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Evolving waste management: The impact of environmental technology, taxes, and carbon emissions on incineration in EU countries

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ABSTRACT

Amid the urgent global imperatives concerning climate change and resource preservation, our research delves into the critical domains of waste management and environmental sustainability within the European Union (EU), collecting data from 1990 to 2022. The Method of Moments Quantile Regression (MMQR) results reveal a resounding commitment among EU member states to diminish their reliance on incineration, which is evident through adopting green technologies and environmentally conscious taxation policies, aligning with the European Union's sustainability objectives. However, this transition presents the intricate task of harmonizing industrial emissions management with efficient waste disposal. Tailoring waste management strategies to accommodate diverse consumption patterns and unique circumstances within individual member states becomes imperative. Cointegrating regressions highlighted the long-run relationship among the selected variables, while Feasible Generalized Least Squares (FGLS) and Panel-Corrected Standard Errors (PCSE) estimates roughly confirmed MMQR results. ML analyses, conducted through two ensemble methods (Gradient Boosting, GB, and Extreme Gradient Boosting, XGBoost) shed light on the relative importance of the predictors: in particular, environmental taxation, consumption-based emissions, and production-based emissions greatly contribute to determining the variation of combustible renewables and waste. This study recommends that EU countries establish monitoring mechanisms to advance waste management and environmental sustainability through green technology adoption, enhance environmental taxation policies, and accelerate the renewable energy transition.

1. Introduction

Incineration is crucial to modern waste management and energy generation due to its many benefits. Incineration reduces landfill use and environmental implications by efficiently transforming non-recyclable garbage into energy (UNEP, 2022; Trinh and Chung, 2023). It diversifies energy sources, reduces dependence on fossil fuels, and generates constant electricity and heat, improving energy security (IPCC, 2019; European Commission, 2020). Its application within sustainable waste management and energy programs must be balanced and well-regulated to address air quality and public perception issues.

Moreover, incineration plays a relevant role in sustainable development in the EU and its member countries. It helps make trash management more efficient and increases landfill lifespans, supporting the European Union's (EU) circular economy (CE) aims. Additionally, it reduces greenhouse gas emissions, particularly landfill methane, and boosts energy security by generating reliable, sustainable energy. Incineration also supports recycling and EU waste management goals by enhancing resource efficiency. Furthermore, it reduces the environmental impact of garbage disposal, improving air and water quality in heavily populated EU cities. Thus, incineration becomes a multipurpose instrument that supports EU sustainability goals, while the historical status of incineration is reflected in Fig. 1.

Environmental technologies and tariffs are crucial to incineration, defining EU waste management and energy generation. Environment-related technologies include many advancements that reduce environmental effects and promote sustainable development. These methods improve incineration efficiency and prevent environmental damage. Advanced emissions control systems reduce incineration air pollutants, meeting EU emissions regulations. Waste sorting and pre-treatment systems optimize waste streams to incinerate only eligible waste and separate recyclables. Energy recovery and cogeneration systems

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maximize thermal energy from burning, improving incineration efficiency. Real-time monitoring and control systems help operators improve performance, minimize emissions, and comply with environmental laws. New waste-to-chemicals and recycling technologies decrease waste and promote a circular economy (CE) (Yu et al., 2022).

Environmental taxes, on the other hand, encourage responsible environmental behavior and fund environmental activities. These EU taxes influence incineration. Carbon taxes and emissions trading programs stimulate greener energy generation and emissions reduction in incineration operations. Landfill taxes divert waste from landfills to incineration. Energy taxes affect the economic viability of incineration facilities, which may influence energy source choice. Waste disposal taxes and levies impact waste management decisions, making incineration more appealing than landfill disposal. Optimizing the environmental and economic outcomes of incineration requires the harmonious integration of environmental technologies and taxes to reduce the environmental footprint and promote responsible waste management and a circular, low-carbon economy in the EU area (Saqib et al., 2023).

In the EU, the interplay among environmental technology, taxes, carbon emissions, and incineration is critical to waste management policies. Advances in environmental technology, such as improved filtration systems and waste-to-energy technologies, have been instrumental in reducing the environmental impacts of incineration facilities across the EU (European Commission, 2019). Additionally, the EU has implemented various taxation measures and carbon pricing mechanisms to incentivize the adoption of cleaner incineration practices and mitigate carbon emissions (European Environment Agency, 2020). These policies aim to internalize the external costs associated with pollution and carbon emissions, encouraging incineration facilities to invest in pollution control technologies and explore alternative waste management strategies (European Parliament, 2021).

Expanding on the previous discussion, the complex link between production-based and consumption-based carbon emissions for incineration highlights the complexity of analyzing waste-to-energy environmental implications. Advanced emissions control technologies make incineration a production-based option with fewer greenhouse gas (GHG) emissions (Rehman et al., 2022). However, incineration emits emissions, and the carbon footprint must include indirect emissions from waste transportation, facility construction, maintenance, and residue management (Magazzino, 2023).

In contrast, consumption-based carbon emissions cover the complete product lifecycle and emissions. This approach recognizes that trash generation, collection, and management are interconnected with consumption patterns and the complex supply chains that drive product and service production. Incinerating garbage instead of landfilling or recycling is only one part of the carbon footprint calculation. A complete consumption-based emissions assessment must include carbon emissions from incineration residue transportation and disposal. Thus, an exhaustive carbon impact evaluation of incineration must consider both direct emissions and the waste's lifecycle carbon footprint. This realization highlights the connection between waste management, consumption patterns, and environmental impacts and is important for developing comprehensive waste management policies and sustainable energy strategies.

The impact of environmental technology, taxes, and carbon emissions on incineration is a topic of significant interest and importance in the realm of waste management and environmental sustainability. Environmental technology encompasses a range of innovative solutions aimed at mitigating the negative environmental impacts associated with incineration processes. Advanced filtration systems, such as electrostatic precipitators and baghouses, are utilized to capture particulate matter and harmful pollutants emitted during combustion, thereby minimizing air pollution and improving overall air quality (Akmal et al., 2023a; Ponce et al., 2023). Additionally, technologies like scrubbers and catalytic converters play a crucial role in reducing the release of toxic gases and GHG emissions, contributing to the overall environmental sustainability of incineration facilities (Wang et al., 2022).

