6925788.3 | 5335 | 0.426 | 1.152 | 0.0049 |
| 29.05 | 0.490 | 23624.944 | 10130065 | 7850 | 0.539 | 1.560 | 0.0074 |
| 34.81 | 0.586 | 28157.426 | 13334342 | 10365 | 0.652 | 1.968 | 0.0099 |
| 40.58 | 0.683 | 32689.907 | 16538619 | 12881 | 0.765 | 2.377 | 0.0124 |
| 46.21 | 0.834 | 47178.326 | 29858758 | 26106 | 0.896 | 3.233 | 0.0187 |
| 51.84 | 0.986 | 61666.744 | 43178898 | 39332 | 1.027 | 4.089 | 0.0250 |
| 57.48 | 1.137 | 76155.163 | 56499037 | 52558 | 1.158 | 4.945 | 0.0313 |
| 63.11 | 1.289 | 90643.581 | 69819177 | 65784 | 1.289 | 5.801 | 0.0377 |
| 68.74 | 1.440 | 105132 | 83139316 | 79010 | 1.420 | 6.658 | 0.0440 |

FIGURE 8
Cluster-based classification of EU member states by recycling performance and selected indicators (2019–2023).

Cluster 1 consisted of countries with high municipal waste recycling rates and strong levels of economic performance, specifically Germany, France, Italy, and Spain. Their average recycling rates over 2019–2023 ranged from approximately 40%–68%, placing them among the more advanced performers in the EU. These countries also reported real GDP *per capita* above 30,000 €, elevated levels of both public and private environmental investments, and relatively high levels of environmental tax revenues. Their GBARD directed at environmental objectives was also above average, indicating a consistent commitment to environmental governance and innovation. While their recycling policies remain heterogeneous, their grouping in the cluster analysis appears to reflect shared economic scale and investment capacity rather than policy similarity. This indicates that structural economic conditions play a stronger role than unified policy approaches in explaining their positioning within this cluster.

Cluster 2 encompassed Belgium, Netherlands, and Luxembourg—small, wealthy Western European states with high GDP, strong urban concentration, and recycling rates around 48%–58%. These countries demonstrated high levels of private investment in circular sectors and government expenditures on environmental protection, with their strength lying in policy coordination, efficient absorption of EU funds, and integration of environmental taxes into broader fiscal structures. Their grouping in the cluster analysis reflects not only economic capacity but also a long-standing tradition of institutional cooperation and alignment with EU environmental objectives, which has supported steady progress in recycling outcomes.

Cluster 3 included Austria, Denmark, Sweden, and Ireland, countries characterized by recycling rates ranging from approximately 42%–59%, and very high real GDP *per capita* (above 40,000 €). These countries also showed substantial levels of environmental taxation and investment, together with above-average shares of GBARD targeting environmental objectives, suggesting robust institutional frameworks for long-term environmental planning. Their cluster profile aligned with leadership in eco-innovation and comprehensive waste management systems. Their grouping is less about uniform recycling strategies and more about strong institutional commitment to sustainability, underpinned by public trust and relatively high societal engagement in environmental initiatives, which create favorable conditions for advancing waste management systems. Although their recycling rates partly overlap with those of Cluster 1, this cluster is differentiated by its strong institutional commitment, extensive reliance on environmental taxation, and high societal engagement, whereas

Cluster 1 is more strongly defined by economic scale and investment capacity.

Cluster 4 included Romania, Greece, Finland, Latvia, Slovenia, Portugal, Hungary, the Czech Republic, and Slovakia. This heterogeneous group was characterized by moderate recycling rates (roughly 30%–40%), diverse economic conditions, ranging from lower-income contexts such as Romania to more affluent countries such as Finland. Institutional capacity also differed, with some countries demonstrating stronger investment in environmental governance and innovation, while others faced persistent infrastructural or financial constraints. This cluster represented a transitional position within the EU, highlighting the need for differentiated policy interventions and tailored support to address country-specific challenges.

