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Review

The potential of Deposit Refund Systems in closing the plastic beverage bottle loop: A review

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ABSTRACT

This critical review assesses the implementation and impact of Deposit Return Schemes (DRSs), also referred to as ‘Deposit Refund Systems’ and ‘Deposit Return Systems’ in international contexts, focusing on plastic beverage bottles. The review explores the multi-dimensional challenges that shape effective DRS implementation. A total of 143 peer-reviewed articles and grey literature studies were analysed based on DRS definitions, scope, year of implementation, materials involved, and impacts across multiple dimensions (technical, social, economic, regulatory, and environmental). Emphasising Europe, the study outlines the multi-dimensional challenges and opportunities associated with DRSs. Key findings highlight the critical importance of balancing redemption locations, deposit values, and public awareness, as reflected in varying return rates in different countries. While industry stakeholders advocate for standardising DRS models to maximise economic and technical value in the plastic bottle value chain, significant European-wide and regional-specific challenges such as harmonizing legal requirements, potential trade-offs, and addressing environmental and transportation costs, persist. This underscores the ongoing need for evaluation and refinement of DRS implementation strategies within evolving waste management practices. As the first of its kind, this study underscores the necessity for future research to inform the sustainability assessment of DRS, policy development, and efforts to promote social accountability.

1. Introduction

Governments worldwide have taken decisive steps to reduce, reuse, and recycle plastic waste, recognizing the urgency as global plastics production reached 390.7 million metric tonnes (Mt) in 2021 (Plastics Europe, 2022). Packaging, a significant flow in the plastics value chain accounting for 44 % of global plastic production (Plastics Europe, 2022), has come under increased scrutiny due to the vast amounts of plastic packaging produced and placed on the market annually (Plastics Europe, 2022). The proliferation of plastic packaging contributes significantly to plastic waste and litter, posing transboundary challenges for environmental and human health.

To address the plastic waste crisis, the European Union (EU) has developed a Plastics Strategy as part of the EU Circular Economy Action Plan, aimed at driving industry efforts to combat plastic pollution. A key component of this strategy is the Directive on the reduction of the impact of certain plastic products on the environment, commonly known as the Single-use Plastics (SUP) Directive (2019/904) (European Commission, 2019). This directive seeks to prevent and reduce the environmental impact of plastic products, marking a significant step towards a more sustainable future. The Directive also sets ambitious separate collection targets for plastic beverage bottles, to achieve a collection rate of 77 % by weight of products placed on the market in a given year by 2025, and 90 % by weight by 2029 (European Commission, 2019). In addition, it mandates that polyethylene terephthalate (PET) beverage bottles must contain 25 % recycled plastic by 2025, and all plastic beverage bottles (regardless of polymer type) must contain 30 % recycled plastic by 2030. This initiative complements the plastic contribution, or "plastic tax", introduced in January 2021 as part of the NextGeneration EU plan. Under this policy, Member States are required to pay EUR 0.80 per

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kilogram of non-recyclable plastic packaging waste, whether produced domestically or imported (European Union Council, 2020). Each country has the discretion to determine its implementation strategy for these mandates. From a regulatory perspective, the Packaging and Packaging Waste Regulation (PPWR) proposal is significant. It aims to amend Regulation (EU) 2019/1020 (concerning market surveillance of certain products) and the Single-use Plastics (SUP) Directive (2019/904) and repeal the EU Packaging and Packaging Waste Directive (94/62/EC). The PPWR proposal sets a minimum recycled content for PET bottles of 30 % by weight by 2030.

PET is the most used polymer in the beverage industry, with a total of 3.6 Mt[1] placed on the EU27 and the UK markets in 2022 (EUNOMIA, 2022). PET beverage bottles are the cleanest SUP waste stream and thereby, the most widely collected plastic packaging material, presenting a relatively high recyclability potential compared to other plastic packaging products (Gerassimidou et al., 2022). However, achieving closed-loop recycling is challenging due to chemical contamination from design components and the inefficiency of waste collection systems, such as kerbside collection (Gerassimidou et al., 2022). To address these issues, the PPWR proposal mandates that Member States implement deposit return schemes (DRS) for single-use plastic beverage bottles by 2029. Nevertheless, an exemption is available for countries that can demonstrate a minimum 90 % collection rate of beverage bottles through other separate collection methods (European Commission, 2022).

DRS, also known as "Deposit Refund System" and "Deposit Return System", particularly in international contexts, is defined as a "*surcharge on the price of potentially polluting products, with a refund of the surcharge granted when pollution is avoided by returning the products or their residuals*" (United Nations, 1997). It combines consumer-centred tax and incentive mechanisms that are designed to encourage the return of used goods, thereby minimizing potential environmental pollution. The core principle is to provide consumers with a rebate or refund of the surcharge added to the beverage product at the point of purchase when the packaging is returned to a designated collection point once emptied (Calabrese et al., 2021; Krzywda, 2022; Malindzakova et al., 2022; Walls, 2011; Zhou et al., 2020). Zhou et al. (2020) and Malindzakova et al. (2022) suggest that DRS can serve several functions within the waste management system. Specifically, they can: 1) increase the quality and quantity of collected materials and reduce littering; 2) contribute to high collection rates of valuable and recyclable materials; and 3) shift costs and responsibilities associated with the product's end-of-life phase from municipalities to producers, emphasizing the importance of Extended Producer Responsibility (EPR) regulations.

In Europe, the first nationwide DRS for PET beverage bottles was institutionalized in Iceland in 1989. Since then, the system has gained increasing traction, with Germany and Sweden enacting DRS for PET containers in 1991, followed by Norway in 1997. Other countries, including Denmark (2002), the Netherlands (2005), Estonia (2005), Croatia (2006), Finland (2008), Lithuania (2016), and Slovakia (2022), adopted DRS in the 2000s. The primary drivers for implementing this collection strategy were studies indicating that DRS for beverage bottles could achieve a return rate of approximately 95 % (Brisson, 1993). The high demand for PET beverage bottle waste and the low contamination levels offered by DRS have made them a compelling collection strategy (Cáceres Ruiz and Zaman, 2022). However, the effectiveness of DRS implementation varies due to country-specific factors (Zhou et al., 2020).

At present, the scientific literature on the potential of DRS to increase plastic recycling rates and wider sustainability benefits is sparse. Most studies focus on one or two aspects, such as economic/financial, logistical, social, environmental, technological, or regulatory/political domains. This study collates evidence from countries that have operationalised and implemented DRS to provide a comprehensive understanding of their potential benefits in closing the PET beverage bottle loop and promoting sustainability within the plastics value chain. It examines DRS across five key dimensions: technical, social, economic, regulatory, and environmental (Section 3). Using existing DRS as case studies, the study explores the conditions under which this system can enhance closed-loop recycling of PET beverage bottles and highlights factors that could enable or hinder its implementation. While recognizing the importance of region-specific factors, the study critically discusses ways in which DRS can be implemented to promote sustainable circularity in the plastic food packaging value chain (Section 4).

