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Municipal solid waste dynamics: Economic, environmental, and technological determinants in Europe

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ABSTRACT

This study examines the factors driving municipal solid waste generation in 33 European countries from 1995 to 2021. Using the STIRPAT model, the research assesses the influence of economic and environmental variables on municipal solid waste generation, analyzing data on Gross Domestic Product (GDP), Research and Development expenditure, tourism, trade volume, renewable energy adoption, and service sector growth. To count for cross-sectional dependence in the data, the study employs Driscoll Kraay Standard Error and performs quantile regression as a robustness test to capture variations across different levels of municipal solid waste generation. The findings reveal a positive relationship between GDP, the service sector, and municipal waste, indicating that economic growth and expansion in European countries increase waste. Conversely, tourism, trade, and renewable energy adoption negatively correlate with municipal waste, suggesting these factors can reduce waste. The study offers policy recommendations for European policymakers, researchers, and stakeholders to develop effective and sustainable waste management strategies, contributing to Europe's broader goal of environmental sustainability.

1. Introduction

Municipal solid waste (MSW) management has become a critical issue in sustainable development, with nations striving to minimize the environmental impacts of economic activities (Ahmad et al., 2024; Sharma and Jain, 2020), including the European Union (EU), which generates substantial volumes of MSW (Hondroyiannis et al., 2024). High volumes of MSW and inadequate management can have severe environmental consequences, turning waste into a significant hazard (Shah et al., 2023a). The EU's approach to addressing waste challenges is rooted in its circular economy (CE) framework, established through the European Environmental Plan (Plan, 2020) and further reinforced by the New Circular Economy Action Plan (CEAP) (European Commission, 2020). Notably, 60%–90% of municipal solid waste (MSW) in most countries originates from households, with the remainder generated by commercial, administrative, and other sources (Rebehy et al., 2023). Although policies increasingly emphasize waste-to-energy recovery and recycling practices (Shovon et al., 2024), the European Union still ranks as the world's second-largest MSW generator, producing 392 million tons annually (Shah et al., 2023b).

As European economies expand, addressing municipal solid waste (MSW) becomes increasingly critical. Over the past two decades, MSW levels have steadily risen across the EU (Maalouf and Mavropoulos, 2023), driven in part by growing economic activity, which is typically linked to higher MSW generation (Malinauskaite et al., 2017; Chakraborty et al., 2022). Similarly, evidence supports that increasing global trade (Faehn and Holmøy, 2003; Khaertdinova et al., 2021), tourism (Gökgöz and Yalçın, 2023), and the service sector (Hondroyiannis et al., 2024) contribute to the rise of MSW in Europe. To decouple GDP, trade, and service activities from MSW, effective policies need to be implemented (Mazzarano et al., 2021). The 7th Environmental Action Plan (EAP), introduced in 2014, set ambitious CE goals, aiming for a 65% reduction in MSW by 2030 to achieve 'zero waste emissions' and foster this decoupling (Cecere and Corrocher, 2016; Chioatto and Sospiro,

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2023). However, research examining the potential of such decoupling remains limited, highlighting the need for further studies.

Socioeconomic indicators and MSW relationships have been studied for individual EU nations or smaller regions within the EU (Kala and Bolia, 2020; Pudcha et al., 2023; Obersteiner et al., 2021; Velis et al., 2023), with some recent studies focusing on larger samples of EU countries (Gardiner and Hajek, 2020; Gökgöz and Yalçın, 2023; Yasmeen et al., 2023). MSW drivers in Europe and other developed countries include population growth (Pudcha et al., 2023), urbanization, agricultural production (Hondroyiannis et al., 2024), Research and Development (R&D), and industrialization (Peng et al., 2023). In terms of sector, tourism and hospitality have been linked to MSW, particularly in countries like Lithuania and Turkey (Perkumienė et al., 2023), although the relationship between tourism and MSW remains underexplored (Diaz-Farina et al., 2020; Gökgöz and Yalçın, 2023). Similarly, the impact of trade on waste generation is mixed; while some studies find positive correlations (Kellenberg, 2012; Iyamu et al., 2020; Meens-Eriksson, 2024), others suggest negative effects, contingent on trade regulations (Qirjo et al., 2021). Most research in the EU context has concentrated on the relationship between MSW and socioeconomic or technological factors (D'Adamo et al., 2024), often overlooking the significant roles of the service, trade, and tourism sectors—key pillars of the EU economy.

Moreover, R&D has emerged as pivotal in advancing waste management technologies and promoting sustainable practices, including recycling, reuse, and reduction (Hondroyiannis et al., 2024). R&D has been linked to enhanced efficiency in waste management (Gardiner and Hajek, 2020; Li and Tan, 2023) and addressing broader socioeconomic issues, such as reducing wage disparities (Kong et al., 2020; Yasar and Rejesus, 2020), though its impact varies based on factors like material reuse and energy-efficient production. Studies by Banacu et al. (2019) and Chen and Pao (2022) highlight that increased R&D expenditure can boost recycling rates and reduce MSW in the EU. Nevertheless, R&D does not always correlate with MSW reduction (Gardiner and Hajek, 2020), as certain technologies may generate significant waste or have minimal impact on waste reduction. Additionally, while the role of renewable energy in reducing emissions is well-established (Sultana and Esquivias, 2024; Martial et al., 2023), its integration into waste management practices remains underexplored. The potential of waste-to-energy initiatives, which can address waste disposal challenges and contribute to energy production, warrants further investigation (Di Foggia and Beccarello, 2021; Malinauskaite et al., 2017).

This study addresses these research gaps by incorporating economic, technological, and environmental indicators, including GDP per capita, R&D expenditure, tourism, trade, renewable energy adoption, and the expansion of the service sector on MSW generation in the EU. Specifically, the study investigates whether economic performance (proxied by GDP per capita), R&D investment, and transitions toward less polluting sectors such as tourism and services contribute to an increase in MSW and whether the adoption of renewable energy sources reduces MSW. To test these hypotheses, the study uses data from 1995 to 2021 sourced from World Development Indicators (WDI) and Eurostat. The Stochastic Impacts by Regression Population, Affluence, and Technology (STIRPAT) model, enhanced with Driscoll-Kraay standard errors (DKSE) and quantile regression, provides a robust framework for analyzing the dynamics of waste management. As Europe experiences increased trade activity (Gereffi et al., 2021), rapid tourism growth (Adamolekun and Kladakis, 2024), and a shift toward cleaner technologies (Imran et al., 2024), understanding how these factors influence waste management practices is vital for shaping effective policies and sustainable strategies.