Cluster 5 comprised Bulgaria, Estonia, Lithuania, Croatia, Poland, Malta, and Cyprus. These countries were characterized by comparatively low recycling rates (often below 30%) and lower GDP *per capita*. They also exhibited limited levels of private and public environmental investment, together with low GBARD allocations directed to environmental objectives. Their grouping reflected shared structural constraints, including delayed infrastructure development and weaker institutional frameworks, which hindered recycling progress. This profile pointed to the importance of substantial EU-level support and capacity-building measures to overcome these barriers and accelerate the transition toward circular economy targets.

These results suggested that countries with higher levels of economic development and more substantial environmental investments generally exhibited higher municipal waste recycling rates. The cluster analysis further enabled the identification of national profiles that could benefit from the transfer of effective policy approaches and institutional practices from peer countries with similar macroeconomic structures but higher recycling performance. Such differentiation offers valuable guidance for the development of EU-level strategies aimed at promoting tailored, evidence-based circular economy interventions.

In conclusion, municipal waste recycling rates within the EU do not represent an isolated indicator but are closely interconnected with broader economic, environmental, institutional, fiscal, and demographic factors. The results of the cluster analysis offer a valuable foundation for policy segmentation and the design of targeted interventions—such as increasing support in countries with persistently low recycling rates, fostering private investment in circular economy sectors, or disseminating best practices from high-performing countries to other regions. These findings may inform strategic environmental policymaking at the EU level.

## 5 Discussion

The findings of this study offered a comprehensive view of the macro-level associations shaping municipal waste recycling performance across EU member states. Rather than operating in isolation, recycling outcomes appeared to reflect a constellation of economic strength, fiscal architecture, and institutional capacity. The results supported a systemic view in which recycling outcomes emerged from the co-occurrence of several macro-level conditions—particularly real GDP *per capita*, environmental taxation, and private investment in circular economy sectors. These conditions did not act in isolation but appeared to operate in parallel, with potential synergies reinforcing their combined contribution to recycling performance.

A positive association between real GDP *per capita* and municipal recycling rates was observed, consistent with previous evidence indicating that economically developed countries tend to exhibit stronger institutional capacity, broader access to advanced waste treatment infrastructure, and higher levels of environmental awareness among the population (Gabor et al., 2023; Holmen et al., 2025). These structural features have been repeatedly identified as critical enablers of effective recycling governance across the EU (Kostakis and Tsagarakis, 2022; Georgescu et al., 2022), which helps explain why affluent countries often maintain high recycling performance supported by sustained and mature administrative systems (Blagoeva et al., 2023). At the same time, higher income levels have also been associated with increased *per capita* waste generation (Tisserant et al., 2017). This indicates that while economic development provides favorable conditions for recycling through stronger institutional capacity, broader access to advanced infrastructure, and higher public awareness, it simultaneously introduces challenges that complicate the notion of linear progress. Economic affluence therefore appears to function as a facilitating but insufficient condition for achieving sustainable waste outcomes, underscoring the need for complementary policies that address consumption patterns and waste prevention alongside recycling. Effective recycling systems in high-income countries likely reflect a combination of financial capacity and broader systemic features, including political will, long-term environmental planning, institutional continuity, and strategic integration of circular economy principles. In practical terms, economic affluence may coincide with both the capacity and the imperative to develop more sophisticated recycling regimes.

