Heliyon 10 (2024) e25182

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Indicators and characteristics of PET packaging collected in a Deposit and Refund System pilot project

Graça Martinho [a,b], Pedro Santos [a,b], Ana Alves [a,b], Mário Ramos [a,b,*]

[a] MARE – Marine and Environmental Sciences Centre / Associate Laboratory ARNET – Aquatic Research Network, Portugal
[b] Department of Environmental Sciences and Engineering, NOVA School of Science and Technology, NOVA University Lisbon, 2829-516 Caparica, Portugal

ARTICLE INFO

Keywords:
Deposit refund system (DRS)
Reverse vending machines (RVM)
Packaging waste
Polyethylene terephthalate (PET) bottles
Operational indicators

ABSTRACT

Countries that have a Deposit and Refund System (DRS) show high rates of selective beverage packaging waste collection, indicating that it is a powerful economic instrument for achieving the European packaging recycling targets. DRS ensure that collected material is of a sufficiently high quality to be incorporated into new products. In Portugal, the Government has decided to implement a DRS for non-reusable beverage packaging as a strategy to increase the packaging recycling rate, which is currently considerably lower than the mandatory European targets. To acquire knowledge and experience for the design and implementation of the future DRS, a pilot project was carried out with polyethylene terephthalate (PET) beverage packaging, using 23 Reverse Vending Machines (RVM) installed at supermarkets across mainland Portugal. The authors monitored the DRS pilot project between March 2020 and December 2022. The main objectives were to determine operational indicators and evaluate the characteristics and quality of the PET deposited, using both the data recorded by the RVM and a characterisation of the packages contained in a sample of 46 bags. The results provided important data for planning the Portuguese strategy, which may also support operational or political decisions in countries in similar contexts. Whilst the recycling plants that received the material collected in these RVM confirmed that its quality allows for the production of PET food-grade flakes, this research identified a need to improve the design of packaging and to communicate this with producers, to better allow for the incorporation of recycled material into food beverage packaging.

1. Introduction

1.1. The plastics and regulation

Plastics, due to their functional advantages in packaging applications, such as protecting and keeping food safe, have the advantage of reducing food waste [1–3]. In addition, the low cost of plastic compared to other packaging materials is one of the main explanations for the increase in the use of this type of packaging in recent decades [3].

According to Plastics Europe [4], European plastics production increased to 57.2 Tg in 2021, following a decrease in 2020 due to

* Corresponding author. Department of Environmental Sciences and Engineering, NOVA School of Science and Technology, NOVA University Lisbon, 2829-516 Caparica, Portugal.

E-mail address: mario.ramos@fct.unl.pt (M. Ramos).

https://doi.org/10.1016/j.heliyon.2024.e25182
Received 11 July 2023; Received in revised form 8 January 2024; Accepted 22 January 2024
Available online 26 January 2024
2405-8440/

the Covid-19 pandemic. In the same year, circular plastics (material within a "closed loop" system) represented about 12.4% of European plastics production, while post-consumer recycled plastics and bio-based/bio-attributed plastics accounted for 10.1% and 2.3%, respectively. Fossil-based plastics accounted for 87.6% of production and, of these, 5.3% were polyethylene terephthalate (PET) plastics.

The demand for plastic was about 50.3 Tg, of which PET represented 7.9%. Packaging represented 39.1% of total production, which is the largest end-use market for plastics [4]. In Europe, by 2020 it was estimated that a total of 3.6 Tg of PET bottles were registered, representing an increase of 6% relative to 2018 [5–7]. The problem has become a significant environmental challenge, because plastics produced with fossil fuels or mineral materials take years to decompose [8–10] and, as far as plastics used in packaging are concerned, they are typically used once or only for a short period of time, according to the Directive (EU) 2019/904 of June 5th.

Approximately 29.5 Tg of post-consumer plastic waste were collected in 2020, in Europe [4]. Of this, 15 Tg were a result of mixed waste collection, where 5% was sent for recycling, 57% to energy recovery, and 38% to landfills. The remaining 14.5 Tg represents waste resulting from separated collection, of which, 65% was sent for recycling, 27% to energy recovery, and 8% to landfills. Another global problem is the quantity of plastics ending up in the oceans and coastal zones, with more than 80% of the annual input of plastic litter to these areas coming from land-based sources [11–13]. According to Hänninen et al. [14], polyethylene (PE) is the most abundantly observed polymer in the ocean, followed by polypropylene (PP). Additionally, through their research, Guan et al. [15] confirmed that the degradation of PET plastic in the ocean becomes increasingly pronounced over time, especially under high pressure in seawater; the plastic surface undergoes a progressive transformation, becoming rougher and developing more pores and cracks.

In 2018 the European Commission published "A European Strategy for Plastics in a Circular Economy" [16], specifying the need to quadruple the capacity for plastics sorting and recycling between 2015 and 2030, and inviting voluntary commitments and responsibilities from the industry groups along the supply chain. In the same year, Directive (EU) 2018/852 of May 6th, amending Directive 94/62/EC of December 20th, on packaging and packaging waste, stipulated that the European Member States should take the necessary measures to promote the high-quality recycling of packaging waste, meeting the quality standards required by the recycling sectors, and established a target for the recycling of at least 50% of plastic packaging by 2025, rising to a minimum of 55% by 2030.

Directive (EU) 2019/904 of June 5th (Single-Use Plastics Directive), which intends to reduce the impact of certain plastic products on the environment, states that European Member States should promote more effective selective waste collection systems, namely through Deposit and Refund Systems (DRS), and should meet targets for the selective collection and recycling of 77% of beverage packaging by 2025, and 90% by 2029. This Directive also stated that from 2025, beverage bottles made mostly from PET must consist of at least 25% recycled plastic and, from 2030 onward, at least 30%. These ambitious goals, assert the urgency of building an effective, but also convenient recycling system to increase beverage packaging recycling rates [10,17,18]. Furthermore, Europe has signed the Plastic Pact [19] to make the lifespan of plastic more circular.

