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The Effectiveness of Deposit–Refund Systems in Packaging Waste Management: A Panel Regression Analysis of EU Countries

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Abstract

Across the European Union, deposit–refund systems (DRSs) are increasingly seen as a crucial response to mounting waste management challenges, including low recycling rates and rising plastic pollution. By attaching a refundable deposit to beverage containers, these systems incentivise civilians to return packaging, thereby significantly reducing litter and improving the quality of recyclable materials. In the context of ambitious EU circular economy and waste reduction targets, DRSs play a key role in addressing resource inefficiency and environmental degradation. The empirical results obtained from a comprehensive panel regression analysis, which accounts for heterogeneity in policy effectiveness, reveal that the effectiveness of a DRS is not uniform across the packaging spectrum in the EU. The results indicate that the presence of a DRS and higher deposit values have a statistically significant and positive effect on packaging waste recycling rates, especially for plastic packaging waste, and that DRSs play a major role in improving and increasing the separate collection of packaging waste, ensuring good quality of the aforementioned fractions. In addition, some structural factors, such as population density and tourism intensity, have a strong impact on recycling efficiency. The findings highlight the importance of implementing deposit systems to achieve circular economy objectives and provide an empirical basis for improving waste management policies in the EU, thereby strengthening evidence-based decision-making.

Keywords: deposit–refund system; waste management; circular economy; recycling; panel regression; economy and business resilience; effectiveness

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Academic Editor: Gabriella Fiorentino

Received: 19 April 2026
Revised: 3 June 2026
Accepted: 12 June 2026
Published: 16 June 2026

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1. Introduction

The largest share of produced plastic is used for packaging purposes. In the European Union, as much as 40% of all plastic produced is used for packaging, 20% for construction, and only about 10% for the automotive industry, including the manufacture of commercial vehicles [1]. The management of plastic waste—particularly its recycling—is considerably more complex than the recycling of metals and other materials, since only a very small proportion of recycled plastic can be reused for alternative purposes. Consequently, packaging waste management is a key area of the EU's environmental policy, especially in the context of the transition from a linear to a circular economy. The circular economy also supports other key EU priorities, including the green transition, climate change mitigation and energy savings, biodiversity protection, and global sustainable development efforts [2].

The EU's ambition is to build a circular and climate-neutral economy by 2050. In recent years, the EU has introduced many new measures to reduce waste and make products more sustainable. New or updated legislation covers eco-design, packaging, greenwashing, the right to repair, waste management and other key areas [3,4]. Despite measures and efforts to reduce packaging, the amount of packaging waste in the EU is growing, particularly because of the increase in online purchases and home deliveries in recent years, as well as in on-the-go consumption. Every single European throws away—often immediately after purchase—half a kilo of packaging every single day. If no action is taken, packaging waste could increase by another 19% by 2030. In recent years, packaging has grown faster than the EU's economy and population. While recycling rates in the EU have increased by 23% compared with 2010, this was not enough to keep up with the increase in the total amount of packaging waste generated. Data shows a gap between the growth of packaging waste and that of recycling [5].

According to the available Eurostat data, the European Union generated approximately 186.5 kg of packaging waste per capita in 2022, while in 2023 the total amount of packaging waste reached 79.7 million tonnes, or 177.8 kg per capita. Across European countries, the share of packaging waste in mixed municipal waste varies, but it is estimated to account on average for 40–50%. Due to its widespread use and the large number of users, packaging is a major source of environmental pollution, especially through littering [6]. Despite substantial investment in prevention and recycling, the upward trend in packaging waste generation continues to pose a challenge to the EU's objectives on waste reduction and greenhouse gas mitigation.

DRSs and similar strategies emerge from the theoretical framework of the circular economy, according to which waste is considered a resource and societal sustainability requires high recycling rates and the development of secondary raw materials markets [7].

The fundamental principle underlying a DRS is the deposit mechanism, which provides a financial incentive for civilians to return used packaging to designated collection points. In this way, the system encourages recycling, specifically the separate collection and sorting of packaging waste by material fractions. The roots of this model can be traced to Pigouvian taxation. A.C. Pigou, a key contributor to welfare economics theory, established the core principles of externality theory by emphasising market failures and the necessary role of the state in ensuring that market prices reflect the full social cost of production. This implies the internalisation of external costs—that is, incorporating the costs into the product price when the product generates pollution [8]. DRSs operate in accordance with this principle. The deposit system consists of a deposit being imposed on each glass, plastic bottle or can product that is sold. It is up to each country how large the deposit is [9].

Although many EU Member States have implemented a DRS, gained extensive practical experience, and published numerous case studies, the academic literature still offers very few quantitative studies supported by systematic research methodologies [10]—specifically, studies employing panel econometric techniques to estimate the effects of DRSs on packaging recycling rates across countries and over extended periods. The existing literature predominantly discusses DRSs from a theoretical perspective, focusing on system functioning, environmental and climate benefits, and system-related costs and drawbacks. By contrast, econometric analyses of the effects of DRSs on national recycling rates remain limited. A recent study by Tarantino et al. [11] provides a systematic literature review using the PRISMA method of the current state of academic research in relation to the five intervention areas (waste prevention, recyclability, recycled content, compostable materials, and reusable systems), introduced by the Packaging and Packaging Waste Regulation (PPWR), assessing the extent to which the scientific literature supports the Regulation's circular economy objectives [11]. The results reveal that waste prevention and reusability

are the most extensively researched areas. Torkelis et al. [12] applied a PESTEL analysis to provide a descriptive comprehensive overview of six critical factors influencing the recycling of plastic and composite packaging waste, encompassing political, economic, social, technological, environmental, and legal dimensions [12]. By contrast, Di Foggia and Beccarello [13] applied multiple-case design to provide an overview of the packaging waste models in selected European countries to gain a comparative view.

Furthermore, the ongoing evaluation of DRS effectiveness lacks evidence on structural factors. Structural factors, such as environmental taxes, deposit levels, demographics and tourism, directly influence DRSs and their effectiveness. For example, survey data from Alberta show that older residents, vehicle owners, homeowners, people living in single-detached homes are more likely to return containers than younger residents, renters, those without access to a vehicle, or people living in higher-density duplexes/triplexes and multi-residence buildings [14]. Geography and tourism can also influence outcomes. Sweden's DRS operator, Returpack, reports higher per capita collection rates in border and tourist municipalities, and notes that cross-border trade with Norway lowers Sweden's collection rate by roughly four percentage points for cans and one percentage point for PET bottles. While deposit levels, programme scope, and the convenience and accessibility of the return network are key factors impacting collection rates, they do not tell the whole story. DRS performance is also influenced by a complex interplay of external factors including cultural and behavioural norms, civilians demographics (e.g., age, income, education, gender), urban form (e.g., population density, housing type, transit access, and car ownership), consumer psychology, and local waste management infrastructure (e.g., presence and frequency of kerbside collection, source separation requirements) [14].

Accordingly, this paper aims to contribute to the literature by addressing the research gap through the application of a panel regression model to a sample of European countries over the period 1997–2023. The study empirically examines the impact of the existence and characteristics of DRSs on packaging waste recycling rates alongside economic factors such as GDP per capita and structural factors (environmental taxes, packaging waste statistics, population density, tourism intensity). The objective is to advance the understanding of the effectiveness of DRSs as policy instruments within the EU's circular economy goals and to provide recommendations for further development of packaging waste management in the EU.

