Zvonimir Majić[1]
Univerisity North,
Koprivnica,
Republic of Croatia
e-mail: zmajic@unin.hr
ORCID 0000-0000-0000-0000

Tomislava Majić
Univerisity North,
Koprivnica,
Republic of Croatia
e-mail: tmajic@unin.hr
ORCID 0000-0000-0000-0000

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AN ANALYSIS OF THE IMPLEMENTATION OF THE EXTENDER PRODUCER RESPONSIBILITY SCHEME IN ACHIEVING WASTE MANAGEMENT OBJECTIVES IN CROATIA

Abstract: *This paper evaluates the effectiveness of Croatia's Extended Producer Responsibility system in achieving national waste management goals. EPR shifts post-consumer waste responsibility from municipalities to producers, supporting the polluter-pays principle and circular economy. Croatia applies EPR to six categories: packaging, ELVs, WEEE, batteries, oils, and tyres. Using a mixed-effects panel data model with monthly data from 2015–2024, the study examines the impact of producer fees, fund investments, and household consumption on waste treatment volumes. Results show that both fees and investments significantly increase treated waste, while higher consumption correlates negatively, indicating infrastructure strain. The analysis aligns with broader European research and highlights Croatia's success in meeting EU targets for packaging, ELVs, and batteries. However, challenges remain in fee alignment and managing complex waste streams like WEEE and oils. The paper concludes with recommendations to refine financial mechanisms and improve data monitoring for a more responsive and efficient EPR framework.*

Keywords: *Extended Producer Responsibility (EPR); Waste Management; Panel Data Analysis; Mixed-Effects Model; Special Waste Categories*

JEL Classification: *Q53; Q58; C23*

1. Introduction

In order to protect the environment and reduce ecological harm, societies have adopted several foundational principles of environmental protection. These environmental principles—such as the precautionary principle, the principle of prevention, the polluter-pays principle, and sustainable development—play a crucial role in shaping decisions, formulating policies, and guiding governance (Pedersen, 2010; Lees & Pedersen, 2025) In the domain of waste management, one of the most widely applied principles is Extended Producer Responsibility (EPR). EPR is a successful approach to internalizing environmental externalities from post-consumption waste by promoting reduced packaging use and recyclable design. It aligns with the waste hierarchy and circular economy goals while shifting financial and organizational responsibility from municipalities and taxpayers to producers, in accordance with the polluter-pays principle (Colelli, Croci, Pontoni, & Zanin, 2022). EPR as a policy approach that emerged from growing environmental concerns in the late 20th century, aiming to shift the responsibility for post-consumer waste from governments and taxpayers to producers. The roots of EPR can be traced back to the 1970s, when the "polluter pays" principle began influencing environmental policy. EPR as a defined policy strategy was introduced by the Swedish academic Thomas Lindhqvist in a report to the Swedish Ministry of the Environment in 1990. The concept was based on analysis of a number of Swedish and foreign recycling and waste management schemes, as well as the use of various policy instruments to promote Cleaner Production (Lindhqvist & Lidgren, 1990; Steenmans, 2025).

As a member of the European Union, Croatia's waste management policies are shaped by EU legislation, particularly the Waste Framework Directive (2008/98/EC), which mandates the implementation of EPR schemes for key waste streams. The Circular Economy Action Plan (2020) further reinforces these obligations by setting ambitious

[1] Corresponding author: Zvonimir Majić

targets for recycling, reuse, and reduction of landfill dependency. Croatia's EPR framework reflects these goals, and in several areas—such as packaging, end-of-life vehicles (ELVs), and batteries—it has already met or exceeded EU-mandated targets. However, challenges remain in harmonizing fee structures, improving data transparency, and expanding treatment capacities, issues that are common across many EU member states. Globally, EPR has gained recognition as a key policy instrument for sustainable waste management, endorsed by organizations such as the OECD and UNEP. More than 40 countries have adopted EPR schemes, with varying degrees of success (Webster, M, 2025). Croatia's centralized fee and investment model offers valuable insights for countries seeking to balance environmental goals with economic feasibility. Moreover, Croatia's progress contributes to broader global efforts to achieve the United Nations Sustainable Development Goals (SDGs), particularly Goal 12 on responsible consumption and production, and Goal 13 on climate action.