Moreover, the implementation of taxes and carbon pricing

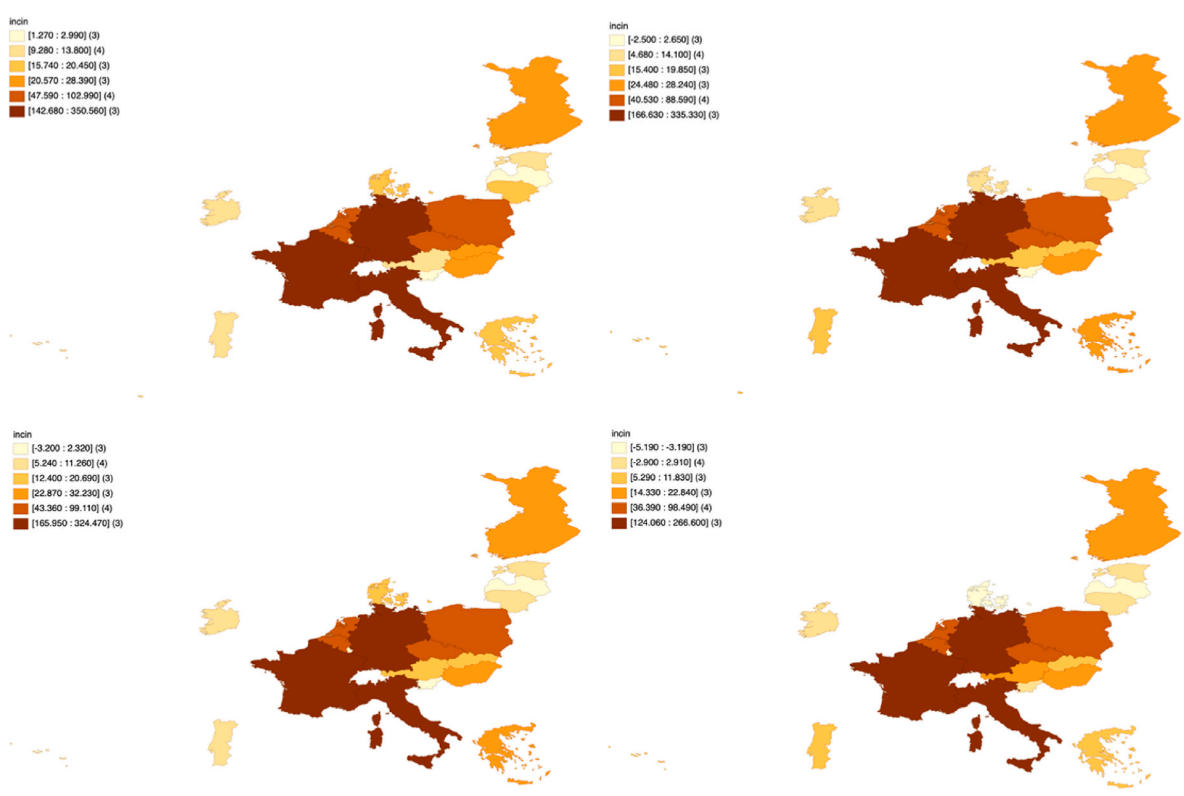

Fig. 1. Transition in incineration (1990, 2000, 2010, and 2022).

mechanisms serves as a powerful economic tool to incentivize the adoption of cleaner incineration technologies and practices. Taxes levied on waste disposal and carbon emissions impose financial penalties on industries engaging in environmentally harmful activities, encouraging them to invest in more sustainable alternatives (Yang et al., 2020). By internalizing the external costs associated with pollution and carbon emissions, such fiscal measures create economic incentives for businesses to transition towards greener waste management practices, including the adoption of advanced incineration technologies equipped with pollution control measures (Attrah et al., 2022).

Carbon emissions are a significant concern in the context of incineration, as the combustion of waste materials releases CO_2 into the atmosphere, contributing to global warming and climate change. Carbon pricing mechanisms, such as cap-and-trade systems or carbon taxes, provide a market-based approach to addressing these emissions by assigning a monetary value to carbon emissions and incentivizing reductions (Zhang et al., 2024). Incineration facilities can mitigate their carbon footprint by investing in cleaner energy sources, implementing energy-efficient technologies, and exploring carbon capture and storage options to sequester CO_2 emissions generated during the combustion process (Desport and Selosse, 2022). Furthermore, carbon pricing mechanisms encourage incineration facilities to explore alternative waste management strategies, such as recycling and composting, which have lower carbon emissions and environmental impacts (Akmal et al., 2023b).

This paper makes a significant contribution to the field of environmental sustainability and waste management, particularly within the context of the EU climate change initiatives. By extending the analysis to include advanced econometric techniques such as cointegrating regressions, panel quantile estimations, and the innovative Dumitrescu-Hurlin causality test, the study provides a nuanced understanding of the long-term equilibrium relationships between variables and the directionality of causal interactions. The incorporation of several Machine Learning (ML) techniques further distinguishes this research, offering a predictive edge and uncovering non-linear patterns and complex interactions that conventional models might overlook. In fact, only a few studies used Artificial Intelligence tools to investigate this topic.

The comprehensive temporal span of the study, covering data from 1990 to 2022, allows for a detailed examination of trends and shifts in waste management practices and their implications for EU policy and sustainability goals. By utilizing the Method of Moments Quantile Regression (MMQR), the research offers a granular view of the EU's progress in reducing reliance on incineration, highlighting the varying degrees of commitment across member states and emphasizing the need for tailored strategies that consider local consumption patterns and circumstances. The findings underscore the determination of EU nations to transition towards greener technologies and enhance environmental taxation policies, reflecting a strategic alignment with the bloc's overarching sustainability objectives. The recommendation for establishing robust monitoring mechanisms paves the way for more informed and effective policy-making, ensuring that advancements in green technology and renewable energy transitions are leveraged to their fullest potential in the pursuit of environmental sustainability within the EU.

The remainder of the study proceeds as follows. Section 2 reviews the literature and categorizes knowledge to build a solid theory. Section 3 describes the empirical methods: MMQR, Feasible Generalized Least Squares (FGLS), Panel-Corrected Standard Errors (PCSE), Canonical Cointegrating Regression (CCR), Dynamic Ordinary Least Squares (DOLS), Gradient Boosting (GB), and Extreme Gradient Boosting (XGBoost) models. Section 4 presents the research findings, revealing complex interactions across factors for EU member states. Section 5 discusses the results and their implications using real-world case studies. Section 6 concludes by summarizing significant insights, emphasizing the seriousness of waste management concerns, and highlighting the research's contributions to the EU sustainability initiatives.

2. Literature review

2.1. *Eco-friendly waste-to-energy*

The interaction between technology, renewable energy supply, and incineration in EU countries is complex and far-reaching in waste management and energy generation. Recent research has revealed the dynamic interactions between these variables, showing a range of potential challenges and opportunities for sustainable waste-to-energy solutions. Zohbi (2023) explained how technology might alter incineration: automation and digitalization have increased trash sorting and pre-treatment efficiency. These advances have improved incineration, increasing material recovery and reducing trash volumes. Thus, incineration becomes a more sustainable and resource-efficient EU waste management solution.

Additionally, Bindra and Kulshrestha (2019) highlighted the symbiotic interaction between incineration and renewable energy. They showed the successful integration of incineration facilities with renewable energy sources like wind and solar through EU case studies. This collaboration reduces GHG emissions and promotes incineration as a sustainable energy source. Incineration matches the EU's sustainability framework because it can dispose of trash and generate clean energy. Trinh and Chung (2023) emphasized renewable energy integration for sustainable waste-to-energy facilities. They examined this kind of integration, focusing on incineration's crucial role in sustainable practices. The findings highlight the benefits of such integration, making incineration a sustainable waste management strategy. Recent literature shows how technology and renewable energy integration have favored EU incineration. Al-Shetwi (2022) emphasizes the importance of technology in sustainable waste-to-energy solutions, particularly incineration. Their assessment clarified the importance of these improvements in enhancing incineration efficiency and environmental performance.

In addition, Sakhuja et al. (2021) placed incineration within a CE framework, highlighting the synergy between waste-to-energy practices like incineration and renewable energy sources. This supports the premise that incineration can help EU countries implement circular and sustainable waste management policies. These findings are in line with Trinh and Chung (2023), who conducted a comprehensive evaluation of renewable energy integration for sustainable waste-to-energy facilities. This relies on incineration, which can improve energy efficiency and environmental sustainability.

These studies guide us toward more sustainable and effective garbage management by providing a comprehensive plan for balancing technology, renewable energy, and incineration for EU sustainability. This integrated method solves today's waste management problems and meets EU sustainability goals, making EU countries more environmentally friendly and sustainable.

2.2. *Greening waste management through taxation*

Recent research provides a multidimensional view of environmental taxation, production-based CO_2 emissions, and incineration in EU waste management and sustainability efforts. These findings illuminate waste management sustainability and advise policymakers and stakeholders. Abbasi et al. (2022) showed that carbon pricing incentives reduce incineration facility emissions. Carbon prices cut GHG emissions and promote investment in greener technology. Incineration is an environmentally friendly waste-to-energy solution because economic incentives match ecological goals.

Meanwhile, the U.S. Department of Energy (2021) suggested that incineration practices may help reduce heavy industry production-based CO_2 emissions, showing how strict emissions laws and clean industrial processes support incineration's emissions reduction aims. This confluence encourages EU sustainability and holistic thinking. In contrast, Briguglio (2021) warned against excessive environmental charges, especially landfill levies, suggesting that these policies may encourage illegal garbage disposal, which could make legal waste-to-energy options like incineration unviable. This study emphasized the necessity for sophisticated environmental taxation policies that encourage sustainable waste management without promoting destructive activity. Danish and Erdogan (2022) analyzed the effects of nuclear energy on production-based and consumption-based CO_2 emissions for the Organization for Economic Co-operation and Development (OECD) countries. The empirical findings show that nuclear energy is beneficial for the decrease of production-based CO_2 emissions. Moreover, the globalization process tends to reduce both production-based and demand-based carbon emissions. Khan et al. (2021) investigated the long-term determinants of carbon emissions in 19 EU countries. The findings illustrate that clean energy, technology, and environmental taxes contribute to controlling emissions.