The paper contributes to the existing literature in the following ways: (a) The application of an econometric panel regression approach represents a substantive advancement over prior analyses of DRSs, which have predominantly relied on single-country case studies and descriptive methods. By employing panel regression techniques across European Union, the study provides a more comprehensive and comparative assessment of the effectiveness of DRSs, as well as a more robust estimation of its impacts. Moreover, the analysis enables a comparative evaluation of the effects of DRSs on recycling rates across different material fractions (plastic, metal, and glass). (b) The study further contributes by incorporating structural factors that may influence DRS performance, including demographic indicators, environmental taxes, and levels of economic development. The inclusion of these variables allows for a deeper understanding of the conditions and determinants shaping DRS effectiveness, offering an important advancement over existing empirical analyses. (c) With respect to the European Union legislative framework, particularly the Packaging and Packaging Waste Regulation (PPWR), the analysis explicitly links the empirical findings on DRS performance with this evolving regulatory context. In doing so, the study moves beyond a purely academic discussion and provides policy-relevant insights, supporting the view that DRSs should be considered an essential instrument in the design and implementation of environmental policies aimed at establishing effective packaging waste management systems.

2. Literature Review

DRSs constitute a market-based environmental policy instrument designed to mitigate negative environmental externalities and reduce waste generation more broadly. As emphasised by Walls [15], a DRS is a combination of a product tax and a subsidy for returned packaging, thereby encouraging waste reduction and higher recycling rates. Moreover, Walls [15] notes that the deposit–refund approach can be applied to address a wide range of environmental problems beyond waste management, including air and water pollution. The assignment of a monetary value has historically served as a key driver in achieving policy goals, including within DRSs, where packaging units are assigned a monetary value (i.e., monetised) that is reimbursed to individuals upon the return of the packaging. Thus, monetary value has proven to be a powerful lever in addressing packaging waste issues.

Empirical evidence from individual countries indicates that DRS implementation leads to very high return rates. In countries where the system operates effectively, collection rates for PET beverage containers range from 65% to 95%, whereas in countries without a DRS, return rates typically range from 22% to 73% (with the exception of Belgium, which achieves an 85% return rate) [16].

The objective of the DRS is to reduce waste and increase recycling rapidly over a short period and to increase recycling rates. The DRS is a means of gathering a significant amount of beverage containers for the purpose of reuse, promoting awareness of sorting waste, and adding value to the waste [17]. Currently, the deposit system in Europe is used by 138 million people (about 1/4 of the population), and it operates in 16 countries: Croatia, Denmark, Estonia, Finland, the Netherlands, Iceland, Ireland, Lithuania, Latvia, Malta, Germany, Norway, Romania, Slovakia, Sweden, and Hungary [9].

Unfortunately, existing deposit systems do not cover all packaging categories. Most systems exclude milk and dairy drinks, as well as wine and spirits [9]. When successfully implemented, DRSs can reform socio-technical practices and applications. They can standardise consumer engagement, transform business models and direct them towards recycling and reuse of containers, and support efforts for stricter environmental policies [18].

Traditional deposit–refund models in place across U.S. states with bottle-bill legislation—except in California and Hawaii—operate through distributors and retailers, with retailers acting as intermediaries [15]. Numerical analyses by Acuff and Kaffine (2011) confirm that the DRS is the least costly instrument for reducing waste, except when reduction targets are very low (<5%) [15].

The first countries to introduce DRSs were Iceland and Sweden in 1989. In recent years, the number of countries implementing such systems has increased substantially. Austria and Hungary are among the most recent EU Member States to adopt a DRS, while the United Kingdom's latest strategy foresees the introduction of a DRS in England, Scotland, and Northern Ireland by 2027 [19]. According to the Strategy on Plastics in a Circular Economy [20], more than 20 countries—including Denmark, Norway, the Netherlands, Sweden, and Finland—achieve packaging recycling rate above 90% owing to the DRS. Germany recorded the highest return rates at 97% (2014 data), followed by Norway at 94% [6].

According to Schneider et al. (2021), beverage packaging collected through DRSs accounted for approximately 34.7% (by mass) of total packaging waste collected across all collection systems in 2017 [6]. The authors characterise this outcome as a significant achievement, given that the collected material represents a high-quality and clean fraction. Although DRSs are limited to beverage packaging, they demonstrate a unique capacity to achieve very high collection rates (regularly above 90%, and, in some cases, surpassing 95%). More importantly, they ensure a sufficient supply of high-quality material for recyclers, resulting in high recycling rates, particularly within closed-loop recycling systems [6].

In contrast, Agnusdei et al. [21], in a study examining whether DRSs and their different configurations affect the reduction in glass packaging waste and increase recycling and recovery rates, indicated that different waste management systems do not influence the level of glass packaging consumption and, consequently, do not affect recycling and recovery rates. Consistent with these findings, a DRS may constitute part of the solution; however, it is not, in itself, a key driver of sustainable glass packaging waste management [21]. A DRS cannot influence the amount of glass packaging placed on the market, as it operates after the packaging has been purchased rather than beforehand [21]. It is therefore reasonable to expect that a DRS affects the quantity of material returned, rather than the quantity of packaging consumed [21]. Using ANOVA, the authors examined the statistical significance of differences among three groups of countries: those with an implemented DRS, Mediterranean countries without a DRS, and other EU Member States without a DRS.

Furthermore, Sidorczuk-Pietraszko et al. [22] emphasise that the presence of a DRS is not directly associated with the overall efficiency of a country's waste management system. High collection rates for PET packaging covered by a DRS are not necessarily accompanied by high recycling rates for total municipal waste. Nevertheless, the authors argue that widespread implementation of DRSs across the EU could enable a relatively rapid and substantial increase in the circularity rate of packaging waste, regardless of the initial efficiency level of national collection systems [22].

According to Consulting and Reloop (2024), several European countries with a DRS, such as Denmark, Finland, Norway, Germany and Lithuania, have already met the EU's 2025 and 2029 PET collection targets, while others, such as the Netherlands and Latvia, are approaching compliance. High return rates, including 98% in Germany, 97% in Finland and 92% in Norway, demonstrate the system's effectiveness. In contrast, countries without a DRS lag-behind: Spain reported a PET collection rate of only 37% in 2022, while France, Italy, and Portugal remain at or below 50%, revealing inefficiencies in their current systems [23].

Croci et al. [24] demonstrated that DRSs increase recycling rates by approximately 5 percentage points for plastic packaging and 15 percentage points for glass packaging. The study further confirms that the deposit amount has a direct impact on return rates: higher deposits lead to higher return rates, whereas deposits set too low fail to provide sufficient incentive for returns. Consequently, deposit levels must be aligned with local price levels and income conditions [22].

DRSs force producers to adopt clean production methods and guides consumers to hand over waste products to specific institutions for recycling, which is the requirement of circular economy and the purpose of DRSs [25]. Similarly, Kang et al. [26] conclude that recycling is the most favourable option for beverage packaging producing the lowest environmental burden in the majority of the impact indicators. The deposit level plays a crucial role in determining the programme's success—the higher the amount, the more effective it is in achieving high recycling rates. However, excessively high deposits may reduce consumption below the social optimum [27].

Insufficient recycling rates of packaging waste may result from a range of factors, including the recent growth of e-commerce, which has led to increased quantities of packaging waste placed on the market. In the EU, this trend has contributed to an almost 15% increase in packaging waste generation per capita [22].

Additional factors include inadequate separation and sorting of packaging waste due to underdeveloped infrastructure for separate collection, as well as a generational gap reflected in lower levels of engagement in separate waste collection practices observed among Generation Z and Millennials [22].