Croatia has significantly advanced its Extended Producer Responsibility (EPR) framework in recent years, aligning with European Union directives and promoting sustainable waste management. The Waste Management Act defines special categories of waste as waste streams for which specific management conditions are prescribed. The following types of waste have been designat-ed as special categories (GRC & Goverment of the Republic of Croatia, 2021): (I) Waste textiles and footwear, (II) Waste packaging, (III) Waste tires, (IV) Waste oils, (V) Waste batteries and accumulators, (VI) End-of-life vehicles (ELV) , (VII) Construction waste and waste containing asbestos, (VIII) Medical waste, (IX) Waste electrical and electronic equipment, (X) Waste from the production of titanium dioxide, (XI) Waste polychlorinated biphenyls (PCBs) and polychlorinated terphenyls (PCTs) I (XII) Single-use plastics and fishing gear containing plastic. For six of these special waste categories (waste packaging, waste tires, waste oils, waste batteries and accumulators, end-of-life vehicles, and waste electrical and electronic equipment), a system of extended producer responsibility (EPR) has been established. EPR systems began to be introduced in 2005 and involves a fee charged to producers for placing products on the Croatian market that, at the end of their life cycle, become a special waste category for which a separate collection and treatment system has been implemented. With the establishment of a circular economy framework, ambitious collection and/or recovery/recycling targets have been set. The targets set of the waste management of above-mentioned special categories of waste are given in Table 1. Achieving these targets requires improvements to existing separate waste collection systems and the promotion of new advanced technologies for collection, recovery, and recycling. This includes ensuring more efficient models of separate collection, encouraging the expansion and modernization of existing recovery and/or recycling capacities, and building new facilities for waste types and materials for which no treatment facilities currently exist.

Special categories of waste in Croatia are governed by dedicated legislation due to their unique environmental, health, and logistical challenges. These waste types often contain hazardous substances (e.g., heavy metals, oils, plastics) that can contaminate soil, water, and air if not properly managed. Also, there is a need to encourage reuse, recycling, and recovery over landfill disposal and furthermore special categories of waste often require dedicated collection systems (e.g., recycling yards, take-back schemes), special handling and treatment technologies and Monitoring and data reporting to ensure compliance and track environmental impact. ELVs warrant particular attention due to the complex and resource-intensive nature of their production processes, which include metal fabrication, welding, assembly, and ongoing maintenance—all of which exert considerable environmental pressure. Additionally, ELVs are composed of diverse materials such as metals, glass, and plastics. Given their substantial volume, it is imperative to incorporate specialized design considerations to facilitate effective end-of-life management (Korica, Cirman, & Žgajnar Gotvajn, Comparison of end-of-life vehicles management in 31 European countries: A LMDI analysis, 2022). Waste batteries have become a significant environmental concern due to the rapid expansion of electric mobility and their widespread application in information and communication technologies (ICT). These batteries contain high concentrations of critical raw materials, such as lithium and cobalt, whose extraction and refining are geographically concentrated in a limited number of countries. Effective battery waste management is essential to prevent the release of pollutants into the soil, air, and water, thereby minimizing environmental and public health risks (Compagnoni, Grazzi, Pieri, & Tomasi, 2025). Waste packaging, particularly plastic, presents significant challenges in terms of recovery due to high costs and low efficiency associated with the classification and separation of materials, which often contain substantial impurities. These difficulties are especially pronounced in packaging composed of mixed materials, the use of additives and surface coatings, contamination of plastic waste, and the presence of thermoset plastics—all of which contribute to the production of materials that are difficult to recycle (Pučnik, et al., 2024). Waste mineral oils pose a significant environmental concern due to their exposure to mechanical and electrical stresses during machinery operation. Over time, these oils become contaminated with various hazardous substances, including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), toxic gases, and heavy metals, which degrade their functional properties. If not properly managed, such contaminated oils can have severe and hazardous impacts on the en-vironment (Tiwari, Agrawal, Belkhode, Ruatpuia, & Lalthazuala, 2024). Waste tyres represent a substantial environmental challenge, with approximately 1.5 billion units discarded annually due to the rapid expansion of the transportation sector. Their non-biodegradable nature renders them highly resistant to physical, chemical, and biological degradation, making their disposal and recycling both environmentally and economically demanding. However, the complex material composition of waste tyres also presents opportunities for resource recovery and the development of new prod-ucts, highlighting their potential value within circular economy frameworks (Egun, et al., 2024). Waste electrical and electronic equipment (WEEE) refers to electronic products that have reached the end of their useful life or have become obsolete, such as computers, televisions, printers, re-frigerators, air conditioners, washing machines, and mobile phones. Globally, approximately 53.6 million metric tons of e-waste are generated each year. However, only about 17% of this waste is officially documented as being collected and properly recycled. The fate of the remaining e-waste remains largely unknown, posing significant risks in terms of resource loss and environmental pollution. (Burgos Melo, et al., 2024).