In addition, Abbasi et al. (2022) examined the creation of efficient environmental tax policies, stressing the relevance of well-structured tax incentives in promoting waste-to-energy technologies and cleaner incineration. This intentional alignment of taxation with sustainability goals promotes incineration as an eco-friendly waste management alternative. In the same vein, Gupt (2023) examined expanding producer responsibility with environmental taxation. The analysis showed that expanding producer responsibility schemes can complement carbon levies by encouraging product design that streamlines incineration and decreases waste carbon emissions. The synergy supports incineration as an eco-friendly waste management method.

Breeze (2018) and the European Commission (2013) explored the real-world effects of environmental tax measures. Breeze (2018) discussed how landfill taxes shift garbage from landfills to waste-to-energy alternatives like incineration. In line with EU sustainability goals, the European Commission (2013) recommended well-implemented tax adjustments to encourage incineration operations to adopt cleaner technologies. Also, Wurzel (2021) analyzed how environmental taxation affects EU member state waste-to-energy technology uptake, including incineration. According to the results, incineration as a sustainable waste management approach in progressive tax countries has increased significantly.

Finally, Achinas et al. (2022) studied environmental taxation, CE concepts, and waste-to-energy technology. The analysis implies that taxation can encourage circular practices, enabling incineration's crucial part in EU sustainable waste management initiatives. Recent research evaluations show the complex link between EU environmental taxation, production-based CO_2 emissions, and incineration. These studies emphasize the need for well-crafted regulations that encourage incineration as a sustainable waste-to-energy alternative while minimizing risks and unintended consequences. This research provides critical insights and a holistic view for policymakers and stakeholders navigating waste management and environmental sustainability.

2.3. Urbanization, consumption-based emissions, and incineration

Within the EU, the sustainability of incineration as a waste management strategy is influenced by a complex interplay of factors, including consumption-based CO_2 emissions and the dynamics of urban migration. Recent literature reviews collectively provide a comprehensive perspective on how these intertwined variables shape the role of incineration in sustainable waste management and energy generation.

Consumer behavior plays a pivotal role in waste generation, and the European Environment Agency (2022) highlighted the potential of informed consumer choices to reduce waste generation. The research demonstrates that environmentally conscious consumer behavior can foster an environment conducive to favoring incineration within a holistic waste management framework. Efficient waste collection and management infrastructure are crucial, especially in rapidly urbanizing areas, as raised by Peng et al. (2020), who underscored that well-designed waste-to-energy solutions, including incineration, are essential tools for mitigating the challenges associated with urban migration. These solutions reduce the burden on landfills and promote sustainable waste management practices in urban regions.

However, the increased waste generation resulting from urban migration can strain existing incineration facilities, as noted by Vargas López and Flores-García (2023). This perspective highlights the necessity of proactive planning and investments in waste management infrastructure to ensure that incineration remains a viable and sustainable option, particularly in the context of urbanization-related waste challenges. Moreover, eco-labeling can influence consumer behavior and waste generation patterns, as highlighted by Reddy and Ellis (2020), who underlined the potential of well-structured eco-labeling schemes to drive environmentally conscious consumption, thereby reducing waste and supporting incineration as an eco-friendly waste management solution. The dynamics of urbanization, migration, and waste management infrastructure are intricately linked, as discussed by Wong (2022). Integrated waste collection systems are critical in urban areas experiencing population growth, aligning with principles of efficient waste disposal and sustainable energy generation through incineration. Anticipating and addressing the challenges posed by urban migration is essential, as presented by the US Environmental Protection Agency (2023), which stressed the importance of being prepared for increased waste disposal demands, potentially requiring the expansion or construction of new incineration facilities.

This study's findings and EU environmental conditions drive the research aims. First, the study examines how environmental technology development affects EU incineration practices to assess if countries investing in green technologies reduce their use of incineration. The paper then investigates how environmental taxation policies affect incineration rates, particularly whether higher taxes stimulate incineration as a sustainable waste management method. The research also inspects the transition to renewable energy and incineration rates to determine if sustainability goals are met by increasing renewable energy use. Additionally, the study analyzes the relationship between production-based carbon emissions and incineration to determine if countries with higher industrial emissions favor incineration, highlighting the challenges of balancing emissions management and efficient waste disposal. Finally, the study explores the complex relationship between consumer-based carbon emissions and incineration to determine whether EU waste management decisions are influenced by consumption. This emphasizes the necessity for specialized waste management systems that accommodate various circumstances, promoting EU environmental sustainability.

3. Materials and methods

In this section, we elucidate the methodological framework underpinning a comprehensive analysis of EU countries' waste management and environmental sustainability. The variables of interest (*Incineration, Development of environment-related technology, Environment-related tax, Renewable energy supply, Production-based CO_2, Consumption-based CO_2, and Urban migration*) and their measurements are summarized in Table 1. Leveraging the quantitative power of panel data, we employ a multifaceted approach together with several diagnostic tests: thus, the MMQR, FGSL, and PCSE regression models are performed. In what follows, we detail each facet of our methodology, emphasizing the rationale for its selection and its relevance in addressing the complexities of the research focus.

First, we consider the development of environmentally related technology, recognizing that technological advancements can drive changes in waste management strategies. Countries actively investing in green technologies often witness a shift away from incineration. Recent studies have highlighted the positive impact of technology development on reducing incineration rates (Burman et al., 2022). Innovative recycling technologies, for instance, have made recycling more efficient and cost-effective, diverting waste from incineration (Imran et al., 2020; Harris and Roach, 2021).

Table 1
Data definitions and sources.

Variables	Measurement	Source
Incineration, *I*	Combustible renewables and waste (% of total energy)	World Development Indicators (2023)
Development of environment-related technology, *DET*	Development of environment-related technologies (% all technologies)	
Environment-related tax, *ET*	Environment-related taxes (% GDP)	
Renewable energy supply, *RES*	Renewable energy supply (% total energy supply)	
Production-based CO_2 emissions, *PCO2E*	Tonnes, Millions	
Consumption-based CO_2 emissions, *CCO2E*	Tonnes, Millions	
Urban migration, *UM*	Net migration, per 1000 inhabitants	

Another critical aspect that our analysis takes into account concerns environmentally related taxes. Environmental taxation policies have emerged as powerful tools in promoting eco-friendly waste management practices. Imposing higher taxes on waste disposal can incentivize industries and individuals to adopt recycling and waste reduction strategies. Research underscores the effectiveness of taxation policies in influencing waste management decisions (IMF, 2019). Furthermore, the role of renewable energy supply in waste management practices is also investigated. The transition to renewable energy sources is integral to sustainable development. Recent studies emphasize the positive relationship between renewable energy adoption and reduced GHG emissions. As renewable energy becomes more prevalent, the environmental benefits associated with reduced incineration are expected to increase (Kovač et al., 2021; Sovacool et al., 2021).

Industrial emissions are closely tied to waste management practices: production-based CO_2 emissions are another key variable in the analysis. High industrial emissions may necessitate more rigorous waste disposal methods, such as incineration, to mitigate environmental impacts. However, there is growing evidence that industries can reduce emissions through cleaner production methods and emissions-reduction technologies, which can lead to reduced reliance on incineration (Haar, 2020; Kim et al., 2022). The significant influence of consumption-based CO_2 emissions on waste generation cannot be neglected. As EU countries address the consumption environmental footprint, waste management choices are evolving; mixed relationships between consumption-based emissions and incineration rates highlight the need for context-specific waste management strategies. The literature on this topic highlighted the importance of addressing consumption-based emissions to achieve sustainability goals (Wiedmann et al., 2020; Xu et al., 2023).