A substantial body of literature documents the positive effects of DRSs; however, many existing studies continue to rely predominantly on single-country case studies and

descriptive approaches. The theoretical study of DRSs can be traced back to 1981, when Bohm, Walls, Sarangi and Kulshreshta analysed the operation mechanism of DRSs and pointed out the policy advantages in pollution prevention and resource recovery [28].

Although the body of literature on DRSs has expanded in recent years, limitations persist. In particular, there is a shortage of comparative analyses across EU Member States, especially panel econometric analyses that differentiate impacts by types of packaging waste collected through DRSs. Therefore, this study aims to address the identified research gap by applying panel regression as an econometric method to a sample of EU Member States. Separate analyses are conducted for plastic, glass, and metal packaging waste. The results are interpreted in the context of European Union circular economy policies. Moreover, although a substantial body of literature addresses DRSs—covering topics such as job creation effects, the influence of social factors on DRS effectiveness, and the OECD's comprehensive reports on DRSs—there is still a need to further supplement the existing literature, particularly regarding economic aspects and a clearer assessment of the extent to which DRSs influence packaging waste outcomes. Accordingly, this paper contributes to the ongoing evaluation of DRS effectiveness, functionality, and relevance, while fostering critical reflection. Its added value lies in contributing new data and focusing specifically on under-researched aspects, particularly in relation to the implications of the PPWR (Packaging and Packaging Waste Regulation) regulatory framework for DRSs.

3. Materials and Methods

DRSs represent a theoretically robust and empirically validated tool. The system can be used to support circular economy aims and goals by combining principles of comprehensive producer responsibility, including end-of-life management, behavioural economics, and systems thinking. The system is an instrument intended to reach high collection rates, to enhance the quality of the containers collected and to boost stakeholder collaboration and the level of consumer acceptance and adoption [18].

To empirically evaluate the multidimensional impact of DRSs on packaging waste recycling, this study utilises an unbalanced panel dataset covering the period 1997–2023 and includes 27 EU Member States and Norway (see Appendix A, Table A1). Furthermore, the analysis disaggregates the dependent variable into specific material fractions—namely plastic, metal, and glass—to capture the heterogeneity of DRS policy effectiveness.

3.1. Data and Variable Specification

The dataset integrates waste management statistics and DRS data with macroeconomic and structural indicators. Data sources include Eurostat (GDP per capita, environmental taxes, packaging waste statistics, population density, tourism intensity [29–31]) and Reloop Platform [14]. The study analyses the recycling rate (%) for specific packaging streams: plastic, metal, glass, and total.

Independent variables of interest include the DRS implementation dummy variable and the real deposit value. The dummy variable takes the value of 1 if a functional DRS exists for the specific material in country i at year t, and 0 otherwise. This measures the structural shift induced by policy introduction. Deposit value represents the monetary value of the deposit (in EUR) to test the price elasticity of recycling behaviour. Finally, system age is included as an interaction term, representing the number of years since the system has been implemented, and is used to test the effects of habit formation. The DRS variable simplifies the diversity of systems across countries, as in practice, return schemes vary considerably in terms of material coverage, the extent of packaging included in the system, infrastructure, and the convenience and accessibility of the system to the civilians. Therefore, the binary DRS variable captures only the existence of an operational system

for a particular material in a particular country and year, while the deposit value variable captures the monetary incentive associated with the return of packaging.

To isolate the policy effect from structural determinants, the model includes a set of control variables. GDP per capita serves as a proxy for the level of economic development and the maturity of recycling infrastructure. Population density controls for logistical efficiency, relying on the assumption that waste collection is more cost-effective in dense urban areas. Tourism intensity, defined as nights spent at tourist accommodation establishments per capita, controls for waste generation by transient populations, which is especially pronounced in Mediterranean countries. For GDP per capita, population density and tourism intensity, which are non-percentage continuous variables, logarithmic transformations were applied. This transformation serves two purposes. First, it reduces skewness in the data distribution and second, it allows the coefficients to be interpreted as elasticities, providing a measure of the percentage change in the recycling rate resulting from a one percent change in the independent variable. Finally, environmental tax revenues (as a % of GDP) are included to control for the general stringency of a country's environmental policy framework. A comprehensive summary of the variables employed in this study, including their specific definitions and data sources, is presented in Table 1.

Table 1. Variable descriptions and Data sources.

Variable Name	Variable Description	Data Source
Rate Plastic	Recycling rate for plastic packaging waste as a percentage of total plastic packaging waste generated	Eurostat [env_waspac]
Rate Metal	Recycling rate for metal packaging waste as a percentage of total metal packaging waste generated	Eurostat [env_waspac]
Rate Glass	Recycling rate for glass packaging waste as a percentage of total glass packaging waste generated	Eurostat [env_waspac]
Rate Total	Total recycling rate for all packaging waste as a percentage of total packaging waste generated	Eurostat [env_waspac]
DRS Active	Binary indicator variable equal to 1 if a DRS is operational for the specific material type in a given country-year, and 0 otherwise	Reloop Platform
Deposit Value	Nominal deposit value in euros for the specific material type. Material-specific deposit values are used for plastic, metal, and glass models; average deposit value across materials is used for total recycling models. Equal to 0 for countries without DRSs or for materials not covered by DRSs	Reloop Platform
System Age	Number of years since the DRS was implemented, calculated as the current year minus the year of DRS introduction. Equal to 0 for countries without DRSs	Reloop Platform
Deposit × System Age	Interaction term between deposit value and system age, capturing the maturity effect of DRSs over time	Authors' calculations
Log GDP per Capita	Natural logarithm of gross domestic product per capita in constant 2020 EUR (chain-linked volumes). Captures economic development and purchasing power	Eurostat [nama_10_pc]
Env. Tax (% GDP)	Environmental tax revenue as a percentage of GDP. Includes taxes on energy, transport, pollution, and resources	Eurostat [env_ac_tax]

Table 1. *Cont.*

Variable Name	Variable Description	Data Source
Log Pop. Density	Natural logarithm of population density measured as inhabitants per square kilometre. Captures urbanisation effects and collection infrastructure feasibility	Eurostat [demo_r_d3dens]
Log Tourism Intensity	Natural logarithm of tourism intensity, calculated as nights spent at tourist accommodation establishments per capita. Captures additional packaging waste from tourism	Eurostat [tour_occ_nim, demo_pjan]

Source: Eurostat and Reloop Platform data. Notes: the empirical dataset covers period 1997–2023. Eurostat variables were collected for all available country/year observations within this period, and DRS-related variables were coded according to the year in which the DRS was implemented in/four each country and material type (plastic, metal, glass).

Table 2 presents the descriptive statistics for the dependent and independent variables, stratified by the presence of a DRS. The data indicate that country-year observations with an operational DRS exhibit higher average recycling rates compared to those without, suggesting a potential positive impact of the policy. However, the statistics also reveal significant structural heterogeneity between the two groups. Countries with implemented deposit systems are generally characterised by higher economic development and stronger environmental fiscal frameworks, yet notably lower population densities. For each country-year observation, recycling rates for plastic, metal, glass and total packaging waste were obtained from Eurostat packaging waste statistics for the available years within the 1997–2023 period. Macroeconomic and structural control variables were also obtained from Eurostat and matched to the same country-year structure wherever available. These include GDP per capita, environmental tax revenues as a percentage of GDP, population density, and tourism intensity. Information on DRS implementation, deposit values, material coverage and system age was compiled from the Reloop Platform [14] and matched with the Eurostat panel according to the year in which the system was operational for the relevant material. Where a country did not have an operational DRS for a given material and year, the corresponding DRS indicator was coded as zero.