In accordance with economic theories emphasizing the role of taxation in internalizing environmental externalities (Pigou, 1920; Fullerton and Metcalf, 2001; Viscusi et al., 2011), environmental tax revenues were identified as a significant explanatory variable for municipal recycling performance in the present analysis. This finding aligned with recent empirical studies that associated higher green tax intensity with improved waste outcomes and recycling effectiveness (Kostakis and Tsagarakis, 2022; Gabor et al., 2023; Imran et al., 2024). Prior evidence has indicated that countries maintaining stronger green fiscal frameworks tend to exhibit greater recycling efficiency, with environmental taxation functioning not only as a disincentive for polluting activities but also as a revenue stream for waste infrastructure development (Gabor et al., 2023; Liu et al., 2021). Importantly, Imran et al. (2024) observed that environmental taxes could reinforce recycling performance by incentivizing cleaner production and directly supporting investments in collection and treatment systems. This reinforces the interpretation that fiscal mechanisms may operate through both behavioral and infrastructural pathways when institutional support is present. Nevertheless, such relationships cannot be interpreted as uniform across all member states. For example, findings by Tantau et al. (2018) illustrated that the positive association between environmental taxation and recycling lost significance when controlling for national heterogeneity, suggesting that the strength of this relationship may be

contingent on deeper systemic factors. These considerations were echoed in the cluster analysis, where countries with similar levels of environmental tax revenues differed markedly in recycling performance. This indicates that the effectiveness of fiscal instruments is shaped not only by their design but also by institutional conditions such as administrative efficiency, governance quality, transparency in revenue allocation, and enforcement capacity. Weak institutions may limit the capacity of environmental taxes to stimulate behavioral change, whereas stronger governance frameworks can amplify their effect. Taken together, these findings underscore the need for policymakers to evaluate the institutional readiness of their national systems before implementing or intensifying environmental tax regimes. In practice, this implies that fiscal interventions will be most effective when aligned with national waste management priorities, supported by transparent use of revenues, and complemented by educational and behavioral change programs.

Private investment in the circular economy was found to be consistently associated with municipal recycling performance in the present analysis. This observation resonated with broader policy developments that have increasingly positioned private capital as a complementary driver of circular transformation (Georgescu et al., 2025). The mobilization of private resources has been viewed as essential for bridging the funding gap created by the transition from linear to circular production and consumption models, particularly in contexts where public financing remains constrained (Dumée, 2021; Marek and Krejza, 2024). The positive association identified in this study appeared to reflect such dynamics, whereby private sector engagement may have contributed to the development of recycling infrastructure, innovation in closed-loop systems, and market-based mechanisms that support waste recovery and material reuse (Dinda, 2020; Schlosser et al., 2021). Empirical evidence has also supported this perspective. For example, countries with higher levels of private investment in circular initiatives tended to demonstrate stronger recycling performance and more dynamic green economic activity (Hysa et al., 2020). A significant positive correlation between private capital flows into circular economy sectors and national recycling performance across EU member states was supported by recent panel data findings (Georgescu et al., 2025), reinforcing the interpretation that financial inputs from the private sector may contribute to progress toward circular economy objectives. While the relevance of private investment for advancing circularity has been widely acknowledged, the specific institutional and economic conditions under which it may be most effective in enhancing recycling performance continue to be the subject of ongoing discussion (Dinda, 2020). In the present study, this interpretation was further supported by patterns observed within the most advanced cluster—comprising Austria, Germany, and Luxembourg, where higher levels of private investment coincided with substantial public expenditure. Such configurations may reflect enabling institutional environments in which public and private financing interact in mutually reinforcing ways. In this context, encouraging private capital participation—particularly through targeted incentives and co-financing mechanisms—may represent a viable pathway to enhance circularity. The effectiveness of such efforts, however, is likely to depend on their integration within a broader governance structure, including long-term strategic alignment, regulatory coherence, and administrative stability.