According to the Croatian Waste Management Plan, Croatia has already achieved in the year 2023. goals for: Packaging Waste - 60% of the weight for paper and cardboard, 22.5% of the weight for plastic, counting only the material that is recycled back into plastic, 15% of the weight for wood; ELV - Reuse and recovery must reach at least 95% of the average weight of the vehicle per year, reuse and recycling must reach at least 85% of the average weight of the vehicle per year; Waste Batteries - the annual collection rate for waste batteries and accumulators must be at least 45% of the average annual quantity placed on the market over the previous three years, achieve recycling targets of 65% of the average weight of lead-acid batteries and accumulators, including recycling of lead content to the maximum technically feasible extent without incurring excessive costs, 75% of the average weight of nickel-cadmium batteries and accumulators, including recycling of cadmium content to the maximum technically feasible extent without incurring excessive costs and 50% of the average weight of other waste batteries and accumulators; EEE - for heat exchange equipment: 85% recovery of collected weight and 80% preparation for reuse and recycling, for screens, monitors, and equipment with screens larger than 100 cm^2: 80% recovery and 70% preparation for reuse and recycling, or lamps: 80% of collected weight must be recycled, for large equip-ment (external dimension > 50 cm): 85% recovery and 80% preparation for reuse and recycling, for small equipment (no external dimension > 50 cm): 75% recovery and 55% preparation for reuse and recycling and for small IT and telecommunications equipment (no external dimension > 50 cm): 75% recovery and 55% preparation for reuse and recycling (GRC, 2023).

Economists frequently employ panel data analysis models to assess the impact of various policies—such as tax reforms, subsidies, and environmental regulations—across regions or countries over time. Panel data, also referred to as longitudinal data, consists of observations collected over time for multiple entities (e.g., firms, countries, individuals), combining two types of effects: fixed effects, which represent parameters associated with the entire population or consistent levels of experimental factors (e.g., the effect of investment or policy), and random effects, which capture parameters linked to individual units drawn randomly from a population (e.g., time periods, regions, or individuals). Utilizing panel data analysis enhances the efficiency, informativeness, accuracy, and reliability of empirical research. Panel regression techniques help mitigate issues such as heteroskedasticity, autocorrelation, model specification errors, and biases arising from unobserved heterogeneity (Zheng, Law, Wong, & Ng, 2024). Among the various configurations of fixed and random effects, mixed-effects models are particularly suitable for studying the impact of environmental policies or energy prices across regions or industries, as they allow random effects to account for location-specific or firm-specific variability. Researchers often choose mixed-effects models due to their greater generalizability and their capacity to incorporate contextual variables measured only at higher levels of

Table 1. Prescribed Waste Management Targets for Packaging Waste, End-of-Life Vehicles, Waste Batteries and Accumulators, Waste Electrical and Electronic Equipment, Waste Tires, and Waste Oils