Table 2. Descriptive Statistics.

Variable	Overall	With DRS	Without DRS	N	Min	Max
Rate Total	58.01 (13.15)	60.87 (10.03)	56.71 (14.17)	619	2.97	85.27
Rate Plastic	33.72 (14.00)	35.03 (12.62)	33.13 (14.56)	619	2.99	81.72
Rate Metal	65.61 (23.21)	70.42 (23.04)	63.42 (22.98)	618	0.00	92.47
Rate Glass	66.84 (25.33)	75.33 (26.75)	63.00 (23.72)	619	0.00	94.29
System Age	4.36 (8.34)	13.97 (9.43)	0.00 (0.00)	619	0	39
Deposit Value	0.04 (0.07)	0.14 (0.05)	0.00 (0.00)	619	0.00	0.22
Log GDP per Capita	10.22 (0.62)	10.51 (0.46)	10.09 (0.64)	619	8.66	11.60
Log Population Density	4.55 (1.09)	3.87 (1.39)	4.85 (0.74)	619	1.16	7.48

Table 2. *Cont.*

Variable	Overall	With DRS	Without DRS	N	Min	Max
Log Tourism Intensity	1.53 (0.72)	1.67 (0.57)	1.46 (0.76)	619	−0.45	3.21
Env. Tax (% GDP)	2.64 (0.69)	2.84 (0.76)	2.55 (0.64)	619	0.85	5.29

Notes: Standard deviations in parentheses. Sample: 619 country-year observations from 28 European countries (1997–2023). 'With DRS': 193 country-year observations. 'Without DRS': 426 country-year observations. Source: Authors' calculations.

3.2. Econometric Strategy

To isolate the impact of DRSs on recycling rates, this study employs a panel data approach. Panel data estimation is methodologically superior to cross-sectional analysis in this context because it allows for the control of unobserved heterogeneity, factors specific to each country that remain constant over time (such as geographic topology, cultural propensity toward environmental preservation, or institutional quality) but which are correlated with the decision to implement waste management policies [32].

A critical methodological decision in panel data analysis is the choice between fixed-effects (FE) and random-effects (RE) estimators. This selection should be based on both theoretical considerations regarding the sampling method and empirical validation through specification testing. From a theoretical perspective, Wooldridge [32,33] argue that the choice of estimator should reflect the nature of the data [9,32]. The random-effects model assumes that the individual specific effects are uncorrelated with the regressors and treats the sample as a random draw from a much larger population. However, our dataset comprises the entire population of interest (EU Member States and Norway), rather than a random sample of nations. As noted by Greene (2018), when the analysis focuses on a specific set of N units and inference is restricted to the behaviour of these units, the fixed-effects specification is the appropriate theoretical choice [34].

Furthermore, the assumption of orthogonality required by the random-effects model is likely violated in the context of waste management. Countries with higher environmental awareness (an unobserved effect) are likely to have both higher recycling rates and more advanced policy instruments (regressors), creating a correlation between unobserved effects and the independent variables. If this correlation exists, the random-effects estimator suffers from omitted variable bias and is inconsistent [35].

To empirically validate this theoretical stance, the Hausman specification test was conducted. The test assesses the null hypothesis that the errors (α_i) are not correlated with the regressors. The results consistently rejected the null hypothesis at the 1% significance level ($p < 0.01$) across all model specifications. This result confirms that country-specific characteristics are endogenous to the explanatory variables, necessitating the use of the fixed-effects estimator to obtain consistent and unbiased coefficients. Countries implementing the DRS should have a good infrastructure for the system to function and thus implement broader waste management reforms (separate waste collection, extended producer responsibility, etc.). Therefore, the estimation of fixed effects cannot completely eliminate the possibility that changes in waste management policies over time coincide with the introduction of the DRS. Therefore, it is necessary to interpret the estimated coefficients as a conditional association between DRSs and recycling, and not solely as an isolated causal effect.

However, to provide a comprehensive view of structural determinants, we also report random-effects estimates as a robustness check (see Appendix A, Tables A2 and A3). As noted by Mundlak [36], while the fixed-effects model removes time-invariant variation, the random-effects model allows for the estimation of slowly changing structural variables (such as population density), which are absorbed by the fixed effects in the FE

specification [36]. Due to the panel structure of the data and possible within-country correlation, heteroscedasticity and autocorrelation were addressed by using country-level robust standard errors.

To capture the multidimensional nature of DRS effectiveness, the analysis is structured around three distinct econometric specifications. The first specification evaluates the average treatment effect of having a functioning DRS. The variable of interest is a binary dummy.

The first specification tests whether the mere existence of the system is associated with an increase in recycling performance:

$$Y_{it} = \beta_0 + \beta_1 DRS_Active_{it} + \beta_2 X_{it} + \alpha_i + \varepsilon_{it} \quad (1)$$

The second specification replaces the binary indicator with the continuous deposit value. This tests the hypothesis that return rates are price-elastic and that higher opportunity costs lead to higher collection rates:

$$Y_{it} = \beta_0 + \beta_1 Deposit_Value_{it} + \beta_2 X_{it} + \alpha_i + \varepsilon_{it} \quad (2)$$

The third specification introduces an interaction term between the deposit value and the system age (defined as the number of years since implementation). The purpose of this specification is to examine whether the association between the monetary incentive and recycling performance varies with the maturity of DRSs (civilians become familiar with the DRS):

$$Y_{it} = \beta_0 + \beta_1 (Deposit_Value_{it} System_Age_{it}) + \beta_2 Deposit_Value_{it} + \beta_3 X_{it} + \alpha_i + \varepsilon_{it} \quad (3)$$

where Y_{it}—recycling rate for the specific material fraction (plastic, metal, glass and total) in country i at year t; X_{it}—a vector of time-variant control variables including log $GDP_per_capita_{it}$, log $population_density_{it}$, log $tourism_intensity_{it}$, and $environmental_tax_{it}$; α_i—country-specific fixed effects; ε_{it}—error term.

4. Results

The empirical results obtained from the comprehensive panel regression analysis indicate that the effectiveness of a DRS varies across the packaging spectrum in the EU. It is highly heterogeneous and dependent on material characteristics and structural economic factors. Therefore, the results identify a distinct heterogeneous material-specific impact, characterising the DRS as a specialised instrument rather than a general policy tool. Specifically, as shown in Table 3, the fixed-effects estimation indicates that the implementation of a DRS is positively and statistically significantly associated with the plastic packaging recycling rate, with the introduction of the system associated with an average increase of 7.1 percentage points, ceteris paribus. The estimated coefficient of +7.121 percentage points on the DRS indicator in the plastic packaging specification (Table 3) has an associated standard error of 1.994, yielding a 95% confidence interval of approximately [3.2, 11.0] percentage points and a p-value below 0.001. This estimate is therefore precisely estimated and statistically significant at the 1% level.

In stark contrast, the coefficients for metal and glass packaging are statistically insignificant in the fixed-effects specification. This lack of statistical significance may reflect the fact that, in European countries—particularly those with long-standing DRSs—recycling rates for metal and glass were already high prior to the DRS implementation. This outcome largely depends on national waste management policies and the maturity of existing waste management systems. Furthermore, in most of the observed countries, glass packaging is

predominantly organised as refillable packaging, whereby containers are collected, washed, and reused multiple times, and therefore is not covered by DRSs. Furthermore, while the random-effects model (see Appendix A, Table A4) yields a positive coefficient for the total packaging recycling rate, the fixed-effects specification shows no significant impact. This implies that countries operating DRS tend to exhibit better overall recycling performance structurally; however, the introduction of the system itself does not generate an immediate and statistically significant increase in the aggregate recycling rates.