2. Methodology

Our study employs a systematized approach to retrieving evidence, which differs from the more stringent systematic evidence-mapping methodology. We adhered to 18 out of the 71 COSTER recommendations, with details provided in the Supporting Information (Table S1). The research question, designed to articulate the study's objectives, was formulated using a PIO (Population-Intervention-Outcome) statement, as outlined in Table 1, given the absence of a comparator.

Search Strategy: A distinct search strategy was developed for each of two types of literature: peer-reviewed literature and grey literature. The search strategy was formulated by employing a combination of notations, utilizing wildcards, proximity operators, and synonyms for terms such as deposit return scheme/system, deposit refund scheme/system, advanced disposal/recovery fee, reverse vending machine/system and beverage plastic container/bottle/packaging. For the peer-

Table 1
PIO statement and eligibility guidelines for the identification of challenges and opportunities of DRS establishment for closed-loop recycling of plastic beverage bottles.

PIO Statement		Inclusion[1]	Exclusion[1]
Population	Countries and communities around the world	Existing or proposed DRS in any geographical location, including studies without country-specific focus	None
Intervention	DRS for plastic beverage containers	DRS in the value chain of plastic beverage bottles	DRS for cans, glass or non-beverage plastic materials
Outcome	Multidimensional value of DRS including technical, social, economic, regulatory and environmental facets	Challenges, opportunities and trade-offs stemming from the implementation of *Intervention* from a multidimensional perspective; Recent evidence (2015 onwards) on DRS features implemented in Europe (a criterion applied in the grey literature)	Content that addresses challenges, opportunities, and trade-offs outside the plastic beverage bottles value chain and is not related to the implementation of DRS; Evidence predating 2015 regarding Deposit Return Schemes (DRS) implemented in Europe, or evidence on DRS features implemented outside of Europe (a criterion applied in the grey literature)

[1] Extrapolated figure based on EUNOMIA report on amount of PET placed on the EU and the UK market and estimates suggesting that 97% of the PET placed on the EU and UK markets has been used in the packaging sector, with beverage bottles accounting for 64% from (EPBP, 2023).

reviewed literature, the search was conducted in two scientific bibliographic databases, Web of Science Advanced Search (WoS) and Scopus. There were no restrictions on publication year, however, non-English papers were excluded. The grey literature was searched separately to collect current evidence in terms of the collection efficiency of DRSs across European countries (Paez, 2017) and obtain more insights into the social, economic and regulatory spheres. From the results, reports published by non-profit organisations and governmental bodies were selected, filtering the results by year (considering studies from 2015 onwards). A total of 15 grey literature studies were identified, using the following parameters: quantitative data on DRS efficiency; quantified impacts on social, and economic regulatory spheres; and challenges and opportunities in the implementation of DRS.

Screening stage: This was carried out with the support of the online tool CADIMA (CADIMA, 2023) following the eligibility guidelines (Table 1) applied to the retrieved reference list from the two scientific databases. The first step of screening, as an initial consistency check step, was carried out by two researchers in parallel, i.e., 143 studies were screened after removing duplicates by reading titles and abstracts. At the end of the consistency check, CADIMA provided a kappa value of 0.6 indicating that the strength of agreement between the researchers is 'fair' therefore the second round of screening by reading the full text was conducted only by one researcher. The screening stage of the grey literature was conducted by only one researcher.

Data Extraction: the following data were extracted from each study: definition of the term *DRS*, geographical scope of the study; year of the study; material of the beverage bottle included in the study; whether the study covers an implemented DRS or a simulation thereof; technical/social/economic/regulatory/environmental dimensions. The evidence synthesis involves an in-depth examination of DRS models implemented worldwide focusing on European countries, as well as a narrative summary of main challenges, opportunities and trade-offs from a multidimensional perspective including economic, social, environmental and technical aspects.

3. Results

A total of 36 eligible studies from peer-reviewed literature were included in this work, as illustrated in Fig. 1 which details all stages of the literature-searching strategy. Four of these studies are literature reviews. Among the 36 studies, 17 focus on Europe and are dated from 2016 onwards. Seven studies focus on the USA, one on Canada, two on Australia, two on China, and one on Iran. The remaining studies address the DRS topic from a generic perspective without a country-specific focus. Regarding the focus of these studies, four European studies concentrate on economic/financial elements and another four on technical aspects. Social, environmental, and regulatory aspects are each covered by two studies, totalling 14 studies that focus on specific impact dimensions. The remaining studies adopt a broader perspective, providing a general assessment of the DRS.

From the grey literature, only six studies were included. Three of these studies provided quantitative data on the efficiency of DRS collection rates across the globe. One study by the Organisation for Economic Co-operation and Development (OECD) focussed on the regulatory and economic synergies between the DRS and the EPR schemes (Laubinger et al., 2022), whereas one study by Eunomia investigated the social and economic impacts of the DRS in New York City. Finally, one study by the Changing Markets Foundation and Break Free From Plastic Movement (2020) provided key figures on DRS in EU countries, with a particular focus on the challenges to the implementation of such a system.

According to the Reloop Platform (2020) report, 46 countries/states/provinces across the globe have implemented a DRS: 10 states in the USA, 11 provinces in Canada, 6 states in Australia, Israel, and 7