Category	Prescribed goals
Packaging Waste	– Separately collect and recover, either materially or energetically, at least 60% of the total mass of packaging waste generated in the Republic of Croatia. – Recycle 55% – 80% of the total mass of packaging waste intended for material recovery. – Recycle at least the following material-specific shares of packaging waste: 60% by weight for glass; 60% by weight for paper and cardboard; 50% by weight for metals; 22.5% by weight for plastics, counting only material that is recycled back into plastic; 15% by weight for wood. – Recycle at least 65% of the total mass of packaging waste, by 31 December 2025. – By 31 December 2025, recycle at least the following shares of materials in packaging waste: 50% for plastics; 25% for wood; 70% for non-ferrous metals; 50% for aluminium; 70% for glass; 75% for paper and cardboard. – Recycle at least 70% of the total mass of packaging waste, by 31 December 2030. – By 31 December 2030, recycle at least the following shares of materials in packaging waste: 55% for plastics; 30% for wood; 80% for non-ferrous metals; 60% for aluminium; 75% for glass; 85% for paper and cardboard. – By 2025, ensure the separate collection for recycling of 77% by weight of beverage bottles (up to 3L, including their caps and lids) made primarily of polyethylene terephthalate (»PET bottles«) placed on the market in a given year, and 90% by 2029. – From 2025, ensure that »PET bottles« contain at least 25% recycled plastic, calculated as an average for all PET bottles placed on the market in Croatia; and from 2030, a share of at least 30% recycled plastic. – Achieve a measurable quantitative reduction in the consumption of single-use plastic products (such as beverage cups, including their caps and lids, and food containers—i.e., boxes with or without lids used to hold food) by 2026, compared to the year 2022. – Achieve a minimum annual collection rate for fishing gear containing plastic that is intended for recycling
End-of-life Vehicles	On an annual basis, achieve the following: • A reuse and recovery rate of at least 95% of the average mass of end-of-life vehicles delivered for treatment • A reuse and recycling rate of at least 85% of the average mass of end-of-life vehicles delivered for treatment
Waste Batteries and Accumulators	Achieve an annual separate collection rate of at least 45% of the average annual quantity of waste batteries and accumulators placed on the market over the previous three years Achieve the following minimum recycling efficiencies: (a) 65% of the average mass of lead-acid batteries and accumulators, including the recycling of lead content to the maximum technically feasible extent without incurring excessive costs (b) 75% of the average mass of nickel-cadmium batteries and accumulators, including the recycling of cadmium content to the maximum technically feasible extent without incurring excessive costs (c) 50% of the average mass of other waste batteries and accumulators
Waste Electrical and Electronic Equipment	Achieve an annual separate collection rate of at least 65% of the average mass of electrical and electronic equipment (EEE) placed on the market over the previous three years, or 85% of WEEE (waste electrical and electronic equipment) generated within the territory of the Republic of Croatia. Recover WEEE annually at a minimum rate of: • 85%, or through preparation for reuse and recycling processes, at least 80% of the mass of collected heat exchange equipment or large equipment with any external dimension greater than 50 cm • 80%, or through preparation for reuse and recycling processes, at least 70% of the mass of collected screens, monitors, and equipment containing display surfaces larger than 100 cm² • 75%, or through preparation for reuse and recycling processes, at least 55% of the mass of collected small equipment with no external dimension greater than 50 cm, or small IT and telecommunications equipment with no external dimension greater than 50 cm • 80% of the mass of collected lamps through recycling processes

Category	Prescribed goals
Waste Tires	Ensure the following: • Systematic separate collection of waste tires • Treatment of all separately collected waste tires • Recycling of at least 80% of the mass of separately collected waste tires within a calendar year in the Republic of Croatia
Waste Oils	**Ensure the following:** • Separate collection of waste oils • Treatment of waste oils

analysis (Bell & Jones, 2015; Kuang, Bolumole, & Whipple, 2025; Ismail, Poudel, Ali, & Dong, 2025). These models are also wellsuited for handling unbalanced panels—where different units are observed over varying time spans—and improve estimation efficiency by capturing both within and between-entity variation. Furthermore, mixed-effects models offer more flexible assumptions compared to fixed-effects-only models, making them a robust choice for complex policy evaluation.

The objective of this paper is to analyse the implementation of the Extended Producer Responsibility (EPR) scheme in achieving waste management objectives in Croatia. The study aims to establish a framework for effectively evaluating the national waste management system and the policies governing the EPR scheme, which currently applies to six special waste categories: packaging waste, end-of-life vehicles (ELVs), electrical and electronic equipment (EEE), waste batteries, waste oils, and waste tyres. Specifically, the paper tests the widely accepted hypothesis that financial contributions from producers (EPR fees) and government investments positively influence the volume of waste recycled within these categories. To capture both temporal and cross-sectional variation, a mixed-effects panel data model is employed. This modelling approach allows for the inclusion of both fixed and random effects, thereby accounting for unobserved heterogeneity across time periods and waste categories. The model incorporates as predictor variables the fees paid by obligated producers under the EPR scheme, payments made to waste management operators, and household consumption levels, with the quantity of waste treated serving as the de-pendent variable. The structure of the paper is organized as follows: Data Preparation, Methodology, Results, Discussion, and Conclusions.