Table 3. Impact of DRS implementation on recycling rates (fixed effects).

Variable	Rate Plastic (1)	Rate Metal (2)	Rate Glass (3)	Rate Total (4)
DRS Active	7.121 ***	−0.725	0.573	0.991
	(1.994)	(3.184)	(3.262)	(1.795)
Log GDP per Capita	22.183 ***	58.571 ***	44.172 ***	25.298 ***
	(3.727)	(5.967)	(5.110)	(3.365)
Env. Tax (% GDP)	2.540 **	4.009 **	8.753 ***	3.072 ***
	(1.223)	(1.960)	(1.701)	(1.102)
Log Pop. Density	48.405 ***	96.399 ***	67.334 ***	62.465 ***
	(8.277)	(13.270)	(11.506)	(7.454)
Log Tourism Intensity	10.245 ***	6.125 **	4.549 *	6.988 ***
	(1.754)	(2.803)	(2.429)	(1.580)
Constant	−56.657 **	−256.235 ***	−330.357 ***	−108.212 ***
	(28.467)	(43.524)	(40.866)	(24.912)
Observations	619	618	619	619
R^2	0.285	0.315	0.227	0.302
Adjusted R^2	0.246	0.278	0.184	0.264
F Statistic	46.683 ***	53.895 ***	34.331 ***	111.194 ***

Notes: *** Significance level at 1%, ** Significance level at 5%, * Significance level at 10%. Standard errors in parentheses. Source: Authors' calculations.

The regression results highlight the critical role of structural economic and demographic factors. GDP per capita exhibits a consistently positive and statistically significant coefficient across all specifications, in line with expectations. While GDP per capita is statistically associated with higher recycling performance, the underlying mechanism cannot be conclusively identified from the data alone. Plausible channels include greater fiscal capacity to invest in collection and sorting infrastructure, broader social acceptance of environmental regulation in wealthier societies and complementary policy frameworks that typically accompany economic development.

Population density emerges as the single largest predictor of recycling efficiency across all materials. The positive coefficient reflects, on average, the lower marginal cost of operating collection networks in densely populated areas, where return points are more readily accessible to citizens compared to remote rural regions. This average relationship, however, masks considerable within-country heterogeneity: highly urbanised settings can face specific constraints, including limited space for return-vending machines, traffic regulations and the prevalence of multi-residence housing without dedicated separation infrastructure, that may attenuate or even reverse the relationship at the most densely populated end of the distribution.

Similarly, tourism intensity shows a positive and significant relationship with recycling rates. This association is likely driven by the high consumption of single-use beverage packaging in tourist zones, which generates a concentrated stream of high-quality recyclable material. Furthermore, tourist areas, particularly during peak seasons, exhibit above-average densities of retail and hospitality establishments, providing a more extensive deposit–refund network. In these high-consumption zones, the collection of returnable

packaging is often organised directly within hospitality and commercial establishments rather than relying solely on household-level returns, ensuring a higher return rate.

Finally, the coefficient for environmental tax revenues is consistently positive and statistically significant across all material fractions. This suggests that the effectiveness of specific waste management instruments, such as DRSs, is often reinforced by a broader national framework of strict environmental fiscal policies.

Beyond the binary presence of the system, the analysis highlights the role of the monetary incentive's magnitude relative to purchasing power. The model testing the relative deposit value (Table 4) yields a large, positive, and statistically significant coefficient for plastic. This result suggests that recycling outcomes for plastic packaging are positively related to the strength of the monetary incentive embedded in the DRS. It is also noteworthy that, although the aggregate effect for the total packaging recycling rate in this model is negative, it remains statistically insignificant. This further supports the conclusion that the price mechanism is primarily effective for the targeted plastic fraction.

Table 4. Impact of deposit value on recycling rates (fixed effects).

Variable	Rate Plastic (1)	Rate Metal (2)	Rate Glass (3)	Rate Total (4)
Deposit Value	27.500 ***	10.903	4.041	−2.043
	(10.203)	(17.167)	(26.475)	(11.441)
Log GDP per Capita	23.832 ***	57.411 ***	44.219 ***	25.948 ***
	(3.687)	(5.856)	(5.082)	(3.311)
Env. Tax (% GDP)	2.508 **	4.070 **	8.728 **	3.049 ***
	(1.229)	(1.961)	(1.698)	(1.103)
Log Pop. Density	47.131 ***	96.493 ***	67.266 ***	62.324 ***
	(8.313)	(13.210)	(11.481)	(7.453)
Log Tourism Intensity	10.477 ***	5.948 **	4.559 *	7.084 ***
	(1.760)	(2.797)	(2.426)	(1.579)
Observations	619	618	619	619
R^2	0.278	0.316	0.227	0.302
Adjusted R^2	0.259	0.278	0.184	0.264
F Statistic	45.180 ***	53.998 ***	34.332 ***	50.713 ***

Notes: *** Significance level at 1%, ** Significance level at 5%, * Significance level at 10%. Standard errors in parentheses. Source: Authors' calculations.

With respect to the non-policy control variables, the coefficients for GDP per capita, population density, environmental tax, and tourism intensity remain positive and statistically significant, consistent with the results observed in the previous specification (Table 3). This stability across different models confirms that structural economic and demographic factors are robust determinants of national recycling performance, operating independently of the specific design features of the deposit scheme.

Finally, the interaction analysis between deposit value and system age (Table 5) reveals that the system's effectiveness evolves differently over time depending on the material. For metal packaging, the interaction between deposit value and system age is positive and statistically significant, which may indicate gradual gains in the efficiency of collection networks as the system matures. For glass packaging the interaction coefficient is negative but not statistically distinguishable from zero, and we therefore refrain from drawing substantive conclusions from its sign. This pattern is, however, consistent with the institutional context: in the most European countries, glass beverage packaging is primarily managed through long-established refillable systems and separate collection schemes that predate DRS implementation, leaving limited scope for additional gains from the deposit instrument. As a result, higher deposit values and longer system duration do not lead

to substantial additional gains in return rates, as the scope for further improvement is limited. In summary, the econometric evidence confirms that while the DRS proves to be an effective tool increasing both the quantity and quality of plastic packaging collected, its aggregate impact on other materials is statistically neutral, serving primarily to improve material purity rather than total collected volume.

Table 5. Impact of system age and maturity on recycling rates (fixed effects).

Variable	Rate Plastic (1)	Rate Metal (2)	Rate Glass (3)	Rate Total (4)
Deposit Value	22.054 **	−11.149	13.137	0.043
	(11.037)	(18.769)	(28.719)	(12.490)
Log GDP per Capita	23.610 ***	56.837 ***	44.564 ***	26.018 ***
	(3.688)	(5.825)	(5.100)	(3.317)
Env. Tax (% GDP)	2.922 **	5.707 ***	8.485 **	2.927 **
	(1.270)	(2.034)	(1.725)	(1.142)
Log Pop. Density	46.051 ***	93.067 ***	67.677 ***	62.606 ***
	(8.351)	(13.188)	(11.495)	(7.488)
Log Tourism Intensity	10.149 ***	4.768 *	4.679 *	7.172 ***
	(1.777)	(2.812)	(2.431)	(1.594)
Deposit × System Age	0.756	3.042 ***	−1.396	−0.293
	(0.586)	(1.078)	(1.705)	(0.702)
Observations	619	618	619	619
R^2	0.280	0.325	0.227	0.302
Adjusted R^2	0.260	0.267	0.184	0.263
F Statistic	37.969 ***	46.862 ***	28.785 ***	42.219 ***

Notes: *** Significance level at 1%, ** Significance level at 5%, * Significance level at 10%. Standard errors in parentheses. Source: Authors' calculations.