Lastly, the process of urban migration continues to shape waste management dynamics; urban areas often produce more waste but also offer opportunities for efficient recycling and waste reduction programs. The impact of urban migration on waste management choices varies across EU member states, necessitating tailored strategies. Urban planning plays a crucial role in promoting sustainable waste management in cities (Imran et al., 2022b; Xu et al., 2023).

$$\begin{aligned} &\textit{Incineration} = f(\textit{Development of environment} \\ &\quad - \textit{related technology}, \textit{Environment} \\ &\quad - \textit{related tax}, \textit{Renewable energy supply}, \textit{Production} \\ &\quad - \textit{based CO2}, \textit{Consumption} - \textit{based CO2}, \textit{Urban migration}) \end{aligned} \tag{1}$$

By incorporating these variables into Equation (1) and drawing on relevant literature, the methodology provides a comprehensive understanding of the factors influencing incineration rates in EU countries. This approach aligns with the study's objective of offering actionable insights for enhancing waste management and environmental sustainability efforts in the EU area.

3.1. Econometric strategies

The preliminary stage of this study entails a rigorous implementation of the methodological structure depicted in Fig. 2, starting the analyses with the slope heterogeneity test, as per the well-established framework put forth by Pesaran (2007). This test concerns the consistency of data distribution. Furthermore, our analytical approach incorporates several tests as delineated in Pesaran (2014) and the comprehensive research conducted by Hsiao et al. (2011). These critical examinations are strategically employed to discern any discernible variations in slope coefficients among the designated variables, a cornerstone of the empirical analysis.

In addition, the research performs a cross-sectional independence test, following Pesaran (2014). This entails a comprehensive examination of the dataset for latent anomalies or irregularities. Subsequently, panel data stationarity tests are run.

Quantile regression offers distinct advantages over Ordinary Least Squares (OLS). Instead of solely focusing on the mean value, as OLS does, quantile regression allows us to estimate various quantiles. We can examine not only the median effect but also the 25th, 50th, 75th, and 90th percentiles. This versatility is crucial when exploring the relationship between the selected variables and waste management strategies in EU countries, given the diverse impacts these variables may have. The quantile regression framework, initially introduced by Koenker and Bassett (1978) and refined by Koenker and Hallock (2001), does not assume a specific distribution for the data, a flexibility highlighted by Belaïd et al. (2020), especially when dealing with variables that may not follow a normal distribution.

Cointegrating regressions, including Canonical Cointegrating Regression (CCR) and Dynamic Ordinary Least Squares (DOLS), along with Dumitrescu-Hurlin causality analysis, are crucial methodologies in econometrics for analyzing long-run relationships and causality between time series variables that are integrated of the same order. CCR was developed as a statistical inference procedure in cointegrating regressions, where the method involves transforming integrated processes using stationary components within cointegrating models. This transformation allows the application of the usual Least Squares procedure to yield asymptotically efficient estimators and chi-square tests, applicable to a wide class of cointegrating models (Park, 1992).

DOLS enhances the estimation of cointegrated systems by introducing leads and lags of the differenced independent variables, addressing the issue of serial correlation and endogeneity in the cointegrating relationship. This approach has been shown to offer superior performance in terms of bias and efficiency in finite samples compared to other estimators (Montalvo, 1995).

The Dumitrescu-Hurlin panel causality test is a nonparametric approach to test for causality in panel data models. This test is particularly useful for identifying the direction of causality between variables in panel settings, accommodating cross-sectional dependence and heterogeneity among the units (Dumitrescu and Hurlin, 2012).

Therefore, this study employs advanced techniques to accommodate the nuanced nature of our data. By examining various quantiles, we gain a more comprehensive perspective on how these selected variables impact waste management strategies in EU countries. This approach allows us to explore the complex relationships within the data, providing a more profound understanding of the dynamics at play in waste management and environmental sustainability.

3.2. Robustness analyses

FGLS and PCSE regression estimates are presented for robustness. FGLS estimator, designed to account for cross-sectional error interdependence, incorporates cross-section averages of regressors, the response variable, and their corresponding lags (Farebrother, 2018). The inclusion of PCSE estimates holds significant value in the context of panel data analysis, particularly in addressing challenges like

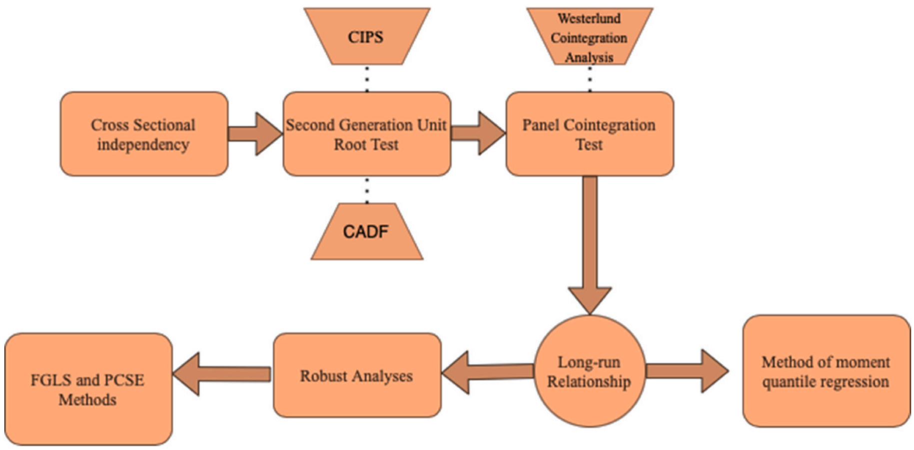

Fig. 2. Methodological framework.

heteroscedasticity and serial correlation. PCSE achieves this by refining the Standard Errors of the coefficients, controlling for the inherent correlation structures within panel data. This adjustment substantially enhances the precision of estimations and the credibility of hypothesis testing. Bailey and Katz (2011) provided compelling validation of the efficacy of the PCSE methodology. Here, PCSE is thoughtfully integrated alongside the MMQR and FGLS model, emphasizing the commitment to conducting a comprehensive and resilient analysis of intricate data dynamics (Fomby et al., 1984).

ML ensemble methods such as GB and XGBoost have significantly contributed to the field of machine learning by improving prediction accuracy through the combination of multiple models. GB is an ensemble technique that builds models sequentially, where each new model attempts to correct errors made by previous models. This method has been widely used in various applications, demonstrating its effectiveness in improving predictive performance.

XGBoost, which is an extension of GB, was designed to be more efficient, flexible, and portable. XGBoost has gained popularity due to its speed and performance and has been used successfully in numerous ML competitions. It improves on the GB model through the use of more sophisticated regularization (L1 and L2), which helps to prevent overfitting and improves model performance. XGBoost also handles missing values internally, providing a robust solution to a common problem in data preprocessing. Both GB and XGBoost operate by constructing new models that predict the residuals or errors of prior models and then combining these models during the prediction phase. This process creates a strong model from a collection of weaker models, leading to improved accuracy on complex datasets.

Research and applications across different domains validate the effectiveness of these ensemble methods. For instance, XGBoost has been applied to supervised outlier detection, combining the strengths of both supervised and unsupervised learning methods for enhanced performance in detecting outliers (Zhao and Hryniewicki, 2018). Furthermore, ensemble methods have been applied to evolving data streams, where XGBoost's adaptability to changing data distributions has been explored, showing promising results in maintaining high predictive accuracy over time (Montiel et al., 2020).

4. Results and discussion

The box plot analysis provides a succinct overview of the distribution characteristics for a range of variables, indicating variability and skewness across the dataset. Several variables exhibit a right-skewed distribution, as evidenced by medians positioned closer to the lower quartile and the presence of outliers, particularly for *I*, *CCO2E*, *PCO2E*, and *UM*, suggesting a concentration of lower values with sparse extreme higher values. Conversely, *DET* and *RES* show more symmetric distributions with outliers that signify occasional but significant deviations from central tendencies. The widespread presence of outliers across these variables underscores the need for careful consideration in statistical analysis, as they may represent influential data points or require specialized treatment to avoid distorted analytical outcomes.

The scatterplot matrix presented in Fig. 3 provides a comprehensive visualization of the pairwise relationships among the six variables of interest. The plots reveal varying degrees of correlation, with some pairs exhibiting a discernible linear relationship, suggesting potential direct or inverse proportionality, while others show more complex patterns that could imply non-linear associations or the absence of a significant relationship. It is notable that the distribution of data points within some plots indicates potential outliers or clusters, which could be indicative of underlying subgroups or exceptional cases within the dataset. The absence of clear patterns in certain plots suggests that some variables do not influence each other strongly, or that their relationship may be affected by other factors not captured in this two-dimensional view.