This study fills critical gaps in the literature by addressing underexamined factors such as trade openness and tourism inflows, while also clarifying the mixed findings on the role of R&D in MSW management (Osińska, 2024; Gardiner and Hajek, 2020). These variables are particularly significant in the EU's highly interconnected economies, where trade and tourism are core activities. Unlike previous research that focuses on individual countries (e.g., Chakraborty et al., 2022, in Italy; Taušová et al., 2020; in Slovakia) or smaller regional groups, this study takes a broader regional perspective. It examines the cumulative impacts of these factors across 33 EU nations, providing new insights into the role of tourism and trade within a highly integrated context. Furthermore, this research links renewable energy adoption and R&D investments to MSW reduction, providing evidence for integrating MSW into renewable energy frameworks. These findings align with the EU's CE goals and offer actionable pathways to support the 7th EAP and CEAP objectives of decoupling economic growth and waste generation.

The paper is organized as follows: the introduction provides an overview of the topic, the literature review explores related studies, the methodology section describes the research approach, and the results and discussion section presents the findings. The paper concludes with key insights, policy recommendations, and directions for future research.

2. Literature review

The EU's primary objective in the industrial sector is to establish a circular economy and implement solid waste management practices that align with the region's socio-economic conditions, address the scarcity of raw materials, and promote environmental sustainability (Mazur-Wierzbicka, 2021). According to Rodríguez-Antón et al. (2022), To achieve the 2030 Sustainable Development Goals (SDGs), the circular economy is a pivotal strategy for the EU. The EU places significant emphasis on CE principles and waste management, guided by specific targets established by the EU Commission, such as 'Roadmap to a Resource Efficient Europe' in 2011, 'Close the Circle: An Action Plan of the European Union for the Circular Economy in 2015, A European Strategy for Plastics in a Circular Economy' in 2018, and 'The European Green Deal' in 2020 (Tutunchian and Altınbaş, 2023). Škrinjarić (2020) found a link between sustainable development and CE across 23 EU countries. However, Marino and Pariso (2020) stated that only a few countries among 28 EU countries with different strategies effectively met the CE objectives, some of which have higher GDP, R&D, and renewable energy use. Most EU countries face severe challenges in reducing and handling MSW, especially with increasing urbanization and changes in consumption patterns (Rosecký et al., 2021). The roles of tourism, the service sector, renewable energy, R&D, GDP, and trade openness are crucial, as highlighted in the following subsections.

2.1. GDP and municipal waste

Numerous studies have demonstrated the relationship between economic growth and MSW generation across various countries and periods, often using GDP as an indicator. For example, Hondroyiannis et al. (2024) and Yasmeen et al. (2023) identified a positive correlation between GDP and MSW generation in the EU. Likewise, utilizing an Error Correction Model (ECM) with data from 2000 to 2018, Hondroyiannis et al. (2024) showed a significant positive impact of economic growth and fertility rate (a proxy for population growth) on waste generation in the EU, suggesting a trade-off between economic expansion and environmental sustainability. Comparable findings were found in Canada (Eslami et al., 2023) and Switzerland with data from 1990 to 2017 (Magazzino et al., 2020), supporting the Environmental Kuznets Curve (EKC). Furthermore, research on a global level found similar findings, such as in the EU, China, and Singapore, with factors including population growth, energy consumption for heating, and economic expansion (Gardiner and Hajek, 2020; He et al., 2023; Maalouf and Mavropoulos, 2023).

Nonetheless, research has also indicated an inverse relationship between GDP growth and MSW generation. Georgescu et al. (2022) analyzed data from 2000 to 2018 for 25 European nations using real GDP growth and found that economic expansion did not positively impact MSW production. Pudcha et al. (2023) also identified that household size, population density, GDP per capita, and expenditures were indicators for MSW reduction, suggesting an inverse relationship between economic indicators and MSW generation. Their study utilized the Grey Model (GM) with data from Thailand between 2011 and 2018. However, Chakraborty et al. (2022) revealed a more nuanced picture in 103 Italian provinces. While some regions successfully decoupled economic growth from MSW, many others still faced a trade-off between the two. These findings highlight the complexity of GDP-waste management relationships, necessitating context-specific analysis for effective policy formulation.

2.2. R&D and municipal waste

Research indicates both direct and inverse relationships between R&D spending and MSW production. Li and Tan (2023) used a differential game model to show how R&D spending and waste technologies impact MSW generation. Similarly, Su et al. (2023) found that technologies and R&D-driven environmental regulations inversely affected MSW generation in OECD nations from 1994 to 2020. These studies demonstrate R&D's role in mitigating waste-related environmental impacts. Yasmeen et al. (2023) also found that technological advancements and informed public behavior can reduce the environmental impact of economic growth, specifically MSW generation. Some recent studies by Hondroyiannis et al. (2024) and D'Adamo et al. (2024) also highlighted the effectiveness of R&D in reducing and managing MSW.

In OECD nations, using data from 2000 to 2020, Shah et al. (2023a) found that R&D spending reduces MSW generation while industrialization and FDI increase it. Similarly, using data from 2000 to 2018 for 25 EU nations, Georgescu et al. (2022) identified an inverse relationship between R&D spending and MSW production. Gardiner and Hajek (2020) also demonstrated that more intense R&D decreases waste generation in EU countries.

2.3. Tourism and municipal waste

Research on the link between tourism and MSW production shows varying results depending on statistical methods and regions. Gökgöz and Yalçın (2023) used an envelopment theoretical model and OLS method with EU data and identified direct correlations among tourism, population density, GDP per capita, and MSW generation. A similar finding was observed by Ezeah et al. (2015) in top EU tourism destinations. More specifically, Diaz-Farina et al. (2020) observed a rise in MSW in Spain from 2004 to 2015, which they attributed to the growth of the tourism industry. Similarly, Obersteiner et al. (2021) identified tourism as a significant driver of MSW in 10 EU pilot cities. Arbulú et al. (2017) quantified this relationship in Mallorca, Spain, finding that a 1% increase in tourism arrivals correlated with a 1.25% increase in MSW generation. Outside of the EU, Voukkali et al. (2024) also found tourism and population growth's impact on MSW generation in Famagusta. Likewise, Molinos-Senante et al. (2023) reported significant negative effects of tourism and population density on MSW efficiency in Chile, considering environmental and regional factors.