5. Discussion

The results of the analysis are highly relevant in the context of the European Union's environmental objectives and the transition towards a circular, low-carbon economy, particularly in light of the evolving regulatory framework shaped by the Packaging and Packaging Waste Regulation (PPWR). The PPWR places strong emphasis on increasing separate collection rates of packaging waste and improving recycling performance, with DRSs identified as a key policy instrument for achieving these goals. Although the results indicate that a DRS does not have a homogeneous effect on the recycling rates of different types of packaging waste (plastic, glass, and metal), this finding implies the need for further research as well as for the adjustment and refinement of more effective, material-specific policies and their implementation across different packaging waste streams. The results show that DRSs do not have the same effect on different types of packaging waste. Their effectiveness depends on the packaging material, as well as on the broader context in which the system operates. The results should be interpreted in a way that takes into account the policies and institutions that guide waste management, because the effectiveness of DRSs depends not only on their implementation, but also on the development of recycling infrastructure, civilian participation, as well as extended producer responsibility systems and the European Union's circular economy goals. The most pronounced and statistically significant effect of a DRS is observed for plastic packaging waste (PET). By contrast, no statistically significant effect is confirmed for metal/aluminium and glass packaging waste in the fixed-effects model. The confirmation of a statistically significant effect of a DRS on PET packaging waste is consistent with EU policy priorities, which place a strong focus on plastic pollution as one of the most pressing environmental challenges due to the relatively low recycling rates of plastic and its substantial environmental impacts.

Furthermore, the deposit level has a strong effect on plastic packaging waste outcomes: a higher financial incentive increases the opportunity cost of improper disposal, thereby contributing to higher return rates through the DRS. In contrast, the effect of DRSs is less pronounced for metal and glass packaging. This can be explained by the fact that return rates for metal and glass packaging were already high prior to the introduction of DRSs, supported by well-developed waste management policies and established separate collection systems. In the case of glass packaging waste, an additional factor is that a substantial share of this packaging is used as refillable, multi-use packaging, which is collected outside the DRS and reused through processes, such as washing, disinfection, and repeated use.

The policy implications derived from this analysis suggest that local infrastructure should align closely with circular economy policies by ensuring the presence of DRSs across all local and/or regional administrative units, extending producer responsibility, and regulating deposit levels in a way that ensures both the effectiveness and the financial viability of DRSs. Such policy measures should be designed with due consideration of structural factors, including population density, tourism intensity, and the existing packaging waste management systems. Structural factors, such as population density, also play an important role in explaining cross-country differences in recycling rates, as does tourism. Tourism has a positive effect because tourist areas typically feature a high concentration of hospitality and retail establishments, which implies a denser and more accessible DRS network (collection points for beverage packaging), alongside higher consumption of beverages in single-use packaging.

These results suggest that DRSs should not necessarily be viewed as a single, one-size-fits-all solution for increasing recycling and collection rates of packaging waste. Instead, their purpose and outcomes should be aligned with national waste management policies, including decisions on deposit levels, the scope and volume of packaging covered by the system, spatial conditions (such as locations and available space for implementation), economic feasibility (implementation costs), and the operational and management costs of the system. The deposit system for beverage packaging is a huge, circular business model of many stakeholders [9]. These include producers, retailers, system operators, consumers, waste management companies, and recyclers, each of whom plays a specific role in ensuring the effective functioning of the system.

These findings have several concrete implications for policymakers. First, although DRS introduction is associated with a statistically significant increase in plastic recycling rates, the magnitude of this effect alone, approximately 7 percentage points, is unlikely to be sufficient on its own to bridge the gap between current EU wide collection rates for plastic beverage containers and the 90% target set under the Packaging and Packaging Waste Regulation. Member States that already operate a DRS but have not reached the 90% threshold face the additional challenge of improving the design and reach of their existing systems rather than relying on the structural shift induced by initial introduction. Second, the absence of a uniform effect across materials cautions against treating the DRS as a one-size-fits-all instrument. The strong response observed for plastic likely reflects relatively low baseline recycling rates for this fraction, while the limited response for metal and glass is consistent with mature collection infrastructure that predates DRS implementation in most of the observed countries.

From a business perspective, the implications mainly involve encouraging producers to adopt eco-design principles that facilitate recyclability, improve compatibility with DRS requirements, and enhance the efficiency of sorting and pre-recycling processes. For producers, deposit-related costs should not be viewed solely as a regulatory burden; rather, they are an integral component of circular packaging waste management and directly

influence production costs. High return rates of packaging waste achieved through DRSs, coupled with high recycling rates, enhance the security of supply for recycled materials, which is a cornerstone of the circular economy, particularly in the context of the PPWR, which mandates increasing shares of recycled content in products.

6. Conclusions

Using a panel regression method, this study examined the impact of DRSs on the recycling rates of packaging waste in European countries for the period 1997–2023. The packaging waste fractions, namely plastic (PET), metal (Al/Fe), and glass beverage packaging waste, and their impact on recycling through DRSs, were analysed separately. The results indicate material specific differences in the associations between the DRS variables and recycling rates with the strongest and most consistent evidence for plastic packaging. For metal and glass packaging, the evidence is weaker, and coefficients are not statistically significant.

The main conclusion is that the DRS is strongly and positively associated with higher recycling rates for plastic (PET) beverage packaging, particularly when the deposit fee is high relative to purchasing power. For metal and glass packaging, the impact of DRSs is not statistically significant, which can be explained by the relatively high recycling rates of these fractions even before the introduction of DRSs, given well-established waste management systems and policies. However, we can conclude that in this case, the DRS plays a role in improving and increasing the separate collection of packaging waste and ensuring good quality of the aforementioned fractions. Successful implementation therefore depends not only on civilian participation but also on coordination across the entire value chain and the availability of adequate collection and recycling infrastructure. Society is also a crucial stakeholder in this system, as its acceptance and active participation are essential for the long-term viability of the deposit–refund scheme.

The analysis also showed that structural factors such as population density and tourism intensity have a strong impact on recycling efficiency, primarily through increased consumption, and therefore on the collection of packaging waste after beverage consumption. In accordance with the existing literature, GDP as a key macroeconomic variable demonstrates a strong influence on efficiency levels, which is also reflected in waste management performance.

Accordingly, the results demonstrate that a well-designed DRS can be a highly effective tool for increasing recycling rates and thus directly contributing to the objectives of a circular economy. Although the DRS is effective in certain segments, it does not constitute a dominant instrument within the circular waste management system. It operates in synergy with other policies and instruments. Overall, research shows that DRSs can contribute to improved packaging waste management, particularly for plastic beverage packaging, but their long-term effectiveness depends on integration with broader waste management policies and circular economy strategies.