The slope heterogeneity test results for EU countries indicate statistically significant differences in the slopes of the tested variables, with both delta and adjusted delta statistics being highly significant, soundly rejecting the null hypothesis of homogeneity (Table 2). This suggests that the relationships under investigation vary significantly among the EU countries, emphasizing the need to consider country-specific factors when assessing waste management and sustainability practices. In summary, the results highlight substantial heterogeneity across the EU in how these relationships are expressed, underscoring the importance

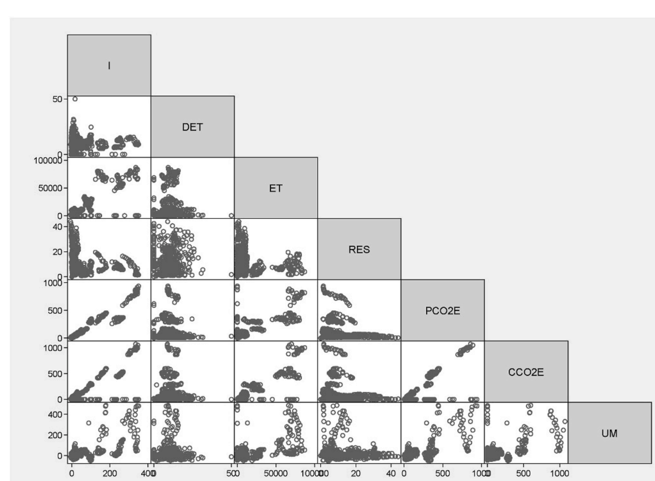

Fig. 3. Scatterplot matrices.

Table 2
Slope heterogeneity test results.

Delta	23.121	Adj. Delta	26.564
P-Value	0.000	P-Value	0.000

of tailored approaches to address waste management and sustainability challenges within each country.

Table 3 shows the results of several cross-sectional independence tests. The findings indicate significant associations between all the variables, highlighting their interconnectedness. Notably, *ET* and *PCO2E* exhibit strong positive correlations, emphasizing their interdependence. These results shed light on the importance of considering these interrelated factors.

In general, these tests unanimously highlight the statistical significance of relationships among the variables in EU countries. The consistently low P-Values strongly suggest that these variables are interconnected.

Table 4 presents the results of two different panel unit root tests (CADF and CIPS), applied to assess the stationarity of the variables. According to the CADF test results, *I*, *ET*, *RES*, *PCO2E*, and *CCO2E* exhibit non-stationarity at levels, suggesting the presence of trends that may require differencing to achieve stationarity. Conversely, *DET* and *UM* demonstrate stationarity at levels. The CIPS test roughly confirms these findings, reaffirming that most variables are non-stationary at the level but become stationary at the first difference. This distinction informs subsequent time series analyses and modelling, highlighting which variables need to be differenced to attain stationarity and reinforcing the robustness of the analytical framework.

Table 5 gives the results of the Westerlund (2007) cointegration test. The test evaluates the presence or absence of cointegration among these variables under the null hypothesis. Notably, *Gt* and *Pt* statistics exhibit low P-Values, indicating the presence of a long-term relationship among the variables. On the other hand, *Ga* and *Pa* statistics suggest the absence of cointegration (the null hypothesis is not rejected). These findings highlight the need for a more nuanced examination of certain relationships.

Table 6 presents the outcomes of the cointegrating regressions. The results indicate that the variable *DET* is negatively associated with the dependent variable in both models, while *ET* shows a positive and highly significant relationship in both models. On the other hand, *RES* is not statistically significant in the CCR model but is negatively significant in the DOLS model. Both *PCO2E* and *CCO2E* exhibit significant relationships with incineration, except for *CCO2E* in the DOLS estimates. Finally, *UM* is significant and negative. The high R-squared values indicate a good fit. Therefore, the development of environment-related technologies, renewable energy supply, consumption-based emissions, and urban migration exert a negative effect on incineration.

The empirical findings using CCR and DOLS estimators find support in the literature through studies that examine the impact of technological advancements on emissions reduction. Chen and Lee (2020) explored the impact of technological innovation on CO_2 emissions across 96 countries, highlighting the role of technological advancements in reducing emissions. Similarly, Erdoğan (2021) investigated the effects of technological innovation on carbon emissions within the building sector in BRICS countries, demonstrating how increased technological innovation contributes to emissions reduction. These studies corroborate the significant role of technological development in environmental sustainability and emissions reduction efforts.

Table 7 reports the MMQR findings. In general, the estimated signs are in line with those obtained through cointegrating regressions, for each regressor. The location-based MMQR estimates provide valuable insights into the region's environmental and waste management initiatives. The negative association between environmental technology and incineration indicates that nations investing in advanced green technologies may be gradually reducing their reliance on incineration for waste disposal (Zohbi, 2023). This aligns with the EU's goals for sustainable and innovative waste management. Countries with higher environmental fees encourage incineration as a waste management strategy and promote environmental responsibility, supporting the EU's taxation plan to promote sustainable, eco-friendly economic practices.

The negative relationship between renewable energy supply and

Table 3
Cross-sectional independence test.

Variables	CD test	P-Value	Mean ρ	Mean abs. (ρ)
I	48.734	0.000***	0.62	0.63
DET	46.171	0.000***	0.58	0.58
ET	71.501	0.000***	0.90	0.90
RES	69.77	0.000***	0.88	0.88
PCO2E	58.531	0.000***	0.74	0.74
CCO2E	77.553	0.000***	0.98	0.98
UM	5.943	0.000***	0.08	0.32
Pesaran	7.333	0.000***		
Pesaran abs. (Average absolute value of the off-diagonal elements)	7.333 (0.462)	0.000***		
Frees	4.527	0.000***		

Notes: ***p < 0.01, **p < 0.05, *p < 0.10.

Table 4
Unit root tests in heterogenous panels with cross-section dependence test results.

Variables	CADF		CIPS	
	I (0)	I (1)	I (0)	I (1)
I	−2.357 (0.465)	−4.336*** (0.000)	−2.912***	−5.626***
DET	−3.747*** (0.000)	−5.441*** (0.000)	−5.504***	−6.420***
ET	−1.990 (0.962)	−3.142*** (0.000)	−2.209	−4.982***
RES	−1.931 (0.981)	−3.957*** (0.000)	−2.195	−5.569***
PCO2E	−2.660* (0.052)	−4.294*** (0.000)	−2.917***	−5.344***
CCO2E	−2.353 (0.474)	−3.918*** (0.000)	−2.431	−5.158***
UM	−1.657 (1.000)	−2.569 (0.123)	−1.904	−3.099***

Notes: Critical Values for CIPS test: 10%: −2.63; 5%: −2.71; 1%: −2.85.

Table 5
Westerlund cointegration test results.

Statistic	Value	Z-Value	P-Value
Gt	−3.261	−3.661	0.000***
Ga	−12.535	0.709	0.761
Pt	−13.256	−3.142	0.001***
Pa	−11.664	−0.846	0.199

Notes: ***p < 0.01, **p < 0.05, *p < 0.10.

Table 6
Results of cointegrating regressions.

Variable	Cointegrating Regressions	
	CCR	DOLS
DET	−0.9302*** (0.2195)	−0.0577** (0.0275)
ET	0.0065*** (0.0006)	0.0002*** (0.0000)
RES	−0.1993 (0.3773)	−0.2617*** (0.0312)
PCO2E	0.1301*** (0.0463)	0.3108*** (0.0150)
CCO2E	−0.2914*** (0.0364)	−0.0403 (0.0520)
UM	−0.1398** (0.0597)	−0.0169*** (0.0035)
R^2	0.9671	0.9998
Adjusted R^2	0.9622	0.9993
SER	3.9689	2.2327
Long-Run Variance	3.8549	3.2710

Notes: Panel method: Weighted estimation. Long-Run covariance estimates (Prewhitening with lags from HQ max-lags = −1, Bartlett kernel, Newey-West fixed bandwidth). Automatic leads and lags specification based on AIC. SER: Standard Error of the Regression.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table 7
MMQR estimates.