On the other hand, studies such as that of Arbulú et al. (2015) indicate that while higher tourism spending increases MSW generation, per tourist spending reduces it. Their analysis, covering EU nations from 1997 to 2010, supports the EKC hypothesis that MSW generation declines as per capita income rises. Mateu-Sbert et al. (2013) found a direct correlation between tourist numbers and MSW production in Spain. However, Chakraborty et al. (2022) discovered a more nuanced picture in Italian regions. They found that regions with higher tourism activity had lower thresholds for decoupling economic growth from MSW, as waste generated from tourism activities, such as plastic, paper, and waste, was less compared to other economic sectors. Giurea et al. (2018) further emphasize the complexity of this relationship, highlighting mixed findings and the significant contribution of tourism to MSW in the EU, with nearly 2.8 million tons annually. These studies underscore the need for further research to fully understand the impact of tourism on waste generation and develop effective waste management strategies.

2.4. Trade and municipal waste

Li et al. (2023), utilizing a multiregional input-output model with data from China and 140 other nations, demonstrated that international trade significantly contributes to the global circulation of hazardous waste. Similarly, Mazzanti and Zoboli (2009) observed that increased trade activities across the EU stimulate production and consumption, resulting in rising MSW. Faehn and Holmøy (2003), Kellenberg (2012), Meens-Eriksson (2024), Liang et al. (2021), and Rossi and Morone (2023) also highlighted the role of trade activities in intensifying consumption and generating waste in high-income regions.

Conversely, Shi et al. (2021) found that trade openness in China reduced MSW, emphasizing the importance of sustainable trade policies and advanced waste management practices. Liu et al. (2023) supported this perspective, noting that trade facilitates the adoption of cleaner technologies and promotes the exchange of secondary materials, such as recycled plastics, reducing virgin resource extraction and its associated waste. Leelah and Mudhoo (2018) similarly emphasized the role of trade in transferring advanced waste management practices globally, contributing to MSW reduction in regions adopting CE principles. These contrasting findings underscore the multifaceted nature of trade's impact on MSW, modulated by policy frameworks, economic priorities, and waste management infrastructure.

2.5. Renewable energy and municipal waste

Renewable energy adoption has been widely recognized as a critical factor in minimizing MSW. Su et al. (2023) identified its significant role in reducing waste in OECD countries, highlighting the importance of integration of waste-to-energy systems that divert waste from landfills and convert it into useable energy. Similarly, Shi et al. (2013) proposed using waste from Chinese tourist areas to generate renewable energy, reducing waste and producing energy simultaneously. Malinauskaite et al. (2017) further emphasized the importance of renewable energy technologies in achieving CE objectives, particularly by repurposing MSW as a resource.

However, challenges persist in implementing renewable energy solutions, particularly in developing nations. These include high initial costs, lack of infrastructure, and inconsistent policy support, as identified by Peiris and Dayarathne (2023) using Life Cycle Assessment (LCA). System Operator (SO) models have the potential to integrate renewable energy into waste management systems, fostering a more sustainable and circular approach (Di Foggia and Beccarello, 2022).

2.6. Service sector and municipal waste

The service sector, with its expansive economic reach and consumer-oriented activities, significantly influences MSW generation. During the COVID-19 pandemic, Peula et al. (2023) observed a decline in MSW from the service sector in Spain, attributed to reduced activities in hospitality and retail. Conversely, Srivastava and Jha (2023) found that increased service sector employment correlates with higher MSW generation in Prayagraj, India, particularly in urbanized regions. This aligns with Pirani and Arafat (2014), who highlighted the hotel industry's significant role in waste generation due to its reliance on disposable items and high turnover rates.

Reynolds et al. (2014) corroborated these observations in Australia, identifying significant waste outputs from service sector operations and supply chains, particularly in retail and hospitality. Hondroyiannis et al. (2024) linked urbanization and the expansion of the service economy to increased MSW generation in EU regions. To address these challenges, Beccarello and Di Foggia (2023) proposed integrating CE principles, such as reusable packaging and mandatory waste audits, into service sector operations. These studies collectively highlight the urgent need for targeted interventions to address the MSW challenges posed by a growing service-based economy.

Although research on MSW in the EU has been growing, significant gaps remain. Existing studies often focus on specific EU nations or a subset of variables, such as GDP, tourism, or R&D, without holistically integrating a broader set of socioeconomic and technological factors. Studies have also explored the service sector individually, but only a few have examined these variables collectively across a macro-level dataset. Moreover, most literature is limited to regional or national case studies, leaving a gap in comprehensive analyses spanning all 33 EU countries.

3. Data and methodology

3.1. Data and variables

This study examines the effects of various socioeconomic and environmental factors on MSW generation across 33 EU countries from 1995 to 2021. The analysis utilizes data sourced from the World Development Indicator (WDI, 2023) and Eurostat (2023), focusing on key variables such as GDP per capita, R&D spending, trade volume, tourist arrivals, renewable energy adoption, and service sector expansion. Previous studies provide a foundation for the examination of these variables: GDP by Gökgöz and Yalçın (2023), Yasmeen et al. (2023), and Shehu et al. (2024); R&D spending by Li and Tan (2023) and Su et al. (2023); trade volume by Li et al. (2023), tourist arrivals by Gökgöz and Yalçın (2023) and Peula et al. (2023), renewable energy by Su et al. (2023), and service sector by Peula et al. (2023). Table 1 details the selected variables and their sources.

Table 2 summarizes descriptive statistics for the study variables (LnMSW, LnGDPpc, LnR&D, LnTO, LnTA, LnREN, and LnSERV) across 33 EU countries. The variables exhibited positive mean values, with the highest being 16.02 for LnTA and the lowest 0.189 for LnR&D. Standard deviations were relatively low (e.g., 0.268 for LnMSW and 1.442 for LnTA), indicating limited variability and data concentration around the means. Minimum values ranged from −2.435 (LnR&D) to 5.412 (LnMSW), while maximum values spanned from 4.494 (LnSERV) to 19.20 (LnTA). These statistics highlight stable distributions and provide a basis for exploring relationships between variables and their effects on municipal solid waste generation in the EU.

3.2. Theoretical framework

Ehrlich and Holdren (1971) first recommended using the IPAT model to explore how population growth affects the environment. They used the following model context:

$$I = P.\,A.\,T \tag{1}$$

"I" represents environmental impact, "P" population size, "A" affluence, and "T" technology level. However, IPAT has limitations. Dietz and Rosa (1994, 1997) proposed modifying IPAT to a stochastic equation,

Table 1
Variable Specification.

Log Form	Variables Specification	Source
LnMSW	Municipal solid waste generation	EUROSTAT
LnGDPpc	GDP per capita (constant 2015 US$)	WDI
LnR&D	Research and development expenditure (% of GDP)	WDI
LnTA	International tourism, number of arrivals	WDI
LnTO	Trade openness (% of GDP)	WDI
LnREN	Renewable energy consumption (% of total final energy consumption)	WDI
LnSERV	Employment in services (% of total employment) (modeled ILO estimate)	WDI

Source: EUROSTAT (2023) and WDI (2023).