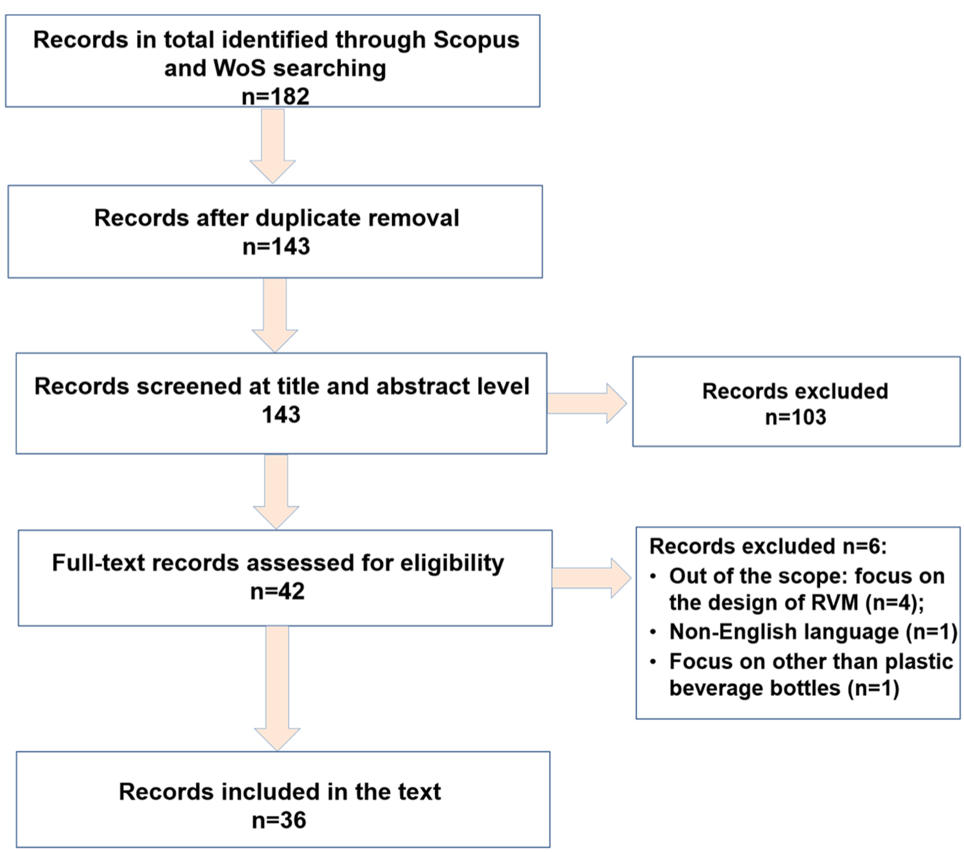

Fig. 1. Flow diagram of the steps of searching and screening the literature on the challenges and opportunities of DRS establishment for closed-loop recycling of plastic beverage bottles. (RVM: reverse vending machines).

islands in Oceania & Caribbean, as illustrated in Fig. 2. Nevertheless, this study focuses on DRS implementation in Europe due to the availability of relevant data and information.

In Europe, 11 countries have formally established a DRS for PET beverage bottles, while 13 more have decided to implement such a system but have not yet done so (EUNOMIA, 2022). Due to inconsistencies in the collection methodologies used across European countries, data on the PET beverage bottle return rates vary and information can be extracted mostly from personal communications between the reporting authorities and DRS operators' officials (Reloop, 2021). An exception to the general lack of rigorous data is a 2010 study by Infinitum in Norway. This study reported that the return rate for PET beverage bottles was 50 % in 1999, which increased steadily to 68 % in 2001, 78 % in 2003, and reached 90 % from 2009 onward (Infinitum (Norsk Resirk), 2010). Commonly, however, all studies emphasise that DRS implementation involves a clearly defined network of stakeholders, with the structure and dynamics of this network varying between countries.

3.1. The DRS stakeholders' network structures and dynamics

Literature evidence indicates that a network of stakeholders is intricately involved in the DRS system, and their in-between interactions and dynamics can lead to diverse DRS models. Dynamics refers to "*the changing attributes, roles, perceptions and intentions of stakeholders involved in the system leading to cause and effect relationships that evolve and change over time*" (Gerassimidou et al., 2022). The DRS stakeholders' network comprises five key groups: 1) DRS operators, 2) bottle producers and importers (upstream of the value chain), 3) wholesalers/retailers (upstream of the value chain), 4) consumers (midstream of the value chain), and 5) waste management chain (WMC) operators, or (re)processors (downstream of the value chain). Specifically, (Spasova, 2019):

- **DRS operators:** oversee the logistics system, regulate and often operate the collection and re-distribution of deposits among stakeholders. This involves the collection of *sales data* from bottle producers/importers, *return data* from retailers/collection points, and the preparation of regular public reports on the system's operation. Sales data, refers to information on the number of bottled products sold within a specific period, whereas return data, refers to the number of empty beverage containers returned to the retailers/collection points within a specific period. The latter involves a *producers' fee*, which is paid by the producers as part of the EPR scheme. Lastly, DRS operators can be a local authority, or a non-profit organisation established by public authorities to implement, administer, monitor and report on the DRS.