Urban population size was found to be inversely associated with municipal recycling performance in the present analysis. This result appeared to reflect the complex interplay between demographic concentration and waste system functionality in urban environments. Although urbanization is often linked to higher waste generation, the presence or absence of supporting institutional frameworks and community engagement initiatives may shape whether such demographic characteristics facilitate or constrain recycling performance. Prior studies have highlighted that while urban growth increases waste pressure, its negative effects may be mitigated when participatory mechanisms are well established (Santoso and Farizal, 2019; Oh and Hettiarachchi, 2020). Similarly, population density has been shown to affect waste management efficiency across EU countries, underscoring the importance of context-specific capacity and policy implementation (Osinska, 2024). Empirical evidence from China and the EU has further shown that population growth and fertility rates can correlate positively with recycling when aligned with awareness and programmatic support (Huang et al., 2020; Kostakis and Tsagarakis, 2022). The latter authors also noted a nonlinear relationship between urbanization and circular economy outcomes, suggesting that beyond a certain threshold, urban concentration may cease to be beneficial unless matched with scalable infrastructure. In the present study, countries such as France and Spain—characterized by high urban population shares but moderate recycling outcomes—appeared to reflect this tension. These cases may illustrate the need for better-integrated governance, particularly in highly urbanized areas where recycling programs must overcome spatial constraints, fragmented responsibilities, and variable access to infrastructure. The findings support the interpretation that urbanization does not inherently enhance or hinder recycling performance but interacts with policy design, service accessibility, and civic mobilization to shape environmental outcomes.

General government expenditures on environmental protection, expressed as a percentage of GDP, were found to be negatively associated with municipal recycling performance in the present analysis. This result contrasted with earlier studies suggesting that increased environmental spending can support infrastructure development and behavioral engagement in recycling systems (Gabor et al., 2023; Jarczok-Guzy et al., 2024; Li et al., 2025). One possible interpretation relates to the implementation lag between financial allocation and observable outcomes. In some countries, elevated spending may reflect reactive policy responses to environmental degradation or inefficient structures rather than proactive system development. Empirical evidence supports this interpretation. For example, the European Court of Auditors (2012) reported that substantial EU-funded investments in municipal waste infrastructure often failed to translate into improved recycling outcomes without complementary reforms. Bulgaria provides a striking example, as it allocates relatively high spending on waste management compared to similar EU countries, yet still landfills nearly half of its municipal waste (World Bank, 2019). Evidence from outside Europe shows similar patterns. At the local level, Abbott et al. (2013) demonstrated that higher municipal expenditures in the United Kingdom did not necessarily improve household recycling rates, where social norms and local "recycling cultures" played a more decisive role. Likewise, Khator (1993) found

that U.S. states with above-average environmental spending were not necessarily more successful in achieving recycling targets. More recently, Kinnaman and Yamamoto (2023) highlighted that public investment in certain waste management pathways, particularly waste-to-energy incineration, may inadvertently suppress recycling progress. When significant resources are directed toward facilities that compete with recycling for material flows, recycling rates can stagnate despite high levels of expenditure. Collectively, these examples reinforce the view that simply increasing public expenditure—without strategic targeting and supportive measures—may not yield commensurate improvements in recycling performance. Previous research emphasized that public environmental expenditures are more likely to be effective when integrated with policy instruments that promote awareness, incentives, and local adaptability (Hornik et al., 1995; Nepal et al., 2023; Nikiema and Asiedu, 2022; Moeini et al., 2023). In practical terms, this suggests that financial inputs must be matched by administrative coordination and strategic alignment at multiple governance levels. Otherwise, spending may be absorbed inefficiently or directed to short-term obligations rather than long-term structural investment. The results therefore reinforce the notion that public expenditure should not be viewed in isolation but as part of a broader governance ecosystem.

More favorable results were observed for government budget allocations for R&D (GBARD) directed at environmental objectives. When expressed as a share of GDP, these investments were positively associated with municipal recycling performance, aligning with existing literature linking R&D to improvements in material sorting, processing technologies, and the accessibility of recycling infrastructure (Guo et al., 2018; Corrado et al., 2022; Shi and Zhou, 2024; Daoud et al., 2025). Several studies have confirmed positive associations between R&D investment and recycling performance across EU countries, further highlighting its role as a foundational input in circular economy transitions and broader sustainability frameworks (Osinska, 2024; Tantau et al., 2018; Georgescu et al., 2022; Georgescu et al., 2025; López-Portillo et al., 2021; Kostakis and Tsagarakis, 2022). The study results supported the interpretation that innovation-oriented public spending may strengthen the operational and technological basis for long-term waste management solutions. In practical settings, such investment enables experimentation with advanced systems, data integration, and adaptation to local material flows, all of which are considered vital for advancing circularity. These findings suggest that increasing public investment in environmental R&D may represent a viable strategy for enhancing recycling performance, particularly when aligned with national innovation priorities and supported by mechanisms that facilitate technology transfer and institutional uptake.