Table 2
Summary statistics.

Variables	N	mean	sd	Min	max
ID	891	17	9.527	1	33
T	891	2008	7.793	1995	2021
LnMSW	856	6.176	0.268	5.412	6.759
LnGDPpc	891	10.02	0.843	7.289	11.63
LnR&D	861	0.189	0.646	−2.435	1.354
LnTO	891	4.556	0.469	3.614	5.961
LnTA	891	16.02	1.442	11.69	19.20
LnREN	851	2.566	1.043	−2.408	4.416
LnSERV	891	4.162	0.199	3.357	4.494

Source: Author's generated using Stata 16

considering random errors in parameter estimation, thus addressing criticisms. This resulted in "Stochastic Impacts by Regression on Population, Affluence, and Technology" (STIRPAT), an updated IPAT formula providing nonlinear relationships between individual activities and environmental impact. Zhang et al. (2022) found the STIRPAT model more robust across various data types, including cross-sectional, time series, and panel data, and more accurate in estimating each variable's influence elasticity. They considered the following formulation.

$$I_{it} = \mathrm{C}P_{it}^{\gamma_1} \mathrm{A}_{it}^{\gamma_2} \mathrm{T}_{it}^{\gamma_3} \varepsilon_{it} \tag{2}$$

In this case, P indicates population, A indicates wealth, and T indicates technology in nation i at time t. In the STIRPAT model, C is a constant term and ε is a random error component. They represent the coefficients of P, A, and T, respectively. The subscripts t and i indicate the year and nation, respectively. Taking the logarithm of variables can reduce heteroscedasticity and collinearity, compress variable scales, and stabilize data, without changing the data structure and correlation. This approach is particularly useful for understanding how changes in each unit of a variable influence MSW generation. By transforming the model, the logarithm simplifies multiplicative relationships into additions. The "elasticity" approach in economics, useful for examining the impact of various variables on municipal waste production, can now explain the regression coefficient. The logarithmic transformation of the model can be written as follows:

$$Ln\, I_{it} = \mathrm{C} + \gamma_1\, Ln\, P_{it} + \gamma_2\, Ln\, A_{it} + \gamma_3\, Ln\, T_{it} + \varepsilon_{it} \tag{3}$$

This study proposes an experimental version of the mathematical framework grounded in the existing literature, aligning with the STIRPAT model's conceptualization. In this framework, tourist arrivals (TA) serve as a proxy for population, while GDP per capita (GDPpc) and trade openness (TO) represent affluence. To capture the technological dimension, the framework incorporates research and development (R&D), renewable energy adoption (REN), and the expansion of the service sector (SERV).

$$MSW_{it} = f(GDPpc_{it}, RD_{it}, TO_{it}, TA_{it}, REN_{it}, SERB_{it}) \tag{4}$$

In this case, GDPpc, RD, TO, TA, REN, and SERV were explanatory variables, whereas MSW was the dependent variable. Equation (4) is shown in Fig. 1. According to Raihan (2023b), the results obtained through natural log transformations are more precise and effective than those obtained using linear models. The empirical model can alternatively be represented in logarithmic form as follows:

$$\begin{aligned} LnMSW\_(it) &= \beta\_(0) + \beta\_(1)\ \ LnGDPpc\_(it) + \beta\_(2)\ \ LnR\&D\_(it) \\ &+ \beta\_(3)\ \ LnTO\_(it) + \beta\_(4)\ \ LnTA\_(it) + \beta\_(5)\ \ LnREN\_(it) \\ &+ \beta\_(6)\ LnSERV\_(it) + \epsilon\_(it) \end{aligned} \tag{5}$$

where β0 is the intercept term, and β1, β2, β3, β4, β5, and β6 are the coefficients of LnGDPpc, LnR&D, LnTO, LnTA, LnREN, and LnSERV, respectively. Ln stands for the natural log, which comes before all elements, and ϵ stands for the model's error term. Subscript t denotes the

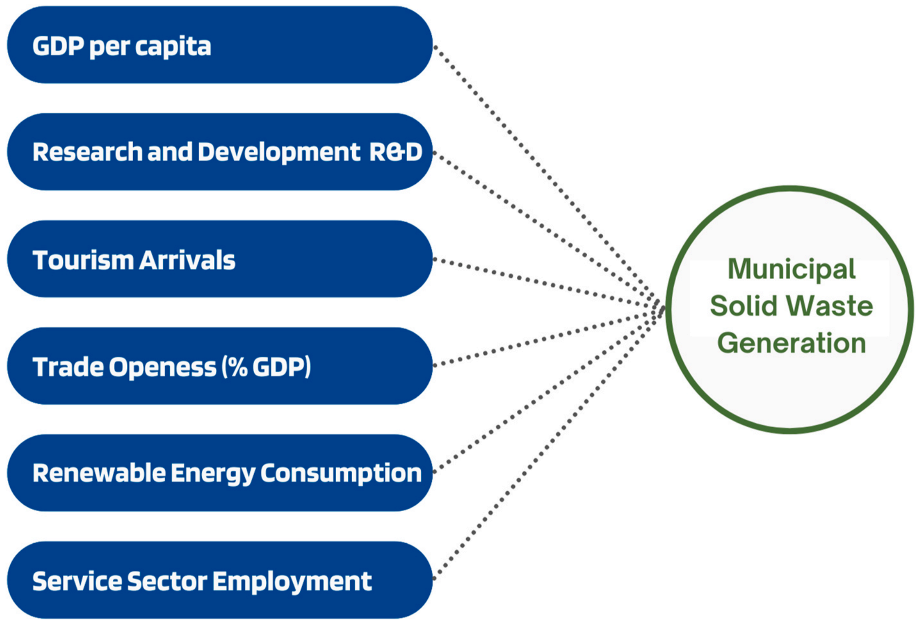

Fig. 1. Effect of GDPPc, R&D, Tourism, Trade Openness, Renewable Energy, and Service Sector on MSW in EU nations Source: Generated by Authors.

time from 1995 to 2021, whereas subscript i represents the cross-sectional units of the 33 EU nations.

3.3. Econometric methods

This section outlines the statistical tests employed in this research. The analysis began with establishing correlations among the variables using the methodologies proposed by Pearson and Filon (1897) and Pearson (1896). Subsequently, slope heterogeneity tests (Pesaran and Yamagata, 2008) and cross-sectional dependence (CSD) tests (Pesaran, 2015) were conducted to determine the appropriate econometric methods. Following this, unit root tests (IPS, ADF, and CIPS) and cointegration tests (Westerlund, 2007) were performed to ensure robustness. For the final analysis, Driscoll-Kraay and Quantile regression methods were applied, following the procedures outlined by Voumik and Sultana (2022).