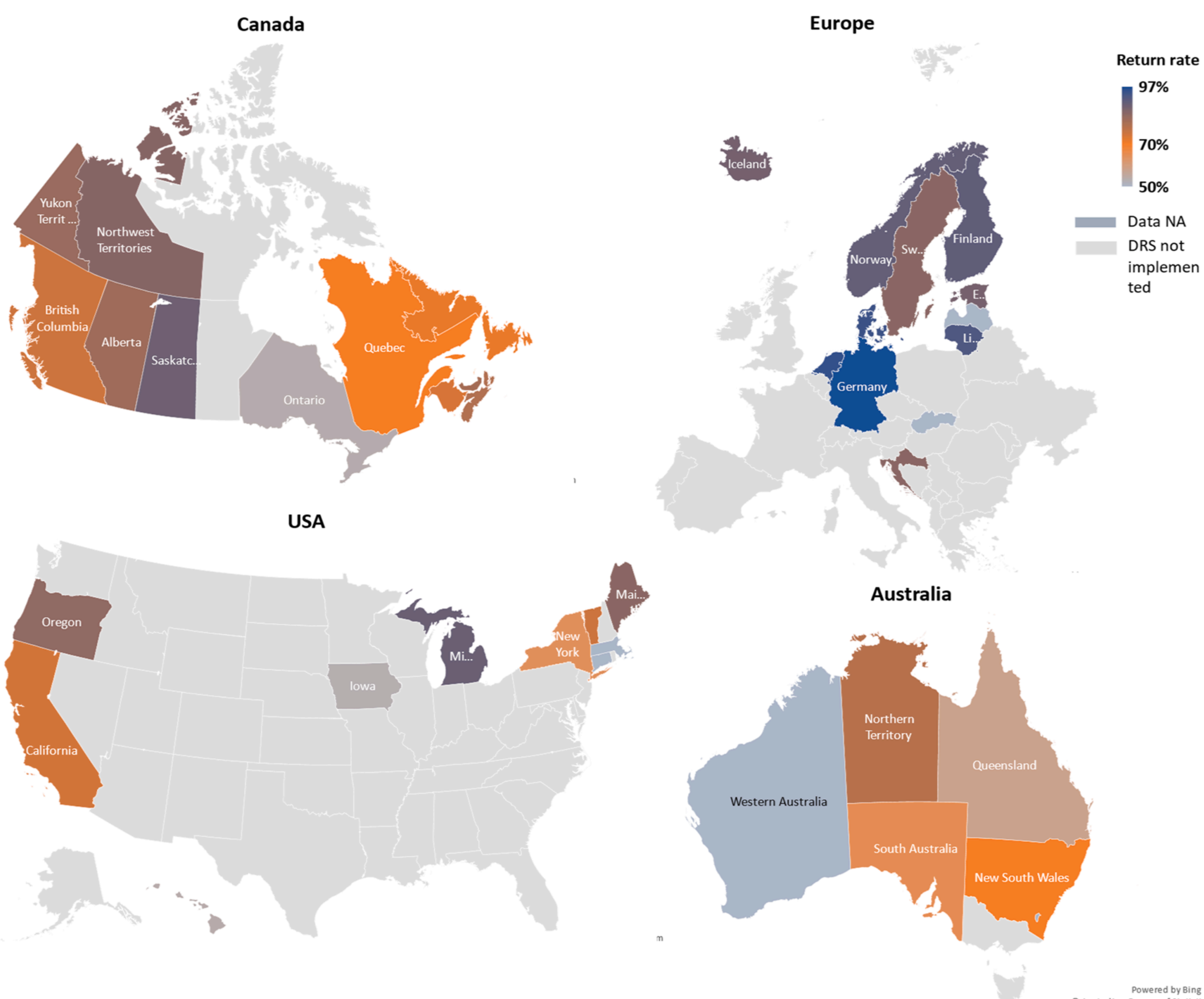

Fig. 2. DRS implementation globally with colour-coded return rates reported Reloop Platform (2020) for the year 2018/2019. Data for Connecticut, Maine, Massachusetts, Michigan, New York, Vermont, Yukon, New South Wales, Queensland, and South Australia are aggregated data, i.e., they are not specific for PET bottles but include other materials as well, e.g., aluminium cans and glass bottles. Note: available in *Supporting Information*, refer to the ratio of empty containers redeemed through the DRS over the total amount of them sold (in per cent, %).

- **Producers/importers**: are the manufacturers, brand owners or distributors of beverage products in plastic packaging. They are responsible for generating and reporting sales data to DRS operators. They are required to label bottles to indicate DRS inclusions and communicate the *deposit fee* to the consumer. The deposit fee is an additional charge on the bottled product, paid by the consumer (included in the price), and is refunded to the consumer upon returning the empty bottle to designated return points or reverse vending machines (RVM).
- **Wholesalers/retailers:** are the selling points for beverages (beverage bottles), and are often responsible for administering the DRS based on their space size (i.e., this determines whether they are small, medium, or large), which varies by country. Small retailers are not usually required to participate in the DRS, whereas big retailers are required to participate. Variations in retailer sizes across European countries, create discrepancies in the way DRS is implemented. For example, in Germany, retailers with a space area of >200 m^2 (Žmak and Hartmann, 2017) are considered large, whereas in Slovakia this is retailers with a space area of >300 m^2 (Malindzakova et al., 2022). Retailers/wholesalers are selling their beverage products; hence, they can also be producers/brand owners. As part of the DRS's value chain they are responsible for generating and submitting return data reports to DRS operators and are entitled to receiving a *handling fee* for storing, sorting and transferring empty beverage bottles to DRS operators. Furthermore, handling fees are calculated to cover expenses on RVM, possible manual collection, electricity, and storage costs, as well as additional required personnel.
- **Consumers**: are the end-users of the product and are responsible for returning empty bottles to collection points, in exchange for the deposit fee. Zhou et al. (2020) and Malindzakova et al. (2022) exemplify the role of consumers in the effectiveness of DRS implementation. As Malindzakova et al. (2022) posit, DRS dictates consumer involvement, as they actively manage the waste they generate, becoming integral stakeholders in the value chain.
- **Waste Management Chain (WMC):** are recipients of empty bottles for further processing. WMC includes the stages of collection, pre-processing (weighting, pre- and post-sorting), transport, shipment, and mechanical recycling.

Because of the varying roles and responsibilities of key stakeholders involved in a DRS, there are, according to Calabrese et al. (2021), four distinct DRS structures, referred to as archetypes. The differentiation amongst the four archetypes is primarily due to the monetary (transactional) flows; highlighting different responsibility levels and roles in orchestrating the collection of PET beverage bottles.

Table 2 provides an overview of the four archetypes of the DRS in Europe, developed based on the works of Calabrese et al. (2021); Reloop Platform (2020); Zhou et al. (2020).

Archetype A is a DRS operator-centred system, in which the DRS operator designs, manages and administers the system and material flows, financed primarily by the producers (Calabrese et al., 2021). It is the most implemented DRS model across European countries. At its final stage, the DRS operator sells the empty containers to the WMC, except in Croatia and Finland where retailers send the empty bottles directly to the WMC. In both cases, the retailers bear the costs of the transport, which is funded by the handling fee they receive from the DRS operator, while the WMC pays the material money value directly to the DRS operator, presenting an interesting dynamic and control mechanism of the flow of empty beverage bottles in the system.

In Archetypes B and C, the DRS operator is only responsible for the design of the DRS, and in C for the administration of the system, as well. Because of this, in Archetype B, there are many DRS operators, instead of one like in Archetypes A, C and D. The material flows and transactions occur mostly between producers (or delegated to a third party) and retailers, and retailers and WMC. The retailers in both archetypes play a central role in the efficient collection and recovery rates of PET beverage bottles. Usually, retailers and producers each have different service providers, which are responsible for collecting the return data and validating them by comparing the market trends and data in the previous years, before sending them to the central database. Because of the absence of a centralised DRS operator that administers and manages the system, the retailers bear the highest costs of material flow transactions in Archetype B, whereas in Archetype C the costs are shared between producers and retailers. It is worth noting that in Archetype C, the retailers pay an additional deposit fee to the producers per unit of beverage bottle purchased, which is not charged to the consumer. This provides retailers with an incentive to establish effective systems to ensure the return of the empty bottles back to the producer. If consumers fail to return the empty beverage bottles, the retailer forfeits the additional deposit fee they initially paid to the producer at purchase, creating a significant disadvantage for them.

Archetype D relies heavily on the active participation of both producers and consumers, with retailers playing a minimal role. After use, consumers are expected to return the empty bottles to designated collection points, which in some cases are set up by the DRS operator, to receive their deposit refund.

3.2. Multidimensional impacts of DRS implementation

This section aims to provide a comprehensive overview of the impacts of DRS implementation from a multidimensional perspective, covering environmental, economic, social, and technical aspects. The analysis is based on the studies included in the systematised evidence mapping, which offer limited insights into some of these domains. This limitation highlights the need for further research to fully understand the benefits and drawbacks of DRS in promoting sustainable circularity within the plastics value chain.