Several studies have also highlighted that R&D investment has been shown to contribute not only to the development of advanced recycling technologies and optimization of material recovery systems, but also to institutional learning, infrastructure modernization, and cross-sectoral cooperation that collectively enable systemic circularity transitions (Murakami et al., 2014; Markina et al., 2024). However, most prior research has relied on aggregate national R&D expenditure, without isolating investments explicitly directed toward environmental objectives (Osinska, 2024; Tantau et al., 2018; Georgescu et al., 2022; Georgescu et al., 2025; López-Portillo et al., 2021; Kostakis and Tsagarakis, 2022). By focusing specifically on GBARD, the present study provides a more targeted perspective on how environmentally oriented R&D contributes to recycling performance under varying institutional and financial conditions. When GBARD directed toward environmental objectives was measured as a share of total GBARD, a negative association with recycling outcomes was observed. This pattern may reflect limited national research capacity, where strong environmental orientation is not accompanied by sufficient overall R&D investment. In such cases, elevated proportions of environmental R&D may mask the weakness of the broader innovation system. These findings align with research advocating for integrated strategies, where environmental research agendas are embedded in multi-sectoral innovation frameworks and supported by effective mechanisms for implementation and policy transfer (Shi and Zhou, 2024; Wilson et al., 2005). The results suggest that emphasizing environmental objectives in R&D is meaningful only when accompanied by adequate funding, institutional capacity, and coordinated policy delivery, ensuring that scientific efforts can be translated into real-world environmental performance.

The cluster analysis provided a nuanced lens through which to interpret recycling performance across the EU, revealing that divergent socio-economic and institutional configurations can yield similar outcomes—or, conversely, that comparable levels of investment or policy ambition may translate into markedly different results depending on the broader national context. Rather than grouping countries solely by performance levels, the analysis identified structural affinities that may inform more targeted and cooperative approaches to circular economy policy (Bodislav et al., 2025). The findings underscored that recycling performance is embedded in complex fiscal, economic, demographic, and institutional ecosystems, where factors such as innovation capacity, urban density, and administrative coordination intersect with resource availability. From a policymaking perspective, the added value of the cluster approach lies in its potential to inform peer learning and tailored policy diffusion. Countries within the same cluster—despite differing in geography or size—may share implementation challenges or institutional bottlenecks that make coordinated solutions more effective than one-size-fits-all prescriptions. For example, clusters with moderate performance and variable institutional strength may benefit more from governance reforms and EU technical assistance than from blanket increases in funding. Conversely, high-performing clusters with mature systems may require innovation incentives or demand-side interventions to sustain progress (Bodislav et al., 2025). This multidimensional segmentation also supports the design of EU-level instruments that are sensitive to member state heterogeneity, enabling strategic alignment between cohesion policy, environmental taxation, and innovation funding. In this sense, cluster analysis is not merely a descriptive tool but a mechanism for anticipatory governance, helping to align circular economy trajectories with national capacities and regional development logics (Bodislav et al., 2025).

Altogether, the study highlighted that recycling outcomes in the EU are shaped by a nuanced interplay of economic, fiscal, institutional, and demographic structures. The combined use of regression and clustering methods offered a dual

perspective—quantifying statistical associations while also contextualizing country-specific performance. This duality contributes to a more targeted policy perspective, suggesting that future strategies should consider the specific profile of each country or cluster. While statistical associations do not imply causality, they may inform differentiated support mechanisms, such as capacity-building in less advanced clusters, cross-cluster learning, and the replication of policy instruments that have proven effective in structurally similar contexts.