While this study offers important insights into DRSs, it has some limitations, notably its reliance on secondary data sources, as data quality can vary over time between the observed countries. In addition, the study did not fully capture differences in packaging waste management practices, public awareness, or civilian behaviour, and did not include the carbon footprint, i.e., reduction in harmful emissions, which could be considered possible directions for future research. Another limitation is the simplified DRS variable. Namely, the binary DRS variable and the deposit value indicator do not fully capture differences in rebate systems such as their coverage of materials, infrastructure, civilian convenience, and other differences that exist in DRSs. Furthermore, important design dimensions such as the spatial density of the return point, the legal obligation of retailers

to accept empty containers, the share of refillable versus single-use containers covered by the system, and the convenience of return-to-retail versus depot-based collection are not directly observable for the entire sample period and may explain part of the cross-country variation in performance that the present specification attributes to structural controls. The construction of a richer DRS design, possibly drawing on detailed information from sources such as the Reloop Platform Global Deposit Book, represents a promising direction for future research.

Author Contributions: Conceptualization, R.N. and L.J.R.; methodology, R.N. and L.J.R.; software, R.N.; formal analysis, R.N. and L.J.R.; resources, R.N.; writing—original draft preparation, R.N. and L.J.R.; writing—review and editing, R.N. and L.J.R.; visualisation, R.N. and L.J.R.; supervision, L.J.R.; project administration, R.N. and L.J.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data used are publicly available.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Al/Fe	Aluminium/Iron (Ferrum)
ANOVA	Analysis of Variance
DRS	Deposit–refund system
EU	European Union
GDP	Gross Domestic Product
OECD	Organization for Economic Co-operation and Development
PET	Polyethylene Terephthalate
PPWR	Packaging and Packaging Waste Regulation

Appendix A

Table A1. Summary information about the DRS across the sample of European countries.

Country	Year of Implementation	Deposit Value (EUR)	Redemption Model	Status
Austria	2025	0.25	R2R	Operational
Belgium	Planned (2026)	0.05–0.30	Partial	Partial
Bulgaria	—	—	—	No
Cyprus	—	—	—	No
Czechia	Planned	—	—	Planned
Germany	2003	0.25	R2R	Operational
Denmark	2002	0.13–0.40	R2R	Operational
Estonia	2005	0.10	R2R	Operational
Spain	Planned (2026)	—	—	Planned
Finland	1996	0.10–0.40	R2R	Operational

Table A1. *Cont.*

Country	Year of Implementation	Deposit Value (EUR)	Redemption Model	Status
France	—	—	—	No
Croatia	2006	0.07	R2R	Operational
Hungary	2024	0.13	R2R	Operational
Ireland	2024	0.15–0.25	R2R	Operational
Iceland	1989	0.12	Depot	Operational
Italy	—	—	—	No
Lithuania	2016	0.10	R2R	Operational
Luxembourg	—	—	—	No
Latvia	2022	0.10	R2R	Operational
Malta	2022	0.10	Hybrid	Operational
Netherlands	2005	0.15–0.25	R2R	Operational
Norway	1999	0.17–0.26	R2R	Operational
Poland	Planned	—	—	Planned
Portugal	Planned (2026)	—	—	Planned
Romania	2023	0.10	R2R	Operational
Sweden	1984	0.09–0.18	R2R	Operational
Slovenia	—	—	—	No
Slovakia	2022	0.15	R2R	Operational

Source: Reloop Platform (Global Deposit Book).

Table A2. Impact of DRS implementation on recycling rates (random effects).

Variable	Rate Plastic (1)	Rate Metal (2)	Rate Glass (3)	Rate Total (4)
DRS Active	9.196 ***	3.613	2.031	3.501*
	(1.987)	(3.184)	(3.164)	(1.800)
Log GDP per Capita	5.933 **	31.384 ***	34.288 ***	13.995 ***
	(2.681)	(4.157)	(3.848)	(2.369)
Env. Tax (% GDP)	−2.685 **	−5.899 ***	3.428 *	−2.332 *
	(1.067)	(1.715)	(1.873)	(0.967)
Log Pop. Density	4.361 **	2.173	8.202 ***	4.137 ***
	(1.733)	(2.612)	(2.709)	(1.499)
Log Tourism Intensity	7.869 ***	2.362	0.469	3.756 ***
	(1.600)	(2.536)	(2.254)	(1.437)
Constant	−53.634 *	−262.435 ***	−330.731 ***	−104.246 ***
	(28.066)	(43.398)	(40.853)	(24.750)
Observations	619	618	619	619
R^2	0.159	0.169	0.147	0.150
Adjusted R^2	0.153	0.162	0.140	0.143
F Statistic	110.315 ***	130.547 ***	117.688 ***	114.355 ***

Notes: *** Significance level at 1%, ** Significance level at 5%, * Significance level at 10%. Standard errors in parentheses.

Table A3. Impact of deposit value on recycling rates (random effects).

Variable	Rate Plastic (1)	Rate Metal (2)	Rate Glass (3)	Rate Total (4)
Deposit Value	35.342 ***	27.784	12.808	11.492
	(10.297)	(17.431)	(26.107)	(11.660)
Log GDP per Capita	6.591 **	30.763 ***	34.318 ***	14.577 ***
	(2.715)	(4.161)	(3.849)	(2.379)
Env. Tax (% GDP)	−2.763 **	−5.889 ***	3.402 **	−2.343 **
	(1.075)	(1.713)	(1.473)	(0.960)
Log Pop. Density	3.590 **	4.091	8.078 ***	3.769 **
	(1.731)	(2.570)	(2.690)	(1.496)
Log Tourism Intensity	8.503 ***	2.509	0.531	3.989 ***
	(1.604)	(2.519)	(2.244)	(1.435)
Constant	−56.637 **	−256.235 ***	−330.357 ***	−108.212 ***
	(28.467)	(43.524)	(40.866)	(24.912)
Observations	619	618	619	619
R^2	0.147	0.171	0.147	0.147
Adjusted R^2	0.140	0.164	0.140	0.140
F Statistic	99.482 ***	131.878 ***	117.400 ***	111.194 ***

Notes: *** Significance level at 1%, ** Significance level at 5%. Standard errors in parentheses.

Table A4. Impact of system age and maturity on recycling rates (random effects).

Variable	Rate Plastic (1)	Rate Metal (2)	Rate Glass (3)	Rate Total (4)
Deposit Value	25.684 **	−3.752	31.962	7.524
	(11.446)	(19.661)	(29.089)	(13.103)
Log GDP per Capita	6.627 **	30.491 ***	31.847 ***	14.624 ***
	(2.746)	(4.197)	(3.849)	(2.379)
Env. Tax (% GDP)	−2.000 *	−3.645 **	2.854 *	−2.106 **
	(1.138)	(1.821)	(1.498)	(1.028)
Log Pop. Density	4.098 **	5.548 **	6.501 ***	3.958 ***
	(1.774)	(2.638)	(2.240)	(1.522)
Log Tourism Intensity	8.191 ***	1.506	−0.628	3.922 ***
	(1.620)	(2.538)	(2.173)	(1.451)
Deposit × System Age	1.170 *	3.800 ***	−2.122	0.497
	(0.616)	(1.133)	(1.766)	(0.748)
Constant	−60.754 **	−264.546 ***	−295.196 ***	−110.169 ***
	(28.748)	(43.847)	(36.716)	(25.124)
Observations	619	618	619	619
R^2	0.154	0.188	0.137	0.149
Adjusted R^2	0.146	0.180	0.129	0.140
F Statistic	105.871 ***	147.184 ***	115.700 ***	112.546 ***

Notes: *** Significance level at 1%, ** Significance level at 5%, * Significance level at 10%. Standard errors in parentheses. Source: Authors' calculations.