3.3.1. Correlation, slope heterogeneity, and cross-sectional dependency tests

Correlations between variables were calculated using Pearson and Filon (1897), and Pearson (1896) (Appendix A1).

Heterogeneity in slopes is significant because weighted panel data econometrics vary across nations. The technique developed by Pesaran and Yamagata (2008) was applied to examine the initial slope heterogeneity. The weighted slope distribution throughout all countries is the foundation for this test. The related test statistics are given in Appendix A2.

According to Tufail et al. (2022), cross-sectional dependency in panel data econometrics is growing because of factors such as decreased trade barriers, improved macroeconomic interconnectedness, and globalization. If cross-sections are assumed to be independent of one another rather than considered, the results may be skewed, inconsistent, or misleading (Westerlund and Edgerton, 2007). Therefore, this study used a test for weakly exogenous cross-sectional dependency in large panel data econometrics developed by Pesaran (2015) to assess the presence of cross-sectional dependency. Appendix A3 briefly describes the standard equation used for the cross-section dependency (CSD) test.

3.3.2. Panel unit root test (IPS, ADF, CIPS)

After determining that there was no slope heterogeneity or CSD, IPS, ADF, and second-generation (CIPS) unit root tests were employed to examine the stationarity of the elements. The necessity of finding a cross-sectional mean for IPS, ADF, and CIPS calculations is demonstrated in Appendix A4.

The CIPS is becoming increasingly popular within the academic community because of its efficacy in handling CSD and heterogeneity. Voumik and Sultana (2022) state that the starting point of the hypothesis is the unit-root series. Before estimating the parameter, the test recommends performing a cointegration test if the variable meets first-difference stationarity.

3.3.3. Westerlund cointegration test

Westerlund (2007) works effectively to determine cointegration elements in cross-sectionally dependent heterogeneous panel data. The variance in the slope, coefficient of determination, and associated errors were considered in this method. It computes error-corrected statistics to confirm the absence of co-integration across the four panels. The traditional format of this second-generation Westerlund (2007) cointegration test consists of the four equations given in Appendix A5.

There are group mean statistics (G_t and G_a) and panel mean statistics (P_t and P_a), each with a unique set of symbols. If one assumes that the model variables are unconnected or "null," the associated insignificant test results are expected; if, on the other hand, one assumes that "there are cointegrating relationships," the associated significant results are expected.

3.3.4. Driscoll-Kraay standard error

According to Driscoll and Kraay (1998), the Driscoll–Kraay standard error estimate approach measures heteroscedasticity and CSD when there are missing data or unbalanced panel settings. Considering the linear model statement, the OLS-Driscoll–Kraay standard error estimation is developed using the following structure:

$$Y_{it} = z_{it}\beta + \varepsilon_{it}, i = 1, 2, 3, \ldots T \quad (6)$$

Here, Y_{it} = is the dependent variable and z_{it} is a scalar representing the independent variables with a (K + 1) × 1 vector. β defines the coefficients with the (K + 1) × 1 vector, and i is the cross-sectional units at time t.

Based on all other observations, the expression is as follows:

$$y = \left[y_{1t1,1}.....y_1T_1, y_2t_2.....y_NT_N\right]' \text{ and } X\left[x_{1t1,1}.....xT_1, x_2t_2.....x_NT_N\right]' \quad (7)$$

The assumption is that x_{1t1} is not associated with the scalar error term ε_{it} for all s, t (strong homogeneity). Moreover, ε_{it} might represent heteroscedasticity and cross-sectional dependence. This explanation is considered relevant in Hoechle (2007) if β is consistently determined by the OLS regression. Therefore,

$$\beta = (X'X)^{-1}X'y \quad (8)$$

For particulars, the squared roots (SˆT) of the asymptotic covariance elements of the matrix can be determined by calculating the coefficient estimates of the Driscoll–Kraay standard errors (DKSE) as follows:

$$V(\beta) = (X'X)^{-1}S_T(X'X)^{-1} \quad (9)$$

3.3.5. Quantile regression

The quantile regression approach is relevant in investigating non-normally distributed nonlinearly correlated outcomes and reflects nonlinear associations with predictor variables. Specifically, Buchinsky (1994) states that given a set of variables, the q^{th}-quantile ($0 < q < 1$) of the dependent variable can be identified as an impermanent distribution, as shown in Equation (10):

$$Q_{Q(y_{IT}|\beta_O\varepsilon_{it}x_{it})} = \beta_O + \varepsilon_{it}^q + \beta_i^q x_{it} \quad (10)$$

where y_t is recycling through time and u_t represents unobservable factors. A vector of explanatory variables (X_{it}) is given separately. According to Cameron and Trivedi (2010), a conclusion from the q^{th} quantile regression requires minimizing the actual value of the residual, as demonstrated by the objective function in Equation (11):

$$Q\left(\beta_i^q\right) = min\ \beta\sum\nolimits_{q,t=1}^{n}\left\|y_{it} - x^{it}\beta_i^q\right\| = min\left[\sum\nolimits_{i:y_{it}\geq x_{it}\beta} q\left|y_{it} - x_{it}\beta_i^q\right| + \sum\nolimits_{i:y_{it}\geq x_{it}\beta}(1-q)\left|y_{it} - x_{it}\beta_i^q\right|\right] \quad (11)$$

Equation (11) can be divided into two parts. The initial stage is to calculate the u_t mean. Following its elimination from the original dependent variable, this component is evaluated using quantile regression. Fig. 2 shows the whole process of the econometric method used in this study.

4. Results and findings

This section establishes connections among variables using correlation, DKSE, and quantile regression to illustrate the significant impact of explanatory variables on MSW. Heterogeneity, CSD, unit root, and cointegration results are also detailed to confirm the appropriateness of the regression methods.

Table 3 shows that LnMSW is positively correlated with LnGDPpc, LnR&D, LnTO, and LnSERV, while negatively correlated with LnTA and LnREN. The strongest correlations are with LnGDPpc and LnSERV, suggesting that economic growth and service industry expansion significantly influence MSW generation. Pairwise correlation values, provided in Table 3, are all below 0.90 (excluding the LnMSW column), indicating no multicollinearity issues (Gujarati and Porter, 2009).

Table 4 indicates that the null hypothesis of no slope heterogeneity is rejected, as evidenced by a p-value of 0.000. This result strongly supports the presence of slope heterogeneity.