Variable	Location	Scale	Q25	Q50	Q75	Q90
DET	−0.221**	−0.039	−0.190**	−0.211**	−0.242*	−0.284
	(0.104)	(0.083)	(0.082)	(0.092)	(0.136)	(0.215)
ET	0.001***	0.001***	0.001*	0.001***	0.001***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
RES	−0.247***	−0.041	−0.213***	−0.236***	−0.269***	−0.314***
	(0.052)	(0.041)	(0.041)	(0.046)	(0.067)	(0.107)
PCO2E	0.376***	0.044***	0.340***	0.364***	0.399***	0.446***
	(0.015)	(0.012)	(0.012)	(0.013)	(0.019)	(0.031)
CCO2E	−0.022	−0.040**	0.011	−0.011	−0.043	−0.087*
	(0.025)	(0.020)	(0.020)	(0.022)	(0.033)	(0.052)
UM	−0.019	−0.071***	−0.039**	0.001	−0.057*	−0.134**
	(0.025)	(0.020)	(0.020)	(0.0219)	(0.033)	(0.053)
Constant	2.155	4.480***	−1.515	0.928	4.536**	9.396***
	(1.449)	(1.156)	(1.167)	(1.306)	(1.923)	(3.016)

Notes: Robust Standard Errors in parentheses.
***p < 0.01, **p < 0.05, *p < 0.1.

incineration suggests that EU countries focusing on renewable sources may be using less incineration, reflecting the region's commitment to cleaner energy sources (Safi et al., 2021). However, the positive connection between production-based CO_2 emissions and incineration shows that some EU states struggle to reduce industrial emissions while improving waste management (Imran et al., 2022a). The scale-based MMQR analysis illustrates the complex interaction of environmental dynamics, technological advances, and waste management policies across quantiles. These findings demonstrate the significant diversity of EU member states' approaches to sustainable waste management and environmental goals (Khan et al., 2022). The negative link between environmental technology and incineration shows a constant and common commitment across quantiles to reduce dependency on incineration through emerging green solutions. This trend supports the EU's goal of eco-friendly waste management, environmental protection, and recycling (Kumar et al., 2022).

The scale-based link between environmental-related taxes and incineration is strong and consistent across quantiles. Environmental taxation regulations may have promoted incineration as an environmentally friendly waste management method throughout the countries. In keeping with the EU fiscal goal to promote sustainability, environmental taxes incentivize incineration.

The persistent negative association between renewable energy supply and incineration shows that this area is reducing its reliance on incineration across quantiles. This aligns with the EU's goal of switching to cleaner, more sustainable energy sources and reducing trash incineration. The scale-based positive link between production-based CO_2 emissions and incineration highlights a shared EU challenge, balancing industrial emissions management with efficient waste disposal. This complicated endeavor involves rigorous policy considerations to meet environmental goals and solve waste issues. The diversity in the scale-based link between consumption-based CO_2 emissions and incineration across quantiles highlights how consumption patterns affect waste management decisions in EU member states (Wahab et al., 2023). Due to recycling initiatives, rising consumption-based emissions may lower incineration. Some quantiles show a negative association. In other quantiles, the association is positive, suggesting waste management issues due to increased consumption-based emissions. These differences highlight the need for country-specific waste management plans that account for consumption, waste generation, and circumstances (Samour et al., 2022).

Moving to quantile-based results, the negative relationship between environment-related technology and incineration is consistent across all quantiles, highlighting EU countries' shared commitment to reducing their reliance on incineration by adopting innovative green technologies (Zohbi, 2023). The positive link between environment-related taxes and incineration highlights the role of environmental taxation policies in encouraging incineration as an environmentally responsible waste management strategy across quantiles. High environmental levies encourage incineration, supporting the EU's budgetary goal to promote green practices (Abbasi et al., 2022).

The negative coefficients for renewable energy supply across all quantiles show that incineration continues to diminish as renewable energy sources become more popular, supporting the EU's goal of switching to cleaner, more sustainable energy (Bindra and Kulshrestha, 2019). However, production-based CO_2 emissions and incineration are positively correlated across quantiles, showing that EU nations with larger industrial emissions use incineration more (Trinh and Chung, 2023). It is difficult to balance industrial emissions management with efficient waste disposal, a concern across EU member states.

In addition, consumption-based CO_2 emissions and incineration vary with quantile. A positive association suggests that increased consumption-based emissions may increase incineration due to waste generation (Chen et al., 2023). Other quantiles show a negative association, suggesting that some countries may be encouraging recycling and trash reduction to reduce consumption-based emissions. Urban migration and incineration also have positive and negative associations across quantiles. These differences demonstrate the necessity for EU member states to tailor waste management policies to their unique needs (Chen et al., 2023).

In conclusion, the MMQR analysis shows that EU countries are adopting ecologically friendly technologies and environmental taxation policies to reduce incineration. Renewable energy sources support the EU's environmental goals, however regulating industrial emissions and waste disposal is difficult. Consumption-based emissions, urban migration, and incineration have different linkages, highlighting the necessity for EU-specific waste management policies. Table 8 summarizes the Dumitrescu-Hurlin panel causality tests to determine causal

Table 8
Dumitrescu-Hurlin panel pairwise causality tests.

Null Hypothesis	*F* Statistics	P-Value
DET ⇏ I	4.9943	0.0071***
I ⇏ DET	0.8620	0.4228
ET ⇏ I	319.3825	0.0000***
I ⇏ ET	63.7580	0.0000***
RES ⇏ I	3.5254	0.0300**
I ⇏ RES	5.9334	0.0028***
PCO2E ⇏ I	2.6043	0.0748*
I ⇏ PCO2E	1.7011	0.1833
CCO2E ⇏ I	40.5892	0.0000***
I ⇏ CCO2E	24.5765	0.0000***
UM ⇏ I	2.3582	0.0954*
I ⇏ UM	10.1619	0.0000***

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

relationships among the variables in panel data. Notably, we discovered a unidirectional causality running from *DET* and *PCO2E* to *I*. On the other hand, a feedback mechanism, implying a bidirectional causality, exists between *ET* and *I*, *RES* and *I*, as well as *CCO2E* and *I*. Finally, incineration seems to Granger-cause urban migration.

Mele et al. (2022) assessed a link between the development of environmental-related technology and incineration. The existence of a feedback mechanism between environmental taxation and combustible renewables and waste is confirmed by Fang et al. (2022). Moreover, Puttachai et al. (2021) found a bidirectional causality between renewable energy and waste. While Magazzino and Falcone (2022) and Razzaq et al. (2021) showed a causal nexus between emissions and waste.

4.1. Robustness checks

The robust analyses conducted using FGLS and PCSE regression methodologies provide additional validation and insights into the relationships identified with MMQR analysis (Table 9).

First and foremost, both FGLS and PCSE regressions consistently confirm the negative relationship between the development of environmental-related technology and incineration. This finding underscores that EU member states, irrespective of the regression technique employed, have been actively adopting green technologies to promote sustainable waste management practices and reduce their reliance on incineration. This alignment with environmentally friendly technologies reflects the collective commitment of this area toward minimizing its environmental impact.

Similarly, the positive correlation between environmental-related taxes and incineration is consistently validated by both FGLS and PCSE methodologies. This robust relationship emphasizes the influential role of environmental taxation policies in incentivizing countries to choose incineration as a sustainable waste management solution. Higher environmental taxes consistently correspond with a greater inclination to opt for incineration, aligning with the EU's broader strategy of utilizing fiscal instruments to encourage eco-friendly practices.

Furthermore, both regression techniques reaffirm the negative relationship between renewable energy supply and incineration. As EU countries continue to adopt renewable sources, there is a sustained reduction in their reliance on incineration for waste management. This robust finding underscores the transformative potential of renewable energy adoption and its consistent impact on shaping waste management practices in line with the EU's sustainability goals (Table 9).

In conclusion, FGLS and PCSE regressions corroborate the key relationships previously identified with the MMQR estimator, providing robust evidence for the importance of adopting green technologies, aligning taxation policies, and transitioning to renewable energy sources. The findings also underscore the persistent challenge of managing industrial emissions alongside waste disposal. Moreover, the nuanced impact of consumption patterns on waste management choices, as highlighted by PCSE results, stresses the need for tailored policies that account for specific circumstances within individual EU member states.

Table 9
FGLS and PCSE estimates.