## 5.1 Policy implications

The findings carry important implications for policy design at both national and EU levels. First, they underscore the need for differentiated policy approaches that reflect the institutional and economic heterogeneity of EU member states. Rather than applying uniform recycling targets or regulatory frameworks, the EU should enable more flexible, cluster-specific strategies, with financial and technical support calibrated to administrative capacity and development status. For advanced economies with established circular practices, policy efforts may focus on scaling eco-innovation, promoting circular product design, and refining market-based instruments to reduce material intensity. In contrast, mid-performing countries require modernization of existing infrastructure and improved coordination between levels of government to ensure efficient policy execution and uptake of EU funds.

For countries with underdeveloped recycling systems, priority should be given to basic institutional strengthening, stable regulatory enforcement, and public awareness initiatives. In these contexts, EU cohesion funding could be targeted more directly toward long-term system-building rather than short-term compliance. Across all clusters, more strategic integration between environmental R&D, fiscal incentives, and public participation is necessary to align technical capacity with behavioral and governance mechanisms. Policymakers are therefore encouraged to adopt a systems-based view of recycling policy—one that bridges macroeconomic, regulatory, and socio-institutional dimensions—rather than treating recycling as a stand-alone environmental issue.

# 6 Conclusion

This study provided a comprehensive macro-level assessment of the determinants of municipal waste recycling in EU countries between 2005 and 2023. By integrating multiple statistical techniques—including regression modelling, temporal trend analysis, and hierarchical clustering—it identified key economic, fiscal, institutional, and demographic factors associated with recycling outcomes. The results confirmed that recycling performance varied markedly across the EU, with only a subset of countries surpassing the 2025 target. Countries with higher real GDP *per capita*, greater environmental tax revenues, and stronger private investment in circular economy sectors were consistently associated with better recycling outcomes. Conversely, larger urban populations and certain public environmental expenditures were linked to weaker performance. The cluster analysis further highlighted the heterogeneity among countries, offering a practical basis for policy segmentation. These findings underscore the relevance of targeted, context-specific strategies to improve recycling outcomes and support the EU's transition toward a more sustainable and circular economic model.

## 6.1 Future directions of research

Further research could benefit from extending the analytical scope beyond macroeconomic indicators by incorporating institutional quality metrics, policy stringency indices, or public attitudes toward waste sorting and recycling. Examining subnational data may uncover regional disparities and more nuanced drivers of recycling performance within countries. Additionally, the use of dynamic panel techniques or time-lagged models could offer deeper insights into the temporal effects of fiscal, institutional, and investment measures. Comparative studies involving non-EU countries could also enhance understanding of policy effectiveness under different governance and economic conditions.

## 6.2 Limitations

Several limitations should be acknowledged when interpreting the findings of this study. First, the analysis was based exclusively on macro-level indicators, which may not fully capture the complexity of institutional, behavioral, or regional dynamics influencing recycling performance. Second, the statistical associations identified in the regression models do not imply causal relationships, as the study employed an observational design and did not control for potential endogeneity between variables. In particular, some explanatory variables—such as public expenditures—may be both a cause and a consequence of recycling performance. Third, the exclusion of variables such as waste collection efficiency or infrastructure quality, due to data constraints, may have limited the explanatory scope of the model. Finally, the clustering results were sensitive to the choice of variables and the averaging window, and should therefore be interpreted as indicative rather than definitive groupings.

# Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

# Author contributions

MC: Conceptualization, Investigation, Project administration, Supervision, Validation, Writing – review and editing. MT: Data curation, Formal Analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review and editing. VI: Conceptualization, Formal Analysis, Investigation, Resources,

Visualization, Writing – original draft, Writing – review and editing. SK: Funding acquisition, Formal Analysis, Resources, Supervision, Validation, Writing – review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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