To ensure the reliability of the regression results, three CSD tests were conducted. Table 5 presents the results, demonstrating interdependence among variables across countries. As the Pesaran, Friedman, and Frees CSD statistics are significant at less than 1%, the null hypothesis of no cross-sectional dependence is rejected.

The variables are categorized as stationary or non-stationary at the level or first difference using the panel unit root test in Table 6. The non-stationarity null hypothesis for the variables was accepted at the level, as indicated by the p-values for the three tests (IPS, ADF, and CIPS), which were all greater than 0.05, and the same null hypothesis was rejected at first difference because the p-values for the three tests (IPS, ADF, and CIPS) were all less than 0.05. Therefore, the test outcomes demonstrate that all the variables are nonstationary at the level and stationary at the first difference.

In Table 7, using four test statistics (Gt, Ga, Pt, and Pa), Westerlund's (2007) cointegration test assesses the long-term correlations between variables. P-values of less than 0.05 for Gt and Pt test statistics support

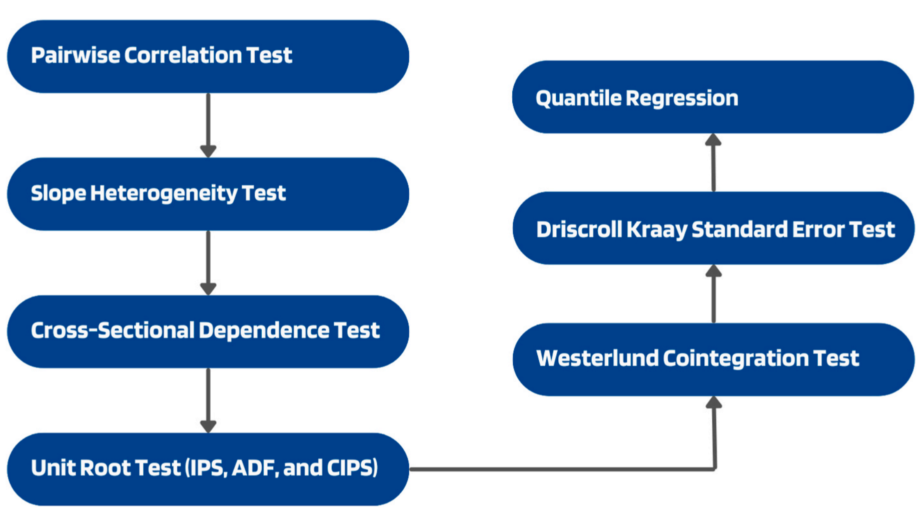

Fig. 2. Flowchart of the statistical tests used in the research.

Table 3
Pairwise Correlation test.

Variable	LnMSW	LnGDPpc	LnR&D	LnTO	LnTA	LnREN	LnSERV
LnMSW	1.000						
LnGDPpc	0.642***	1.000					
LnR&D	0.356***	0.733***	1.000				
LnTO	0.161***	0.204***	−0.030	1.000			
LnTA	−0.128***	−0.008	0.061*	−0.383***	1.000		
LnREN	−0.184***	−0.064*	0.224***	−0.247***	−0.149***	1.000	
LnSERV	0.573***	0.842***	0.568***	0.338***	0.052	−0.116***	1.000

Note. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
Source: Generated by Authors using Stata 16

Table 4
Slope heterogeneity test.

	Delta	p-value
	16.631***	0.000
	21.053***	0.000
Adj.		

Note. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
Source: Generated by Authors using Stata 16

Table 5
CSD test.

CSD Tests	T-Statistics	P-Values
Pesaran	5.179***	0.000
Friedman	55.063***	0.0068
Frees	6.586***	0.01

Note. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
Source: Generated by Authors using Stata 16

the rejection of the null hypothesis, which indicates the presence of cointegration and a steady, long-term association among the variables in the panel dataset.

4.1. Empirical results

The DKSE regression analysis (Table 8) offers detailed insights into the relationships between MSW generation and six key variables across 33 EU nations. GDP per capita (GDPpc) shows a positive and statistically significant relationship with MSW (coefficient: 0.144, $p < 0.01$). This finding indicates that a 1% increase in GDPpc corresponds to a 0.144% rise in MSW, underscoring the environmental challenges associated with economic growth. R&D Spending, while negatively associated with MSW (−0.0102), does not exhibit statistical significance, suggesting that the potential for R&D to influence waste reduction remains underutilized or context-dependent in the current dataset.

An increase in tourist arrivals (TA) emerges as a significant negative predictor of MSW (−0.0333, $p < 0.01$). This result implies that higher levels of tourism are associated with reductions in waste, potentially reflecting enhanced waste management systems in tourism-intensive regions. Trade openness (TO) displays a negative coefficient (−0.0491, $p < 0.10$), indicating that greater trade openness may reduce MSW through improved resource efficiency and access to cleaner technologies, though its effects vary by scale and context. Renewable energy adoption (REN) exhibits a consistent and significant negative relationship with MSW (−0.0471, $p < 0.01$), highlighting the role of renewable energy systems in reducing waste, particularly through waste-to-energy initiatives. The service sector (SERV) is positively and significantly associated with MSW (coefficient: 0.180, $p < 0.01$), reflecting the sector's contributions to waste generation, particularly through consumer-facing activities in retail, hospitality, and office services.

Table 7
Results of Cointegration
Westerlund (2007) test for cointegration.

Statistic	Value	P-value
Gt	−2.150***	0.000
Ga	−0.145	0.845
Pt	−5.264***	0.010
Pa	−0.245	0.758

Note. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
Source: Generated by Authors using Stata 16

Table 8
Driscoll Kraay standard error results.

Variables	DKSE	t-value
LnGDPpc	0.144*** (0.0112)	12.82
LnR&D	−0.0102 (0.00975)	1.04
LnTA	−0.0333*** (0.00475)	−7.01
LnTO	−0.0491* (0.0245)	−2.00
LnREN	−0.0471*** (0.00991)	−4.75
LnSERV	0.180*** (0.0551)	3.27
Constant	4.857*** (0.292)	16.64
Observations	891	
Number of groups	33	
R-squared	0.386	

Note. Standard errors in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table 6
Results of panel unit root test.

Variable	IPS		ADF		CIPS	
	I (0)	I (1)	I (0)	I (1)	I (0)	I (1)
LnMSW	0.512	3.786***	5.432	21.874**	0.976	3.532***
LnGDPpc	0.784	−2.054*	7.576	18.35***	−1.367	−2.8***
LnR&D	0.985	−1.742**	12.191	15.715**	−3.0***	−3.2***
LnTA	1.014	−1.589**	10.307	21.147*	−2.39**	−2.9***
LnTO	0.254	−3.00***	9.347	28.89***	−1.541	−3.2***
LnREN	−0.985	−4.25***	6.286	45.98 ***	−1.995	−5.1***
LnSERV	0.737	5.631***	2.145	15.892**	1.104	8.032**

Note. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
Source: Generated by Authors using Stata 16

Table 9
Quantile regression results.