Variable	FGLS	PCSE
DET	−0.150***	−0.221***
	(0.008)	(0.083)
ET	0.001***	0.001***
	(0.000)	(0.000)
RES	−0.247***	−0.247***
	(0.005)	(0.042)
PCO2E	0.370***	0.376***
	(0.002)	(0.010)
CCO2E	−0.014***	−0.022**
	(0.002)	(0.010)
UM	−0.016***	−0.019
	(0.001)	(0.013)
Constant	1.613***	2.155**
	(0.123)	(0.947)
Wald χ^2	95653.42***	10779.17***
	(0.0000)	(0.0000)

Notes: Robust Standard Errors in parentheses.
***p < 0.01, **p < 0.05, *p < 0.1.

Finally, an ML experiment is conducted through ensemble methods to check previous empirical findings with a completely different methodology. The results from the GB and XGBoost models are shown in Table 10.

ML methods roughly confirm panel data estimates. However, both boosting models highlight the importance of a sub-set of regressors in influencing the dependent variable. In particular, GB and XGBoost's findings stress the relevance of consumption-based emissions, environmental taxes, and production-based emissions. The diagnostic metrics show the good performances of the models, with very high R-squared values and very low values for MSE, RMSE, and MAE. These findings align with those from past studies; de Barros Martins et al. (2023), Unegg et al. (2023), and Lee et al. (2018) assessed the impact of CO_2 emissions on incineration. In addition, De Weerdt et al. (2022) and Andretta et al. (2018) established a link among incineration, environmental taxation, and CE.

4.2. Discussion

The empirical results presented so far offer valuable insights into the nuanced dynamics of environmental factors, technology development, and waste management choices. These findings underscore the diverse strategies employed by EU member states in their pursuit of sustainable waste management and environmental goals.

4.2.1. Promoting green technologies: the case of Germany

Germany's exemplary waste management practices are rooted in its commitment to green technologies. The country's implementation of the Dual System for waste separation and recycling, where citizens are encouraged to separate recyclables from general waste, has been widely successful (Park, 2018). Moreover, the country's innovative technologies include advanced recycling facilities, waste-to-energy plants, and cutting-edge sorting systems, all contributing to reduced waste generation and minimized reliance on incineration (Zohbi, 2023). Furthermore, Fig. 4 highlights the practical application of technology-driven waste reduction in the EU countries, aligning perfectly with the results of previous estimates.

4.2.2. Leveraging environmental taxes: the Swedish success story

Sweden's use of environmental taxation policies to stimulate waste-to-energy practices has been a game-changer in sustainable waste management. The Swedish waste incineration tax, implemented in the 1990s, has driven a significant shift towards eco-friendly waste disposal.

Table 10
GB and XGBoost estimates.

Variable	GB	XGBoost		
	Importance Score	Gain	Cover	Frequency
CCO2E	46.3832	0.9047	0.2017	0.1304
ET	33.4761	0.0153	0.1538	0.1816
PCO2E	18.1804	0.0760	0.2035	0.1603
RES	0.7718	0.0005	0.1628	0.1620
DET	0.7491	0.0033	0.1155	0.2327
UM	0.4394	0.0002	0.1627	0.1330
MSE	0.0143	0.0039		
RMSE	0.1195	0.0625		
MAE	0.0737	0.0327		
R^2	0.9865	0.9965		

Notes: MAE: Mean Absolute Error; MSE: Mean Squared Error; RMSE: Root Mean Squared Error.

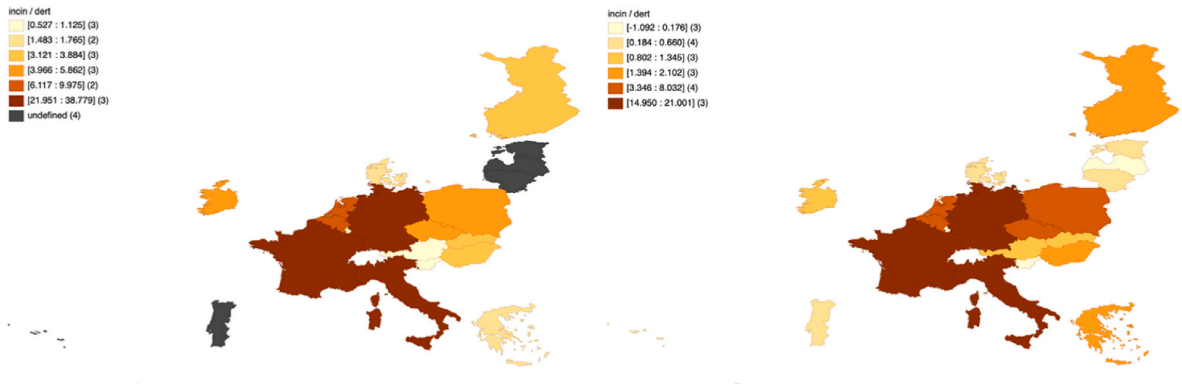

Fig. 4. The ratio of incineration to development of environmental-related technologies (1990–2022).

The tax incentivizes waste-to-energy solutions, contributing to the national impressive waste-to-energy capacity, which surpasses domestic needs and even includes waste imports for energy generation. Revenue generated from these taxes is reinvested in sustainability initiatives, creating a self-sustaining model for eco-friendly waste management (Magazzino et al., 2022). This real-world example demonstrates the transformative power of taxation policies in promoting sustainable waste management practices, reinforcing our analysis.

4.2.3. *Transitioning to renewable energy: the Dutch example*

The Netherlands' transition to renewable energy sources, particularly wind and solar power, has significantly reduced the carbon footprint associated with waste incineration (Nepal et al., 2021). The Dutch government's substantial investments in renewable energy infrastructure have not only cut greenhouse gas emissions but have also contributed to a decline in waste incineration rates (Bindra and Kulshrestha, 2019). Fig. 5 serves as a beacon for other EU countries looking to align their energy transition goals with waste management strategies. It illustrates how sustainability objectives can be interconnected and mutually reinforcing.

4.2.4. *Balancing industrial emissions: Belgium's dual challenge*

Belgium's experience exemplifies the complex interplay between industrial processes and waste management. The country's strong industrial base necessitates rigorous emissions management alongside effective waste disposal (Centre for American Progress, 2023). This dual challenge highlights the need for coordinated government policies, industry collaborations, and the implementation of best practices to achieve a balance between environmental protection and industrial growth. Fig. 6 underscores the importance of integrated approaches to address both emissions and waste disposal, an issue that resonates with many EU member states.

5. Conclusions and policy implications

The urgency of studying waste management and environmental sustainability in EU countries is underscored by the global imperatives of combating climate change and preserving our planet's resources. To address these complex challenges effectively, advanced methodologies have been employed, including the slope heterogeneity test, cross-sectional dependence test, second-generation unit root tests, panel cointegration tests, MMQR, FGLS, PCSE estimates, and ensemble ML algorithms. These methods explored the multifaceted nature of waste management and environmental factors in the EU area from 1990 to 2022.

The findings reveal a commitment to reducing reliance on incineration through the adoption of green technologies and environmental taxation policies, aligning with the EU's sustainable waste management goals. Conversely, the scale-based results highlight the diverse approaches employed across quantiles, emphasizing the collective reduction in incineration reliance, driven by green technology adoption and taxation policies. The consistent trend towards reducing incineration reliance aligns with the EU's transition to sustainable energy alternatives but poses a challenge in balancing industrial emissions with efficient waste disposal practices. The variable relationship between consumption-based emissions and incineration underscores the need for tailored waste management strategies that account for each country's unique circumstances and consumption patterns.