3.2.1. Environmental aspects

Among scientific studies examining the environmental aspects of dedicated PET bottle collection, none specifically evaluate the environmental performance of formally established DRS in Europe. Kuczenski and Geyer (2013) conducted a life cycle assessment (LCA) of the DRS in California for the years 2007 to 2009. This assessment considered collection routes via drop-off stations (at retailers or recycling centres) as well as at the kerbside (Kuczenski and Geyer, 2013; Reloop Platform, 2020) and focused on the environmental impacts associated with transportation distances throughout the value chain. However, the specific boundary conditions of this LCA are unique to California's DRS, making direct comparisons with systems in other regions difficult.

Transportation's significant contribution to environmental impacts was also noted by Simon et al. (2016). Similarly, Abejón et al. (2020) found that integrating DRS into existing waste management systems would result in higher negative impacts across all LCA categories except for Abiotic Depletion Potential (ADP), with emissions rising largely due to increased transportation demands.

3.2.2. Economic impacts

The main economic implications arising from DRS implementation are related to capital and operational costs. These costs are substantial and can be shared amongst the DRS stakeholders, as shown in Table 2; yet, generally, they are borne by the retailers. Retailers that are responsible for the return of empty beverage bottles have wide-ranging investment and operational costs, which vary depending on the collection system in place. High investment costs are usually associated with the procurement of reverse vending machines (RVMs). Cudečka-Puriņa et al. (2019) compared DRS implementation in Estonia (established in 2005) and Lithuania (established in 2016) and reported initial investments in the two countries of EURO 15 million and EURO 30 million, respectively (Cudečka-Puriņa et al., 2019; Laubinger et al., 2022). Concerning operational costs, manual collection and sorting entail higher staff requirements and transportation costs due to the

Table 2
Differences and similarities of the DRS archetypes currently implemented in Europe for plastic beverage bottles, with a focus on money flows. Adapted from Calabrese et al. (2021), Reloop Platform (2020), and Zhou et al. (2020). The money flows are denoted with either a (+) to indicate revenue/income or (-) to indicate cost. Each stakeholder is colour-coded to make their in-between interactions distinct. WMC: waste management companies.

		Archetype A	Archetype B	Archetype C	Archetype D
	Implemented in (implementation model may vary in Archetype A)	Sweden, Norway, Denmark, Estonia, Lithuania, Slovakia, Croatia, Finland, Latvia	Germany	The Netherland	Iceland
Stakeholders' roles and interactions					
Producers[2] Produce/Import the bottles and distribute finished beverage products in the market with a deposit fee attached	(-) Fee to the **DRS operator** for the design of the deposit-refund system		√		
	(-) Fee to the **DRS operator** for the administration of the deposit-refund system	√			
	(-) Handling fee to the **DRS operator** established based on the cost of managing the flow of empty bottles[3]	√		√	√
	(-) Registration fee to the **DRS operator** (induction (one-off), and per unit package handled)	√			
	(-) Deposit fee to the **DRS operator** for the beverage bottles they sold	√			
	(-) Handling fee to a third party for the administration of the deposit-refund system		√	√	
	(0)[4] Return the deposit fee to the **retailers** for the empty beverage bottles they receive		√	√	
	(-) Costs of collection, transport to **WMC** and preparing stores and personnel for sales/return data (often delegated to a third party)			√ (shared with **Retailers**)	
	(+) Unredeemed deposit fee from the **Retailers**		√	√	
	(+) Unredeemed additional deposit fee from the **Retailers**			√	
	(+) Selling the empty bottles to **WMC**			√	
Retailers Display/Market the beverage bottled products and collect the empty beverage bottles (except in Archetype D)	(-) Cost of each unit of beverage bottle and deposit fee to **producers**	√	√	√	√
	(-) Additional deposit fee per unit of beverage bottle purchased to **producers**			√	
	(-) Operation of the take-back system and its set-up (e.g., Reverse Vending Machines (RVM) purchase and maintenance)	√	√	√	
	(-) Return to **consumers** the deposit fee when they return the empty beverage bottle	√	√	√	
	(-) Administrative fee to the **DRS operator** for the design of the deposit-refund system				
	(-) Fee to the **DRS operator** for the administration of the deposit-refund system	√	√		
	(-) Cost of storage and transport of empty beverage bottles to **WMC**		√		
	(-) Costs of collection, transport to **WMC** and preparing stores and personnel for sales/return data (often delegated to a third party)			√ (shared with **Producers**)	
	(+) Cost for setting a take-back system and its operation from the **DRS operator**	√			
	(+) Cost for handling each unit of empty beverage bottle collected from the **DRS operator**	√		√	
	(-) Unredeemed deposit fees to the **DRS operator**	√			
	(-) Additional unredeemed deposit fees to **Producers**			√	
	(+) Selling the empty bottles to **WMC**		√		
	(-) Deposit cost of empty beverage bottles not returned		√	√	
Consumers Purchase beverage bottles and may return empty beverage bottles to point of purchase or collection point[5]	(-) Cost of beverage that includes the bottle deposit fee to the **retailers**	√	√		√
	(+) Return of deposit fee from **retailers**	√	√		
	(+) Return of deposit fee from the **DRS operator or WMC**				√
DRS operators Design and administer the deposit-refund system[6]	(-) Cost of the DRS design	√	√	√	√
	(-) Cost for the administration/management of the DRS	√		√	√
	(-) Cost for empty beverage bottle handling (disposal/selling)	√			√
	(+) Administration fees from **producers**	√	√		
	(+) Administration fees from **retailers**	√	√		
	(+) Administration fees from **WMC**				√
	(+) Cost for handling each unit of beverage bottle sold by the **producers**	√		√	√
	(+) Fee to **retailers** for setting a take-back system and its operation	√			
	(-) Handling fee for each empty beverage bottle collected by the **retailers**	√		√	
	(+) Unredeemed deposits received from the **retailers**	√			
	(+) Unredeemed deposits				√
	(+) Selling the empty bottles to **WMC**	√			√
WMC Produce recycled plastic material that is placed on the market[7]	(-) Buy empty beverage bottles, from **DRS operator**	√			√
	(-) Buy empty beverage bottles, from **Retailers**		√		
	(-) Buy empty beverage bottles, from **Producers**			√	
	(-) Return to **consumers** the deposit fee when they bring back the empty beverage bottles				√
	(-) Return the unredeemed deposit fee back to the **DRS operator**				√
	(+) Selling recycled material to **producers** – MoF	√	√	√	√