2. Materials and Methods

2.1. Data preparation

A panel dataset was constructed using internal records from the Croatian Environmental Protection and Energy Efficiency Fund (the Fund), encompassing the management of six special waste catego-ries: packaging waste, end-of-life vehicles (ELVs), electrical and electronic equipment (EEE), waste batteries, waste oils, and waste tyres. The dataset includes information on: (1) fees paid by obligated producers for placing products on the market that ultimately become waste; (2) payments made by the Fund to waste collectors and treatment facilities; and (3) quantities of waste treated—defined as recycled and recovered—for each of the six categories.

The case study covers the entire territory of the Republic of Croatia and spans the period from 2015 to 2024. Monthly data were compiled for two key variables: the amount invested in waste management (InvestedinWM), expressed in euros, and the quantity of waste treated (Treated), measured in tonnes. Since data on fees paid by obligated producers (EPRpayed), also in euros, were originally recorded on an annual basis, they were proportionally distributed across the twelve months of each year, assuming an equal monthly allocation (i.e., annual value divided by 12). Additionally, the variable representing household consumption (HC), expressed in millions of euros, was sourced from the Eurostat database, specifically from the dataset titled Gross Domestic Product (GDP) and Main Components (Output, Expenditure and Income) (Eurostat, 2025). As this data is originally reported on a quarterly basis, it was proportionally distributed across twelve months of each year by dividing each quarterly value equally among the three corresponding months. To ensure comparability over time, all financial variables—namely, the amounts invested in waste management (InvestedinWM), fees paid by obligated producers (EPRpayed), and household consumption (HC)—

Table 2. Descriptive Statistics of Variables Related to Fees Paid by Obligated Producers for Market Placement of Products, Fund Payments to Waste Collectors and Treatment Facilities, Quantities of Waste Treated, and Household Consumption

	count	mean	std	min	median	max	mode
Treated	720	3603,4	4697,68	0	1897,87	19457,66	N/A
EPRpayed	720	2164688	3262744	36215,92	676933,8	15055612	392965,4
InvestedinWM	720	1830935	492030,5	0	1864830	2921234	N/A
Collected	720	3696,64	4765,91	0	2131,34	19508,93	N/A
Household- consumption	720	5614,85	2026,75	3199,79	4926,00	11506,29	4606,85

were converted from current prices to real prices. This adjustment was made using the implicit price deflator (base year 2015 = 100), also obtained from the same Eurostat dataset (Eurostat, 2025). The variable InvestedinWM captures financial transfers related to waste management activities. For packaging waste, it includes payments made to sellers, collectors, packaging management centres, and treatment facilities. For the remaining five categories—end-of-life vehicles (ELVs), electrical and electronic equipment (EEE), waste batteries, waste oils, and waste tyres—it comprises payments to collectors and treatment facilities only. Due to the absence of data for packaging waste in the year 2015, missing values were retrospectively estimated using a linear re-gression model based on available data from 2016 to 2024. This backcasting approach enabled the construction of a continuous time series, which is essential for robust panel data analysis. The results of the descriptive analysis are presented in Table 2.

2.2. Panel data methodology

This study employs a quantitative panel data approach to evaluate the effectiveness of Croatia's Extended Producer Responsibility (EPR) scheme across six special waste categories by using the datasets including monthly observations for each waste category, capturing three independent variables:

- Fees paid by obligated producers (EFRpayed),
- Investments in waste management (InvestedinWM),
- Household consumption data (HC); and the dependent variable:
- Quantities of waste treated (Treated).

To account for both temporal and cross-sectional heterogeneity, a mixed-effects regression model was employed. Mixed-effects models are particularly wellsuited for panel data as they allow for the inclusion of both fixed effects (to estimate the average effect of predictors across all groups) and random effects (to capture unobserved group-level variation), thereby addressing the nonindependence of repeated measures within groups (Gelman & Hill, 2007; Snijders & Bosker, 2012; Gudmestad & Metzger, 2025). The model specification is given in an Equation 1. The model was estimated using maximum likelihood estimation (MLE), and the significance of the random effects structure was confirmed via a likelihood ratio test comparing the mixed-effects model to a standard linear regression (Raudenbush & Bryk, 2002; Hammer, i dr., 2025).

$$\text{Treated}_{\text{it}} = \beta_0 + \beta_1\, EFRpayed_{it} + \beta_2\, InvestedinWM_{it} + \beta_3\, HC_{it} + u_i + \varepsilon_{it} \quad (1)$$

Where i indexes the waste category and t indexes time (month), u_i represents the random intercept for each time group and ε_{it} is the idiosyncratic error term.