Furthermore, the study provides valuable insights into waste management choices across different quantiles through the MMQR. This approach unraveled nuanced and context-specific strategies employed by EU member states. Regardless of their specific quantiles, the findings reveal a collective commitment among EU countries to reduce reliance on incineration. Notably, countries actively developing environmentally related technology have been at the forefront of embracing innovative

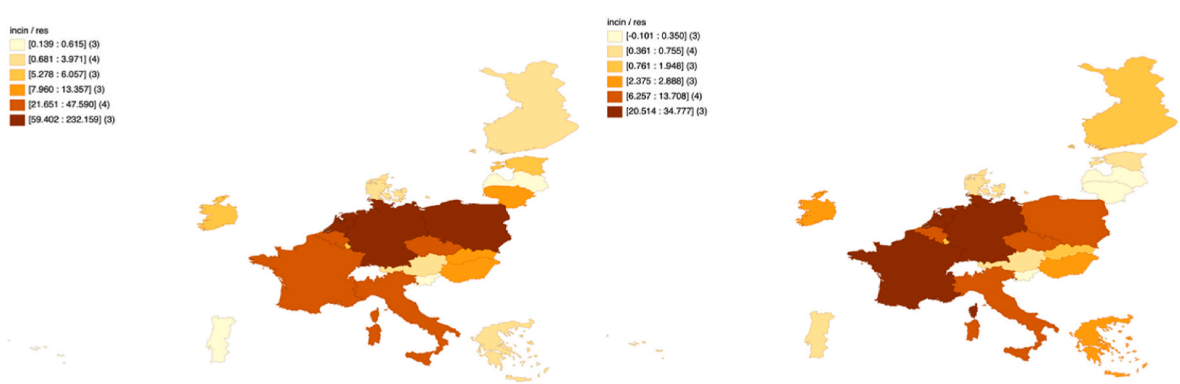

Fig. 5. The ratio of incineration to renewable energy supply (1990–2022).

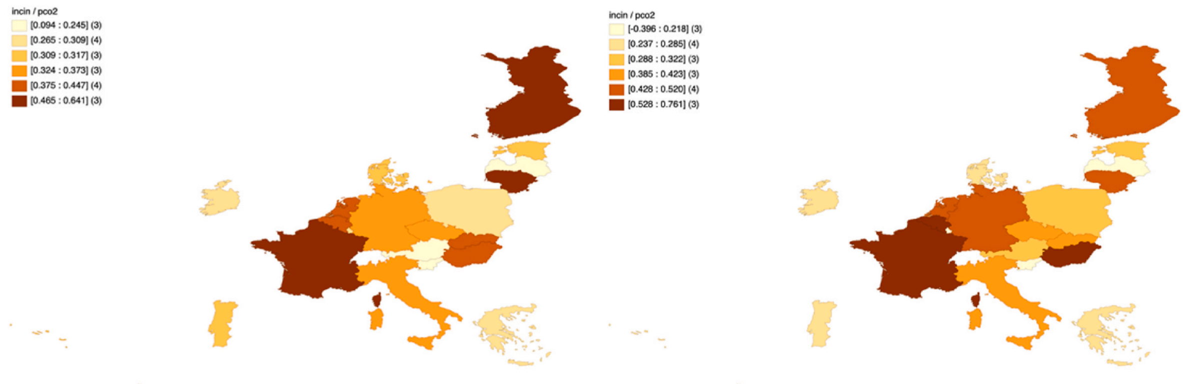

Fig. 6. The ratio of incineration to production-based CO_2 (1990–2022).

green technologies, showcasing the EU's dedication to eco-friendly waste management and reduced environmental impacts. The quantile-based results consistently emphasize this shared commitment to minimizing incineration through innovative technologies and environmental taxation policies. This signifies a broader transition towards cleaner and more sustainable energy alternatives while grappling with the challenge of balancing industrial emissions and waste disposal. The varied relationships observed between consumption-based CO_2 emissions, urban migration, and incineration across quantiles underscore the importance of customized waste management strategies tailored to the unique circumstances and goals of individual EU member states.

Cointegrating regressions (CCR and DOLS) highlighted the long-run relationship among the selected variables, while FGLS and PCSE estimates roughly confirmed MMQR results. In fact, all estimation methods highlighted that the development of environment-related technologies, renewable energy supply, consumption-based emissions, and urban migration exert a negative effect on incineration; on the contrary, environmental taxes and production-based emissions are found to negatively affect the dependent variable. Quantile regressions revealed that the effect of renewable energy supply, consumption-based emissions, and production-based emissions is more pronounced moving from lower to higher quantiles. ML analyses, conducted through two ensemble methods (GB and XGBoost) shed light on the relative importance of the predictors: in particular, consumption-based emissions, environmental taxation, and production-based emissions greatly contribute to determining the variation of combustible renewables and waste. Causality test results showed the inextricable link of incineration with environmental taxes, renewable energy supply, and consumption-based emissions, evidenced by a feedback mechanism.

Finally, this study sheds light on the paramount importance of sustainable waste management and environmental sustainability in the EU. Through robust empirical analyses, we unearthed a resounding commitment among EU nations to diminish their dependence on incineration, accomplished via the adoption of green technologies and environmentally conscious taxation policies. This concerted effort resonates with the EU's overarching goals of sustainable waste management. Conversely, the scale-based results accentuate the multitude of strategies employed across quantiles while reinforcing the collective push to reduce incineration. This aligns harmoniously with the EU's transition to cleaner energy alternatives, albeit with the intricacies of managing industrial emissions and waste disposal. The variances in the relationship between consumption-based emissions, urban migration, and incineration underscore the necessity of individualized waste management approaches that cater to the unique needs of EU member states. Ultimately, our study underscores the EU's dedication to a greener, more sustainable future, guided by innovative technologies and responsive policies, as it navigates the complexities of waste management and environmental stewardship.

Based on the insights derived from our empirical analysis and the relevance of ongoing case studies, the following policy recommendations for EU countries can be derived, to further enhance the EU waste management and environmental sustainability efforts.

- **Promote Green Technology Adoption and R&D**: Encourage the development and adoption of innovative green technologies for waste management. Invest in research and development initiatives to support eco-friendly waste reduction and recycling solutions.
- **Strengthen Environmental Taxation Policies**: Enhance environmental taxation policies to provide incentives for responsible waste management practices. Consider imposing taxes on waste incineration while offering tax breaks for sustainable alternatives.
- **Accelerate Renewable Energy Transition**: Continue the shift towards renewable energy sources to reduce the environmental impact of incineration. Provide financial incentives and regulatory support for renewable energy projects.
- **Tailor Waste Management Strategies**: Recognize regional variations in waste generation behaviours and consumption patterns within EU member states. Customize waste management strategies to suit the specific circumstances and needs of each region.
- **Address Industrial Emissions Responsibly**: Develop comprehensive strategies to balance industrial emissions reduction with efficient waste disposal practices. Encourage industries to adopt cleaner production methods and invest in emissions reduction technologies.
- **Monitor Progress and Foster Collaboration**: Establish clear waste management benchmarks and targets while encouraging collaboration and knowledge-sharing among EU member states. Regularly monitor and report on progress toward waste reduction and recycling goals.

These consolidated recommendations offer a focused and comprehensive approach to advancing waste management and environmental sustainability in EU countries. Future research may investigate the relationship among incineration, taxation, and emissions for different groups of countries using alternative methodologies, such as Panel Vector Auto-Regressions, Spatial Analysis, or Wavelet Analysis, trying to compare the results for alternative samples or from diverse empirical approaches. Finally, the limitations of this study are related to the data availability and the generalization of the results to other countries.

CRediT authorship contribution statement

Muhammad Imran: Writing – review & editing, Project administration, Investigation, Data curation, Conceptualization. **Zhang Jijian:** Visualization, Validation, Resources, Project administration. **Arshian Sharif:** Visualization, Validation, Supervision. **Cosimo Magazzino:** Writing – review & editing, Visualization, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

There is no conflict of interest between the authors.

Data availability

Data will be made available on request.

Abbreviations

BRICS	Brazil, Russia, India, China, and South Africa
CADF	Cross-Sectional Augmented Dickey-Fuller
CE	Circular Economy
CCR	Canonical Cointegrating Regression
CIPS	Cross-Sectional Im, Pesaran, and Shin
CO_2	Carbon Dioxide
DOLS	Dynamic Ordinary Least Squares
EU	European Union
FGLS	Feasible Generalized Least Squares
GB	Gradient Boosting
GHG	Greenhouse Gas
ML:	Machine Learning
MMQR	Method of Moments Quantile Regression
OECD	Organization for Economic Co-operation and Development
OLS	Ordinary Least Squares
PCSE	Panel-Corrected Standard Errors
QR	Quantile Regression
XGBoost	Extreme Gradient Boosting

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