References

1. Council of the European Union. Packaging Policy. 2024. Available online: https://www.consilium.europa.eu (accessed on 12 January 2026).
2. Avilés-Palacios, C.; Rodríguez-Olalla, A. The sustainability of waste management models in circular economies. *Sustainability* **2021**, *13*, 7105. [CrossRef]
3. European Union. Circular Economy—EU Law. 2026. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:circular_economy (accessed on 10 January 2026).
4. European Union. Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on Packaging and Packaging Waste. Official. J. European Union. 2025. Available online: https://eur-lex.europa.eu/eli/reg/2025/40/oj (accessed on 10 January 2026).

5. European Parliament. Sustainable Waste Management: What the EU Is Doing. 2024. Available online: https://www.europarl.europa.eu (accessed on 10 January 2026).
6. Schneider, R.D.; Tomić, T.; Raal, R. Economic viability of the deposit refund system for beverage packaging waste-identification of economic drivers and system modelling. *J. Sustain. Dev. Energy Water Environ. Syst.* **2021**, *9*, 1090386. [CrossRef]
7. OECD. *Deposit-Refund Systems for Beverage Containers: Lessons for Implementation*; OECD Publishing: Paris, France, 2021. Available online: https://www.oecd.org/en/publications/deposit-refund-systems-and-the-interplay-with-additional-mandatory-extended-producer-responsibility-policies_a80f4b26-en.html (accessed on 24 November 2025).
8. Fullerton, D.; Wolverton, A. *The Case of a Two-Part Instrument: Presumptive Tax and Environmental Subsidy*; Working Paper; National Bureau of Economic Research: Cambridge, MA, USA, 1997; p. 5993.
9. Zarębski, A.; Zarębska, J.; Marosek, K. Implementation of the deposit system in Poland as a tool for implementing the circular economy. *Energies* **2024**, *17*, 5489. [CrossRef]
10. Picuno, C.; Gerassimidou, S.; You, W.; Martin, O.; Iacovidou, E. The potential of Deposit Refund System in closing the plastic beverage bottle loop: A review. *Resour. Conserv. Recycl.* **2025**, *212*, 107962. [CrossRef]
11. Tarantino, M.; Mosconi, E.M.; Tola, F.; Gianvincenzi, M.; Delussu, A.M. A comprehensive and multidisciplinary framework for advancing circular economy practices in the packaging sector: A systematic literature review on critical factors. *Sustainability* **2026**, *18*, 192. [CrossRef]
12. Torkelis, A.; Dvarionienė, J.; Denafas, G. Factors influencing recycling of plastic and composite packaging waste. *Sustainability* **2024**, *16*, 9515. [CrossRef]
13. Di Foggia, G.; Beccarello, M. An overview of packaging waste models in some European countries. *Recycling* **2022**, *7*, 38. [CrossRef]
14. Reloop Platform. Deposit Return Systems: Key Factors Impacting Performance. 2025. Available online: https://www.reloopplatform.org/wp-content/uploads/2025/11/20251124_Key-factors-impacting-DRS-performance_FactSheet_vFinal.pdf (accessed on 24 November 2025).
15. Walls, M. *Deposit-Refund Systems in Practice and Theory*; RFF Discussion Paper 11–47; Resources for the Future: Washington, DC, USA, 2011.
16. GS1 in Europe. *Deposit Return Schemes in Europe. Version 1*; GS1 in Europe: Brussels, Belgium, 2024.
17. Konstantoglou, A.; Fotiadis, T.; Folinas, D.; Falaras, A.; Rotsios, K. Accessing consumer perceptions of the effectiveness of the deposit refund system. *Sustainability* **2023**, *15*, 9429. [CrossRef]
18. Folinas, D.; Rotsios, K.; Agapitou, C.; Folina, M.-T.; Fotiadis, T. Challenges in implementing deposit refund systems: A stakeholder analysis of the beverage industry. *Recycling* **2025**, *10*, 222. [CrossRef]
19. Waste Managed. The UK Deposit Return Scheme Explained. Available online: https://www.wastemanaged.co.uk/our-news/laws-regulations/the-uk-deposit-return-scheme-explained/ (accessed on 14 January 2026).
20. European Commission. *Strategy on Plastics in a Circular Economy*; European Commission: Brussels, Belgium, 2017.
21. Agnusdei, G.P.; Gnoni, M.G.; Sgarbossa, F. Are deposit-refund system effective in managing glass packaging? State of the art and future directions in Europe. *Sci. Total Environ.* **2022**, *851*, 158256. [CrossRef] [PubMed]
22. Sidorczuk-Pietraszko, E.; Piontek, W.; Larsson, A. Are deposit-return schemes an optimal solution for beverage container collection in the EU? An Evidence Review. *Sustainability* **2025**, *17*, 8791. [CrossRef]
23. Calabrese, A.; Costa, R.; Di Pillo, F.; Haqbin, A.; Ghiron, N.L.; Tiburzi, L. Turning waste into value: A design strategy for sustainable deposit-refund systems. *Bus. Strat. Environ.* **2026**, *35*, 1532–1548. [CrossRef]
24. Croci, E.; Colleli, F.; Zanini, F.Z.; Pontoni, F. *Screening the Efficiency of Packaging Waste in Europe*; Bocconi University, GREEN Centre: Milan, Italy, 2022.
25. Zorpas, A.A. Promoting circular economy: The transformative impact of deposit refund systems. *Waste Manag. Res.* **2024**, *42*, 1093–1095. [CrossRef] [PubMed]
26. Kang, D.; Auras, R.; Singh, J. Life cycle assessment of non-alcoholic single-serve polyethylene terephthalate beverage bottles in the state of California. *Resour. Conserv. Recycl.* **2017**, *116*, 45–52. [CrossRef]
27. Lavee, D. A cost-benefit analysis of a deposit–refund program for beverage containers in Israel. *Waste Manag.* **2010**, *30*, 338–345. [CrossRef] [PubMed]
28. Zhou, G.; Gu, Y.; Wu, Y.; Gong, Y.; Mu, X.; Han, H.; Chang, T. A systematic review of the deposit-refund system for beverage packaging: Operating mode, key parameter and development trend. *J. Clean. Prod.* **2020**, *251*, 119660. [CrossRef]
29. Eurostat. Eurostat Database. Average Full-Time Adjusted Salary per Employee. 2025. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/nama_10_fte__custom_19292890 (accessed on 12 November 2025).
30. Eurostat. Eurostat Database. Packaging Waste by Waste Management Operation. 2025. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/env_waspac__custom_19286369 (accessed on 21 October 2025).
31. Eurostat. Eurostat Database. Recycling Rates for Packaging Waste. 2025. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/env_waspacr__custom_19088779 (accessed on 21 October 2025).

32. Baltagi, B.H. *Econometric Analysis of Panel Data*, 6th ed.; Springer: Cham, Switzerland, 2021. [CrossRef]
33. Wooldridge, J.M. *Econometric Analysis of Cross Section and Panel Data*, 2nd ed.; MIT Press: Cambridge, MA, USA, 2010.
34. Greene, W.H. *Econometric Analysis*, 8th ed.; Pearson: New York, NY, USA, 2018.
35. Hausman, J.A. Specification Tests in Econometrics. *Econometrica* **1978**, *46*, 1251–1271. [CrossRef]
36. Mundlak, Y. On the pooling of time series and cross section data. *Econometrica* **1978**, *46*, 69. [CrossRef]

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