1. In some countries, producers be subject to an environmental tax, and fees to public authorities, that vary by country and regulatory landscape and may and may not be aligned with the tonnage of products sold, leading to an additional money flow (-).
2. Handling fee includes the cost of the collection and disposal activities for every unit of the beverage bottle placed on the market and the management of the deposits (empty bottles).
3. This is neutral as the deposit fee for bottles was paid by the retailers at the purchase.
4. In Archetype C, consumers bear no additional fee during purchase but may return the empty beverage bottles to the purchase points (i.e., Retailers).
5. DRS operators also manage the logistics of the deposits and the resale of empty beverage bottles and the collection from the Retailers and resale of empty beverage bottles to WMS, usually through a designated third party (in Archetypes A and D).
6. WMC receive empty beverage bottles for processing from DRS operators (Archetype A), Retailers (Archetype B), Producers (or designated third party) (Archetype C), and Consumers (Archetype D).

volume of empty beverage bottles. The latter is less of an issue with the use of RVMs, as they are usually programmed to compact the bottles disposed of. In addition, RVMs require lower staff commitment and transportation costs, making them an economically favourable component of an effective DRS operation (Gaines and Wolsky, 1983; Zhou et al., 2020). The RVMs also offer an automated verification system for the reported return data, which limits fraud (Malindzakova et al., 2022). An Ecorys study (as cited in Oosterhuis et al., 2014) reported a deficit of EURO 286 million in 2011 (including all materials) of the German DRS. It is important to note that at this time, the market value of collected recyclable materials was lower than at present, and there is no further insight on this topic.

Producers also play an important role in the economic viability of the DRS. The producer's registration and annual fee to the DRS operator (if any), the revenues from selling the collected material as well as the unredeemed deposits contribute to financing the costs of the DRS operation (Malindzakova et al., 2022; Schneider et al., 2021). The structure of producers' fees varies from country to country. Malindzakova et al. (2022) calculated a cost for producers of around EURO 534.5 per tonne of PET bottles placed on the Slovakian market, which is reflected in the administrative fees they pay to the DRS operators (Malindzakova et al., 2022). In Croatia, the producer only pays a waste management fee, to ensure the correct disposal of the package, whereas in Norway the producers pay a multi-levelled fee, which includes a fee for each new product placed on the market along with the standard fee per unit. In Norway, further design-related fees apply, with the fee increasing per unit of packaging that is 1) covered by a label for more than 75 % of its surface, 2) has a transparent light blue colour, and 3) has packaging made of another colour and has a label covering more than 75 % of its surface (Spasova, 2019). In addition, drinking bottles have a bottle tax of about EURO 0.13 per container, separate from the EPR fee and regardless of the design and composition. In addition to the bottle tax, a return rate-dependent tax is applied, which is calculated based on the return data reported to the DRS operator in Norway. Retailers or manufacturers are not charged a return-rate tax if a return rate higher than 95 % is reported. In other cases, the tax increases with decreasing return rates (Numata, 2016).

While the benefits of implementing a DRS and its effectiveness in reducing packaging waste have been well-documented (Krzywda, 2022), evidence from systems with low return rates suggests that producers often lack significant interest in whether containers are returned. This is largely due to the absence of penalties for failing to meet collection targets, as seen in states like Massachusetts and New York (TOMRA, 2021). Additionally, the DRS operators - often local authorities in these states - might have a financial interest in bottles not being returned as they profit from unredeemed deposits. A DRS managed by a not-for-profit operator helps address this issue. In such cases, public authorities should ensure the accuracy of return data to maintain transparency, especially in countries where producer fees are determined by return rates (Numata, 2016).

In Latvia, the implementation of the system has faced challenges due to: a) retailers' reluctance to participate because of increased operating and investment costs; and b) claims from waste management companies that the system reduces profits by decreasing the amount of valuable material in the municipal waste stream (i.e. mixed recyclable materials). Additionally, there are concerns that the current system for separately managing paper/cardboard, glass, and PET bottles may not be economically viable (Cudečka-Puriņa et al., 2019).

In Austria, a coalition of retailers and producers have been strongly opposing a DRS implementation through Altstoff Recycling Austria (ARA), the largest packaging waste management entity, covering circa 70 % of the market share. A DRS would eliminate the requirement for producers to pay licensing fees to ARA, causing annual losses of circa 24 million euros just for plastic bottles (Changing Markets Foundation and Break Free From Plastic Movement, 2020). Along with ARA, major retailers and plastic producers have been signatories of letters to the government against the introduction of a DRS in the country thereby becoming outspoken opponents to the DRS implementation, including big retailer chains that are concerned about high investment costs, increased costs for more personnel, maintenance and space.

Outside individual cases outlined above, implementing a DRS is perceived to generate overall positive economic impacts. This is particularly the case for stakeholders in the European beverage sector: the Union of European Soft Drinks Association (UNESDA) and the Natural Mineral Waters Europe (NMWE) strongly advocate for the establishment of common guidelines for a widespread implementation of DRS in Europe. This will allow the recovery of high volumes of high-value recyclable PET material, as well as achieve the Single Use Plastics Directive requirements, which calls for 30 % recycled content in PET beverage bottles by 2030.

3.2.3. *Social aspects*

Studies specifically addressing the social implications and drivers of DRS implementation in European countries are limited. To gain insights, findings from recycling behaviour studies have been adopted. Saphores and Nixon (2014) investigated the recycling practices and preferences of American consumers, revealing that gender, ethnicity, education, and household size influence recycling behaviours. They found that individuals aged between 45 and 59, as well as those over 65, were more likely to recycle. Additionally, rural residents showed higher recycling tendencies compared to urban residents (Saphores and Nixon, 2014), though rural states in the US have generally lower recycling rates than states that are more urbanized due to the lack of collection infrastructure.

Similar trends have been observed in Europe. Specifically, Mager et al. (2022) reported that rural communities are more willing to participate in DRS than urban communities. Furthermore, Chung and Poon (1996) found that women are more likely to recycle beverage bottles. These insights suggest that social factors, such as location and gender, may similarly influence the effectiveness and adoption of DRS in Europe.

The implementation of DRS has the potential to create jobs. A study by Eunomia in New York State revealed that DRS generates 5726 direct and indirect jobs across various roles, including administration, collection, counting, sorting, and processing. The study also highlighted the role of informal collectors, emphasising how DRS supports the livelihoods of economically disadvantaged individuals, as highlighted by Yu (2021). In support of these informal collectors, the city of Copenhagen has introduced bins that allow consumers to 'donate' their deposits to people in need (Burlakovs et al., 2020). The ability to reclaim the deposit fee is a key driver of consumer participation in DRS. Wang et al. (2020), suggest gradually increasing the deposit fee when implementing DRS in a new country to help consumers familiarise themselves with the system and feel sufficiently incentivized to return the empty beverage bottles. Without such incremental adjustments, drastic improvements in participation rates may not be achieved. Additionally, Van Rensburg et al. (2020) emphasise the importance of targeted awareness campaigns to increase DRS participation.