2.3. Results and discussion

The results of the mixed-effects maximum likelihood regression model are presented in Table 3. The model was estimated using 720 observations, grouped into 120 time-based clusters (i.e., year-month combinations), with each cluster containing between 5 and 15 observations. The dependent variable in the model is the quantity of waste treated, while the independent variables include fees paid by obligated producers (EFRpayed), investments in waste management (In-vested-inWM), and household consumption (Household-consumption).

All three predictor variables are statistically significant at the 1% level. The coefficient for EPRpayed is positive and highly significant ($\beta = 0.00110$, $p < 0.001$), indicating that higher financial contributions from producers under the EPR scheme are associated with increased quantities of waste treated. Similarly, InvestedinWM also demonstrates a positive and statistically significant effect

Table 3. The results of the mixed-effects maximum likelihood regression model

Variable	Coefficient	Std. Error	z-value	p-value	95% Confidence
Interval	0.0013725	0.0000189	72.70	<0.001	[0.0013355, 0.0014095]
EFRpayed	0.0007508	0.0001395	5.38	<0.001	[0.0004774, 0.0010242]
InvestedinWM	-0.3609367	0.0344325	-10.48	<0.001	[-0.4284232, -0.2934501]
HC	1284.166	242.4877	5.30	<0.001	[808.8988, 1759.433]

($\beta = 0.00072$, $p < 0.001$), suggesting that greater investments by the Fund in waste collection and treatment infrastructure contribute to improved waste treatment outcomes.

In contrast, Householdconsumption exhibits a strong negative relationship with the quantity of waste treated ($\beta = -0.911$, $p < 0.001$). This result may reflect the counteracting effect of increased consumption, which could lead to higher waste generation and potentially strain the capacity of the existing waste management system.

The model includes random intercepts for each time group (ym_id), capturing unobserved heterogeneity across time periods. The standard deviation of the random intercepts is 1,593.54, indicating substantial variation in baseline waste treatment levels over time. A likelihood ratio test comparing the mixed-effects model to a standard linear regression yields a chi-square statistic of 25,259 ($p < 0.001$), confirming that the inclusion of random effects significantly improves model fit.

The results align with expectations regarding statistical significance, particularly for the variable InvestedinWM, which represents payments made to waste collectors and treatment facilities for the six special waste categories. This variable is positively associated with the total quantity of waste treated. However, it is important to note that this relationship is likely bidirectional: while increased investment may facilitate greater treatment capacity, the volume of waste treated also directly influences the level of investment, as the Fund disburses payments based on the quantity of waste collected and processed. Therefore, the observed association between InvestedinWM and treated waste quantities should be interpreted as a correlation rather than a causal effect. This distinction is critical for policy interpretation, as it suggests that higher treatment volumes may drive higher expenditures, rather than the reverse.

The dynamics of the variables examined in this study over the period from 2015 to 2024 are illustrated in Figure 1. An analysis of these trends reveals that household consumption patterns throughout the year generally align with the fees paid by obligated entities under the Extended Producer Responsibility (EPR) framework. The observed increase in household consumption over the analysed period reflects a corresponding rise in the population's standard of living. In contrast, the quantities of waste collected do not closely correspond with the fees disbursed by the Fund to collectors and treatment facilities. This discrepancy is primarily attributable to the fact that fee levels remained largely unchanged during most of the observed period. As a result, increases in the volume of waste collected and treated did not lead to proportional increases in fee payments. Legislative amendments introduced in 2023, which stipulate that fee values will be adjusted based on market conditions, have led to a closer alignment between waste collection volumes and fee payments in the final two years of the study period (MESD, 2023). Household consumption is widely recognized as a key economic indicator and is frequently employed in panel data analyses to investigate behavioural, environmental, and policy-related outcomes across time and across entities such as regions, households, or countries—particularly in the context of waste generation. When incorporated into panel data models, household consumption enables researchers to account for both time-invariant heterogeneity (i.e., differences between units that remain constant over time) and temporal dynamics (i.e., changes within units over time). In their study, Korica et al. conducted a panel data analysis using seven socio-economic variables—household consumption, income, environmental taxation, education, unemployment, youth population ratio, and population density—applying both fixed-effects and random-effects models. Their findings identified household consumption as the most significant variable influencing waste generation. However, the study did not extend its analysis to examine the relationship between household consumption and subsequent waste treatment processes (Korica, Cirman, & Žgajnar Gotvajn, Are We Reversing the Trend in Waste