Variable	Q25	Q50	Q75
LnGDPpc	0.237***	0.174***	0.187***
	(0.0333)	(0.0189)	(0.0244)
LnR&D	−0.0177	−0.00596	−0.0276
	(0.0301)	(0.0171)	(0.0221)
LnTA	−0.00655	−0.000914	−0.0268***
	(0.0113)	(0.00640)	(0.00829)
LnTO	−0.0334	0.0230	0.0309
	(0.0355)	(0.0201)	(0.0261)
LnREN	−0.0454***	−0.0424***	−0.0324***
	(0.0146)	(0.00826)	(0.0107)
LnSERV	0.143	0.0201	−0.160
	(0.136)	(0.0768)	(0.0995)
Constant	3.440***	4.367***	5.493***
	(0.394)	(0.223)	(0.289)

Note. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Standard errors in parentheses.
Source: Generated by Authors using Stata 16

The quantile regression results (Table 9) align with the DKSE findings, confirming a positive influence of GDPpc on MSW across quantiles, with the strongest effects observed at lower quantiles (Q25). Renewable energy consistently demonstrates a robust negative association with MSW across quantiles, while the effects of R&D and tourism vary, becoming significant in specific quantiles. Trade openness initially reduces MSW but yields mixed outcomes in higher quantiles. Meanwhile, the service sector exhibits a less pronounced influence in the quantile analysis, indicating regional variability in its impact.

5. Discussion

This study provides valuable insights into the determinants of MSW generation across EU nations, focusing on GDP per capita, R&D spending, tourist arrivals, trade openness, renewable energy adoption, and the service sector. The findings highlight both short- and long-term implications for sustainable waste management under the EU's New Circular Economy Action Plan (CEAP).

The positive association between GDP per capita (GDPpc) and MSW underscores the environmental challenges linked to economic growth. The study's findings indicate that higher economic activity leads to higher waste generation, indicating a failure to achieve the decoupling of economic activity (GDP) from MSW in the EU. This aligns with Aydinbaş and Erdinç (2023), Grdic et al. (2020) and Hondroyiannis et al. (2024), who reported similar results in Turkey and certain EU regions. The results underscore that economic growth in the EU remains closely tied to higher MSW production, reflecting a significant environmental trade-off associated with economic expansion (Adhikari et al., 2024; Gardiner and Hajek, 2020; Magazzino et al., 2020). However, these findings contrast with those of Georgescu et al. (2022) and Pudcha et al. (2023), who identified negative correlations in regions where economic maturity has facilitated better waste management practices, leading to reduced waste production. This supports the Environmental Kuznets Curve (EKC) hypothesis. Melidis and Russel (2020) argue that economic growth's impact on waste diminishes in more developed economies, highlighting the importance of stronger environmental regulations in less developed EU member states to mitigate the environmental impact of economic expansion.

The negative yet statistically insignificant relationship between R&D spending and MSW (−0.0102) suggests that, while research and innovation have the potential to reduce waste, their impact remains underdeveloped. This find ing is supported by Gardiner and Hajek (2020), Gökgöz and Yalçın (2023), Laureti et al. (2024), and Su et al. (2023), who collectively emphasize that R&D investments contribute to reducing MSW through several mechanisms. These include advancements in recycling technologies, enhanced efficiency in MSW management, reductions in waste generation, and increased productivity in waste processing and reuse systems. However, Li and Tan (2023) and Georgescu et al. (2022) observed mixed outcomes, suggesting that the impact of R&D depends on regional implementation and the focus on technological innovation. Policymakers should explore barriers to effective R&D utilization, as these investments hold promise for achieving CEAP goals.

Tourism's impact on MSW reveals a significant negative association (−0.0333, $p < 0.01$), suggesting that increased tourist arrivals are correlated with lower waste generation. This finding aligns with Adhikari et al. (2024), Chakraborty et al. (2022), and Diaz-Farina et al. (2020), who noted that tourism activities can lead to more efficient waste management practices. However, our findings diverge from those of Gökgöz and Yalçın (2023), who reported a positive correlation between tourism and MSW in EU regions, and Molinos-Senante et al. (2023), who observed increased MSW generation linked to tourism in Chilean municipalities. Similarly, studies by Diaz-Farina et al. (2020) and Arbulú et al. (2017) highlighted positive associations between tourism activities and MSW in Spain, while Obersteiner et al. (2021) documented a similar trend in 10 EU pilot cities, emphasizing the waste challenges posed by high tourism inflows in these regions. These mixed results highlight the importance of region-specific waste management policies (Vardopoulos et al., 2021), particularly in tourism-intensive areas, to balance between economic growth and environmental sustainability.

The negative coefficient for trade openness (TO, −0.0491, $p < 0.10$) indicates that increased trade can reduce MSW, potentially through improved resource efficiency and cleaner production methods. Aydinbaş and Erdinç (2023) observed similar results in Turkey, while Li et al. (2023) reported opposing findings in China, where trade-driven consumption increased waste production. This disparity underscores the importance of aligning trade practices with CE principles. Studies like Liu et al. (2023) and Leelah and Mudhoo (2018) highlight the role of trade in facilitating the transfer of cleaner technologies and promoting the trade of recycled materials, contributing to lower MSW and more efficient use of resources.

Renewable energy adoption demonstrates a consistent negative association with MSW (−0.0471, $p < 0.01$), confirming its effectiveness in reducing waste. This aligns with Su et al. (2023) in OECD countries and Malinauskaite et al. (2017) in the EU, who emphasized that renewable energy technologies, particularly waste-to-energy systems, play a critical role in reducing waste disposal (i.e., landfill dependency) and promoting sustainable energy practices. Di Foggia and Beccarello (2021) further highlight how integrating MSW into renewable energy frameworks can advance CE goals as it supports more efficient MSW management. Policymakers should prioritize renewable energy adoption to reduce MSW and improve waste management efficiency across EU regions.

The service sector (SERV) shows a significant positive association with MSW (0.180, $p < 0.01$), reflecting increased waste generation from service-driven economies. This aligns with Srivastava and Jha (2023), who observed that rising consumerism and disposable practices in retail, hospitality, and office activities contribute significantly to MSW. As the EU transitions toward service-oriented economies, targeted interventions are essential to mitigate the environmental impacts of this sector. Hondroyiannis et al. (2024) emphasize the need for circular economy practices within the service industry, including waste audits and reusable packaging initiatives.