3.2.4. *Technical aspects*

In Canada the fragmented operational structure of DRS limits its effectiveness, highlighting the need for a system that is uniform across both geographic and population scales (Baxter et al., 2022). A well-organised system is crucial for ensuring high-quality beverage bottle collection. This reduces cross-contamination, which in turn offers two key benefits: 1) it minimises the need for extensive processing, saving resources and energy in decontamination; and 2) it enhances circularity by reducing the downcycling rate. While there is broad consensus that DRS results in clean material with low levels of contamination (EUNOMIA, 2022), there is a lack of studies addressing this issue. The only relevant scientific paper, by Snell et al. (2017), analysed the quality of PET flakes from various collection systems, including DRS, and found that polymer contamination is higher in household collection systems compared to DRSs.

Fig. 3 summarises the multidimensional impacts presented above as well as the future research needs addressed in the next sections.

4. Discussion

Different countries have implemented various DRS, making it challenging to identify performance similarities and differences that could guide implementation in other regions. This variability is influenced by the network of stakeholders involved and the interplay of social, cultural, economic and legislative factors, which are crucial for the success of DRS (Krzywda, 2022). Nonetheless, DRS is recognised as an effective way of capturing and recycling plastic beverage bottles with low contamination levels (Cáceres Ruiz and Zaman, 2022). This makes beverage packaging more suitable for closed-loop recycling, which in turn conserves resources needed for virgin plastic production and associated environmental impacts (less energy, lower greenhouse gas emissions, and reduced consumption of raw materials). It also helps meet EFSA requirements for food contact applications of recycled material and complies with the SUP regulation (EUNOMIA, 2022), which mandates a maximum non-food PET content of 5 % by weight (EFSA, 2012); both of which are essential in maximising value recovery from plastics waste and reducing pollution.

Nevertheless, the success of DRS hinges on balancing several factors, with a key interdependency being the relationship between the number of return locations (or the ratio of return locations to population), the deposit value per PET bottle, and the public's awareness and motivation to achieve high return rates. The value of the deposit on empty PET bottles significantly influences these return rates, while the ratio of return points relative to population could be an important factor. Table 3 compares DRS performance in four European countries, highlighting that higher return rates in Germany are due to the higher deposit value and the greater number of return points relative to the population. In contrast, Norway and Estonia, with lower deposit values, show varied return rates, with Norway presenting an interesting case due to the high number of return points relative to population.

Table 3
Comparison between deposit fee value, return rate and number of return points to population ratio.

Country	PPP-adjusted deposit value	Ratio between deposit value and PIFB	Return rate	Return points to population ratio
Germany	0,34	0,32 %	97 %	1:639
Lithuania	0,21	0,21 %	92 %	1:1117
Norway	0,23	0,16 %	89 %	1:356
Estonia	0,17	0,16 %	87 %	1:1073

PPP: Purchase Power Parity, data elaborated from OECD (2022). PIFB: Price level Index for Food and non-alcoholic beverages, data elaborated from Eurostat (2022). Return points to population ratio data elaborated from and Raal (2019); TOMRA (2021).

From an economic and technical perspective, stakeholders in the PET bottle value chain advocate for the standardisation of DRS, as it can fundamentally change the dynamics of existing waste management systems by shifting the responsibility for bottle collection and management to DRS operators – typically local authorities – and producers. This shift can result in higher-quality secondary raw materials, cost savings for local authorities, improved compliance with EPR regulations for producers and more efficient waste management practices. Despite these benefits, there is a lack of comprehensive studies that systematically analyse the environmental losses and gains of DRSs. Some studies demonstrate that mechanical recycling generates economic and environmental advantages compared to the production of virgin plastics (Shamsuyeva and Endres, 2021; The Association of Plastic Recyclers, 2020; Uekert et al., 2023), while others suggest that the logistics of DRS can create an imbalance. While DRS can reduce some environmental impacts it can exacerbate others, such as transportation emissions from the collection, transport and processing of returned packages. In addition, factors such as existing waste management practices and