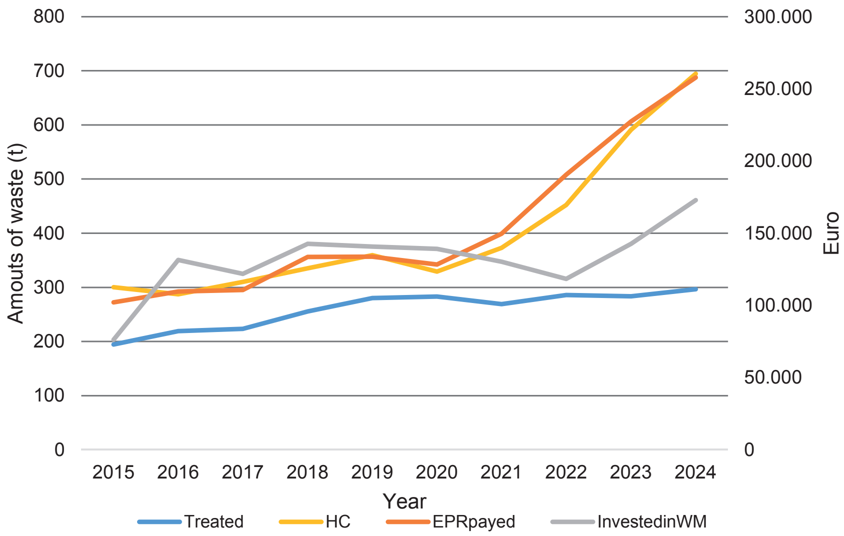

Figure 1. Trends in Treated Waste Volumes, HC, and EPR Fee Values (2015–2024)

Generation: Panel Data Analyses of Municipal Waste Generation in Regard to the Socio-Economic Factors in European Countries, 2020). In another study, Jin et al. employed a panel Tobit model to investigate the impact of upgrading household consumption on the eco-efficiency of municipal solid waste (MSW) management, analysing two dimensions: consumption scale and consumption structure alongside other socio-economic factors. Their findings revealed that consumption scale had a negative effect on the eco-efficiency of MSW management, which aligns with our results. Conversely, consumption structure exhibited a positive influence, suggesting that, overall, the proposed upgrades in household con-sumption patterns contribute positively to eco-efficiency (Jin, Li, Li, & Wang, 2024). The study conducted by Hondroyiannis et al. examined the relationship between the circular material use rate at the macro level and various macroeconomic indicators across a panel of 28 European countries. Using panel data analysis, the authors found that countries with higher gross domestic product (GDP) tend to exhibit elevated levels of consumption, which, in the short term, correlates with a lower circular material use rate. As GDP increases, so does consumption, potentially leading to greater resource use and waste generation. This dynamic presents challenges for the implementation of circular economy practices, particularly in high-income economies (Hondroyiannis , Sardianou, Nikou, Evangelinos, & Nikolaou, 2024).

In their analysis of national Extended Producer Responsibility (EPR) systems using panel data, Zhidebekkyzy et al. applied the difference-in-differences method to evaluate the impact of EPR implementation. The study utilized panel data from 27 manufacturing enterprises across the Czech Republic, Poland, Slovakia, Romania, Estonia, Hungary, and Bulgaria, covering the period from 2010 to 2022. The results of the difference-in-differences analysis revealed a statistically significant positive effect of the EPR system on the circular material use rate, indicating that EPR policies effectively enhance circularity within the electronics manufacturing sector, particularly in relation to waste electrical and electronic equipment (WEEE) (Zhidebekkyzy, Temerbulatova, Kotaskova, & Németh, 2024). Colelli et al. argue that although econometric panel-based approaches offer a valuable means of directly quantifying the influence of various economic variables, they fall short in ac-counting for the heterogeneity of EPR system characteristics and in evaluating the economic efficiency of these systems (Colelli, Croci , Pontoni, & Zanin, 2022). In contrast, Favot et al. (2022) utilized a unique dataset to conduct an econometric analysis of the impact of competition and regulatory frameworks on the costs associated with managing WEEE. Their panel data-based statistical analysis provided robust evidence that a more competitive market structure can achieve equivalent collection outcomes at a reduced cost (Favot, Grassetti, Massarutto, & Veit, 2022). Joltreau (2022), in his analysis of data from 25 European countries covering the period from 1998 to 2015, employed temporal variation within an original panel dataset on EPR compliance costs across four packaging materials. The results indicated that the financial incentives embedded in EPR schemes led to a statistically significant, albeit modest, reduction in packaging use. However, the study found no consistent evidence of substitution effects between different packaging materials (Joltreau, 2022).