6. Conclusion

The growing challenge of MSW generation presents a significant threat to sustainable development in the EU. This study analyzes the factors influencing MSW across 33 EU countries from 1995 to 2021 using the STIRPAT model, Driscoll-Kraay standard errors, and quantile regression techniques. The findings reveal important insights into the drivers of waste generation. GDP per capita is positively and significantly associated with MSW, illustrating the environmental trade-offs of economic expansion. Renewable energy adoption and trade openness demonstrate a consistent and significant negative impact on MSW, underscoring their potential as effective strategies for sustainable waste reduction. Tourism shows a negative association with MSW, which may reflect improved waste management systems in high-tourism areas. Meanwhile, the service sector has a notable positive impact on MSW, highlighting the need for interventions in consumer-driven industries. R&D expenditure shows a limited and statistically insignificant impact on MSW reduction, raising concerns about the effectiveness and allocation of investments in waste management innovation.

These findings emphasize the need for targeted policy measures. Expanding renewable energy use and integrating sustainability into trade and tourism policies can help reduce MSW while fostering economic growth. The positive correlation between GDP and MSW calls for stricter waste management regulations and strategies to decouple economic development from waste generation. Additionally, efforts to overcome barriers in the implementation of R&D innovations are necessary to enhance its role in achieving waste reduction goals. This study provides a robust framework for understanding the drivers of MSW and offers actionable insights for policymakers. By addressing regional and sectoral disparities, the EU can make substantial progress in meeting the CEAP objectives and transitioning toward a sustainable waste management system that aligns with long-term environmental and economic goals.

The positive association between the service sector and MSW suggests the need to account for consumer-driven industries in modeling environmental impacts, which is often overlooked in traditional STIRPAT applications. Similarly, the negative link between renewable energy adoption and MSW underscores the need to integrate energy transitions into waste management, suggesting an expansion of the STIRPAT model to incorporate technological and policy factors. The findings on R&D's limited impact on reducing MSW challenge the assumption that technological advancements reduce environmental harm.

The findings emphasize the need to adopt sustainable strategies such as recycling, enacting and enforcing regulations, and enhancing waste management systems. These measures should be integrated into efforts to manage economic and service sector expansion. Governments can leverage renewable energy sources, trade openness, and tourism activities as effective tools for mitigating waste generation. Additionally, R&D initiatives must be strategically guided to ensure they significantly contribute to reducing MSW. By addressing the growing MSW challenge, EU countries can accelerate their transition toward a more sustainable and circular waste management system. Innovative approaches are essential to decouple economic growth from its environmental impact, reducing the positive correlation between economic activitues and waste production. These efforts underscore the importance of implementing an integrated waste management strategy tailored to the specific circumstances and needs of EU nations.

7. Policy recommendation and limitations

7.1. Policy recommendations

This study offers actionable policy recommendations to address MSW challenges in alignment with the EU's CE goals. Investment in waste-to-energy facilities can manage waste while meeting energy demands, converting waste into a productive resource. This supports CE principles by fostering a relationship between waste reduction and GDP growth. Policies should include financial incentives and technical support for WTE systems integrated into regional energy grids. In addition, industrial policies should prioritize the reuse and recycling of secondary raw materials to reduce landfill use and meet CE targets. Di Foggia and Beccarello (2022) highlight that fostering market competition through transparent contracting enhances efficiency. Measures could include mandatory recycling quotas for industries and incentives for using recycled materials in production.

Though R&D spending shows limited immediate effects on MSW, targeted funding for innovations in recycling and upcycling technologies can convert waste into valuable resources. Governments should offer grants and subsidies for technologies that improve resource recovery, reduce reliance on raw materials, and enhance waste management efficiency. Moreover, policymakers should implement subsidies for renewable energy projects, tax breaks for waste-to-energy initiatives, and financial incentives for clean energy adoption. The System Operator (SO) models proposed by Di Foggia and Beccarello (2022) can integrate renewable energy into waste management systems.

In high-tourism regions, implementing advanced waste management strategies is essential. Key initiatives include infrastructure investments for waste segregation and recycling, eco-awareness campaigns, and partnerships with the tourism sector to promote sustainable practices. Certification programs rewarding eco-friendly tourism operators can encourage compliance. Furthermore, given the service sector's growing contribution to MSW, targeted interventions are crucial. These include promoting paperless systems, reusable packaging, and take-back schemes for consumer goods. Mandatory waste audits for service businesses and public education campaigns can nurture a culture of accountability and sustainability. Beccarello and Di Foggia (2023) stress integrating CE practices within service operations.

Tailored initiatives are necessary to address the diverse challenges faced by the 33 EU countries. International collaboration can facilitate the exchange of effective methods and coordinated strategies to tackle MSW. Tax incentives for adopting circular economy practices and targeted support for regional innovation hubs can expedite the transition to sustainable systems.

7.2. Limitations and future research

This study provides insights into MSW generation in 33 EU countries but has limitations. By excluding other developed economies, the findings' generalizability is constrained, as waste generation dynamics may differ due to varying socioeconomic, cultural, and policy contexts in those regions. Although the STIRPAT model is reliable, it lacks some variables affecting MSW generation. Future research should include factors like technological progress, education levels, policy effectiveness, and socioeconomic uncertainties for a comprehensive understanding of MSW drivers.

The 27-year data span shows significant trends but may not fully capture long-term shifts from technological advances, changing consumer habits, or policy changes. Extending the timeframe could better reflect these impacts. Additionally, the study could explore sector-specific MSW contributions, such as food waste in restaurants or digitalization's impact on waste streams, to develop targeted waste reduction strategies. Sectoral analyses are crucial for identifying actionable interventions. Expanding future research to include non-EU regions would enhance relevance and applicability, revealing unique patterns and informing global sustainable waste management strategies by accounting for regional variations in policies, economies, and technologies.

CRediT authorship contribution statement

Afsana Akther: Writing – original draft, Methodology, Conceptualization. **Farian Tahrim:** Writing – review & editing, Visualization. **Liton Chandra Voumik:** Writing – original draft, Data curation. **Miguel Angel Esquivias:** Writing – review & editing, Supervision, Project administration. **Dulal Chandra Pattak:** Writing – review & editing, Validation, Formal analysis.

Consent for publication

All authors have provided consent for publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clet.2024.100877.

Data availability

The data used in this study are openly available to the public and can be accessed from EUROSTAT (2023) and World Development Indicators (WDI, 2023)

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