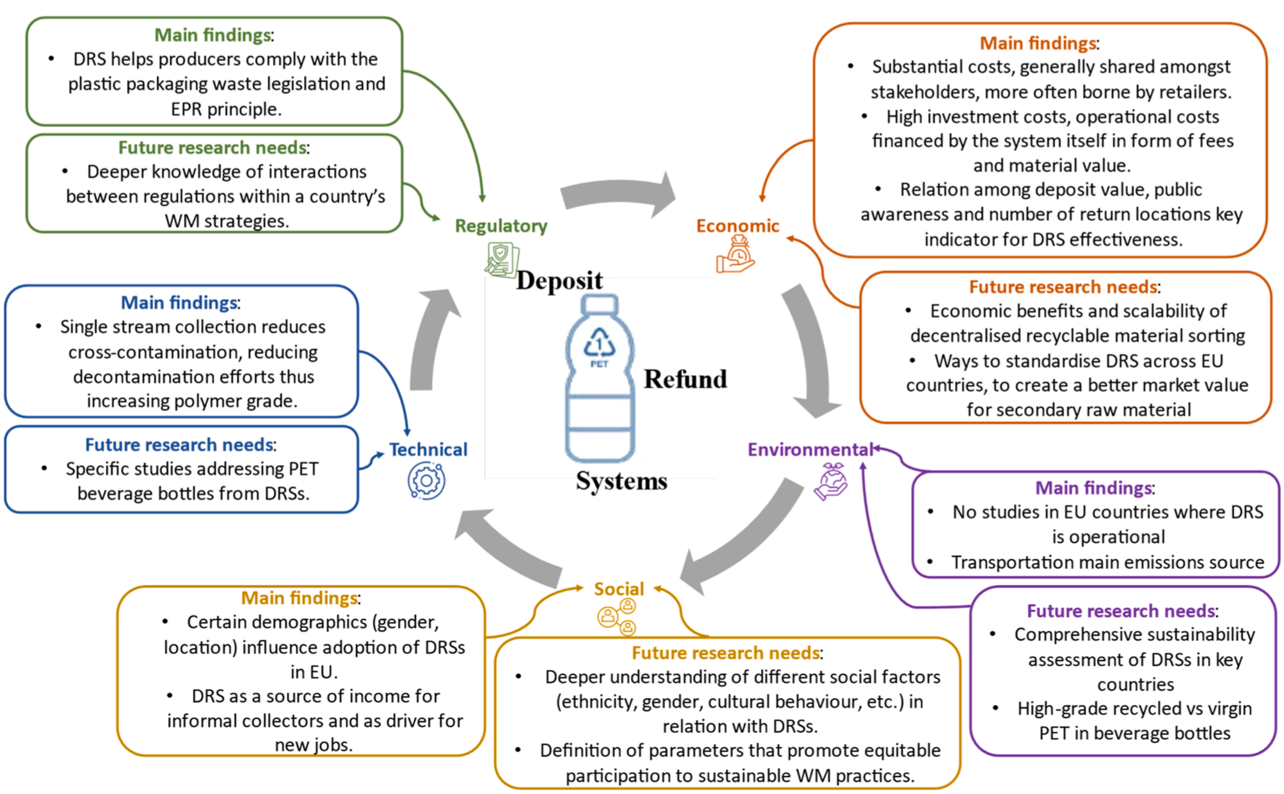

Fig. 3. Main findings of multidimensional assessment analysis and future research needs.

infrastructure, location and availability of waste treatment facilities can influence the environmental benefits of DRS (Zhou et al., 2023; Abejón et al., 2020); therefore, its success and sustainability performance should be assessed on a case-by-case basis. Addressing these challenges and carefully weighing potential trade-offs is essential. Harmonizing legal requirements for beverage bottle quality and quantity could enhance the effectiveness and broader implementation of DRS, leading to more efficient and sustainable operations.

From a social perspective, DRS helps consumers view plastics as a valuable resource by attaching a financial incentive to them (Patrick ten Brink et al., 2016). This incentivises proper disposal and recycling, leading to undeniable environmental benefits by reducing plastic pollution and marine littering. Considering that beverage bottles are major contributors to ocean pollution (Erüz et al., 2023; Morales-Caselles et al., 2021), this measure can be effective in aiding behaviour change. The integration of environmental and social considerations is pivotal, particularly in supporting the livelihoods of informal collectors who play a crucial role in the recycling process. Designing DRSs with these social impacts in mind should be a priority.

The Extended Producer Responsibility (EPR) principle offers a potential solution. EPR shifts the responsibility of waste management to producers and importers under the 'polluter-pays principle'. Producers are obligated to manage and recover waste materials under the Producer Responsibility Organisations (PROs) that are established to ensure compliance with statutory obligations in exchange for a financial contribution (European Commission - Joint Research Centre, 2018). This system allows packaging manufacturers or importers to transfer recovery responsibilities to PROs via financial contributions or licence fees (Da Cruz et al., 2014). Each type of packaging material – in this case, plastic – has a distinct license fee based on the volume placed on the market. Once responsibility is transferred to the relevant PROs, producers are no longer accountable for the packaging at its end-of-life (EoL) phase, as this is transferred to other stakeholders in the plastics value chain (Changing Markets Foundation and Break Free From Plastic Movement, 2020). In this context, DRS supports the implementation of the EPR principles by helping producers comply with the (plastic) packaging waste legislation (Laubinger et al., 2022), and contribute to financing improvements in the recycling infrastructure. This can enhance the market value of recycled materials, and facilitate the scaling of new technical solutions across the value chain, creating a level playing field among stakeholders (Kahlert and Bening, 2022).

Furthermore, fostering competitive businesses across the value chain can lead to broader sustainability impacts. In such a complex system with a diverse network of stakeholders, return rates alone may not be the only success metric. Historically, financial challenges arose from collecting smaller amounts of recyclable materials at the municipal level (Alter, 1993; Clapham, 1984). However, these issues appear to have become less pronounced due to several key factors:

- The system's monetary flows are designed to operate on a subsidy-based financial structure rather than cost-based operations, particularly in Europe.
- The handling fees help offset additional costs incurred by retailers.
- The clear design, administration, and operation of DRS by operators ensure transparency and effective management.

The economic benefits and scalability of decentralised recyclable material sorting (in this case of beverage bottles), as well as the way of operationalisation warrant further investigation. Such research could drive a cultural shift towards more responsible and efficient collection and recycling. Additionally, it could pave the way for return systems that promote reusable solutions, enhancing overall sustainability.

5. Conclusions

This critical review provides a comprehensive analysis of the status quo of DRS, particularly in Europe, by highlighting the challenges, opportunities, and trade-offs. It represents a novel examination of DRS performance, across multiple dimensions, including environmental, economic, social, technical, and regulatory. The study emphasizes that successful DRS implementation relies not only on high return rates but also on realizing efficiency, across the economic environmental and social domains, while creating a level playing field for all stakeholders involved in the plastics value chain. The greater the transparency of the scheme and the tighter the coordination, the better the DRS performance.

Future research should focus on three key areas:

1. **Sustainability impact assessment:** there is a pressing need for detailed environmental, economic, social and technical impact data, particularly in countries with established DRS. Research efforts should concentrate on performing holistic sustainability assessments of the benefits of using high-grade recycled PET versus virgin plastics. This data will enable policymakers to better evaluate the efficiency and effectiveness of DRSs, leading to improvements in collection and recycling rates.
2. **Policy development:** a deeper knowledge of how different policies and regulations interact with a country's waste management strategy is crucial. Research should explore the role of DRSs into an integrated waste management approach, inclusive of the needs of the many different stakeholders involved in DRSs. Effective policy design and implementation are essential for advancing waste management practices that maximize value capture and promote circularity. As the regulatory landscape evolves, stakeholders must remain vigilant and adapt to emerging requirements to ensure sustainable and efficient packaging waste management.
3. **Social cohesion and accountability:** developing inclusive and effective DRS strategies requires a deeper understanding of social factors such as ethnicity, gender, cultural behaviour and demographics. Insights into these areas will help tailor DRS initiatives to meet diverse community needs and promote equitable participation in sustainable waste management practices. Improved understanding of the social and environmental aspects will also inform the adaptability of DRS to different types of plastic packaging and contexts.

Addressing these areas can guide the implementation of an effective DRS and support its role in achieving an integrated sustainable waste management strategy that promotes circularity and the recovery of value from resources.

CRediT authorship contribution statement

Caterina Picuno: Visualization, Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Spyridoula Gerassimidou:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Weimu You:** Conceptualization, Writing – review & editing, Funding acquisition. **Olwenn Martin:** Writing – review & editing, Methodology. **Eleni Iacovidou:** Writing – original draft, Formal analysis, Visualization, Funding acquisition, Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Olwenn V. Martin reports a relationship with Food Packaging Forum that includes: consulting or advisory. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.resconrec.2024.107962.

Data availability

No data was used for the research described in the article.

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