Interesting findings were presented in the study by Ridwan et al., which focused on the Nordic region. The authors applied the STIRPAT model and quantile regression to data spanning from 1995 to 2021, highlighting that resource productivity and environmental taxation are key drivers of circularity. Consistent with the findings of this paper, their results demonstrate that environmental taxes not only influence recycling outcomes but are also shaped by them, reflecting adaptive and coevolving institutional arrangements (Ridwan, et al., 2025). Korica & Žgajnar Gotvajn conducted an analysis of the effectiveness of public co-financing in reducing mixed municipal waste and enhancing the separate collection of biodegradable waste, employing logarithmic mean Divisia index (LMDI) models. Their results indicated a moderate positive impact of separate waste collection and investments in biodegradable waste management on the total amount of composted waste, which aligns with the findings of this study (Korica & Žgajnar Gotvajn, 2025).

The findings of this study underscore the critical role of financial mechanisms in enhancing waste treatment performance and highlight the importance of incorporating consumption patterns into the design and evaluation of Extended Producer Responsibility (EPR) policies. Panel data anal-ysis once again proves to be a highly effective tool for assessing the impacts of environmental policies; however, its reliability is inherently dependent on the quality and completeness of the underlying data. In the context of this study, a key limitation arises from the lack of comparable data for packaging waste in the year 2015. This gap is attributed to systemic changes that rendered earlier data incompatible with subsequent years, introducing a degree of uncertainty into the analysis. Additionally, the reliability of the results was affected by inconsistencies in the temporal resolution of the data. Specifically, the variable representing fees paid by obligated producers (EPRpayed) was reported annually, while household consumption (HC) data was available on a quarterly basis. Although both datasets were transformed into a monthly format to enable comparison, this transformation introduced additional variability that may have influenced the outcomes. Despite these limitations, the analysis yielded valuable insights into the functioning and effectiveness of Croatia's EPR framework, offering evidence-based recommendations for future policy refinement.

3. Conclusion

This study provides a comprehensive evaluation of the implementation and effectiveness of the Extended Producer Responsibility (EPR) scheme in Croatia, focusing on six special waste categories: packaging waste, end-of-life vehicles, waste electrical and electronic equipment, waste batteries, waste oils, and waste tyres. By employing a mixed-effects panel data model using monthly data from 2015 to 2024, the analysis captures both temporal and cross-sectional variation, offering robust insights into the performance of the national EPR framework.

The findings confirm that financial contributions from obligated producers (EPR fees) and government investments in waste management infrastructure have a statistically significant and positive effect on the quantities of waste recycled, thereby supporting the hypothesis. These results underscore the critical role of economic instruments in enhancing the operational effectiveness of EPR systems. Conversely, household consumption was found to have a statistically significant negative effect on waste treatment volumes, suggesting that rising consumption levels may increase waste generation and place additional pressure on existing waste management capacities.

The study also underscores the importance of aligning fee structures with actual waste volumes and prevailing market conditions, as evidenced by recent legislative adjustments in Croatia. Furthermore, the analysis reveals that while Croatia has met or exceeded several EU-mandated targets for waste collection and recycling, further improvements are required in data monitoring, infrastructure development, and policy responsiveness to ensure long-term sustainability.

Overall, the research demonstrates that Extended Producer Responsibility (EPR) is an effective policy instrument for advancing circular economy objectives and enhancing waste management outcomes. However, its success depends on continuous adaptation to evolving consumption patterns, technological advancements, and regulatory developments. Future research should investigate the causal mechanisms underlying the observed relationships and assess the long-term environmental and economic impacts of EPR implementation across different waste streams.

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