According to usage data, PET is one of the most frequently used plastics in food packaging (predominantly for bottles, typically beverage bottles such as water and soft drinks [20]) and also the most regularly recycled, due to its properties and low absorption of post-consumer contaminants relative to other plastics [3,21]. Furthermore, PET bottles, due to their shape and design, can be collected for recycling in high volumes, which means that the collected beverage packaging becomes a resource with a market value and that bottle-to-bottle recycling is a possibility [7,10]. However, mixing transparent PET with coloured PET will make the mixed PET fraction darker, resulting in a lower sale value compared to lighter-coloured PET, which consists of higher proportions of transparent PET. The results of the Life Cycle Assessment (LCA) undertaken by Cremiato et al. [22] illustrated that the separate collection of recyclable materials, to serve as alternatives to raw materials in the production of goods, contributed to a reduction in both the direct and indirect impacts of the materials throughout their entire life cycle. Furthermore, the use of non-virgin PET marked an initial effort to mitigate environmental burdens.

Sorting and recycling rates vary widely across the European Union, according to the quantity, type, purity, and complexity of the materials received [23–25]. There are collection requirements to maintain the value of products intended for contact with food to avoid contamination, namely that plastics must come from separate recycling collections [5,26]. This allows high-purity post-use flows of plastic at competitive prices, an important factor in the economics of recycling [27,28].

1.2. Quality control of collected plastic

In Europe, recycled plastic has to comply with several regulations to be used for food purposes. It has to be licensed by a competent authority according to the recommendations of the European Food Safety Authority (EFSA), a source of scientific advice that communicates risks associated with the food chain [29]; and it has to comply with the new Regulation (EU) 2022/1616 of September 15th, repealing Regulation (EC) 282/2008 of March 27th, which concern recycled plastic materials and articles intended to come into contact with food.

The aforementioned Regulation (EU) 2022/1616 establishes criteria that will ensure recycled plastics can be safely used as a food contact material, encourages the recycling of plastics intended for food contact and stipulates the rules for the production of the recycled plastic, in terms of the development and operation of recycling technologies, processes and installations. The aim is to control the inputs and the contamination, adhering to food contact material legislation. Plastic input must come from a closed loop, where any contamination can be excluded or the process of contamination reduction to levels that do not pose a risk to human health must be demonstrable through scientific evidence [30,31]. Additionally, Brouwer et al. [32] demonstrate that PET bottles in mono-collection systems accumulate fewer contaminants than PET bottles in co-collection systems, and can potentially contain more recycled material without exceeding the acceptable limits for critical bottle properties such as haziness, yellowing, and migration. According to Franz and Welle [33], it is probable that the recycling feed stream of typical collection systems will contain around 5% of non-food PET, importantly, this would not present any risk to the consumer. Also, the same study shows that fractions of up to 20%, which may occasionally occur, would not raise safety concerns for the end-user either.

For a circular economy of plastic packaging, it is necessary that producers adopt clean production methods (*e.g.,* fewer additives, single-material, the incorporation of recycled plastic) and that consumers return their packaging waste for recycling, in quantity and quality [28]. One recent European initiative to facilitate the transition towards a circular economy as part of the European Plastics Strategy, which started on the January 2021, is the implementation of the "plastics own resource" policy that consists of a national contribution based on the amount of non-recycled plastic packaging waste (at a rate of 0.80 € per kilogram), helping to reduce packaging waste [34]. Another policy that aims to increase recycling rates, which many countries have already introduced, is the necessity to implement a DRS for non-reusable beverage packaging, complying with the European targets for the separate collection of plastic beverage bottles by 2029 [5,10,35,36].

1.3. The deposit and Refund System solution

One of the objectives of the DRS is to provide better quality input materials, enabling a sufficient supply of high-quality feedstock to recyclers. It is expected that this will lead to higher levels of recycling (such as bottle-to-bottle, closed-loop recycling) and, with this, meet the requirements of the European Union's circular economy principles, since it is the most effective method to collect one-way beverage packaging [17,21,37,38].

As pointed out by Matthews et al. [30], the quality and safety of recycled post-consumer PET for incorporation into new food packaging depends on the quality of the packaging, limited by factors such as cleanliness; the incompatibility of the materials used for labels and lids; additives; multilayers of different plastic polymers; the cross-contamination with other waste or co-collection with non-food plastic (which occurs in many municipal selective collection systems); and the mechanical recycling process.

The DRS for single-use packaging is intended to collect packaging for recycling, avoiding the need for virgin material, reducing littering, and improving circularity [35]. Also, it can reduce up to 80% of the climate impact of packaging, lowering the demand for virgin material, which in turn results in a significant reduction in global carbon emissions [3,8,35]. Moreover, results demonstrate a cleaner waste stream, free from the levels of contamination experienced in a mixed collection, increasing the quality of the recycled output created [9,10,17], and incentivising positive behaviour change [18]. Furthermore, alongside increased recycling rates, certain areas boost collection rates exceeding 90% for particular items, with waste surveys indicating 40-90% reductions of items that are subject to deposits. This system influences consumer behaviour, which is difficult to achieve with other Extended Producer Responsibility policy instruments [37].

According to Zhou et al. [10], more than 40 countries in the world have implemented a DRS for end-of-use beverage packaging. Taking into account the latest information available in 2023, in Europe, DRS exists in 13 countries, with around 144 million people using a DRS that collects high levels of PET [35]. Sweden was the first country to introduce the system in 1984, and the latest countries to implement DRS in 2022 were Latvia, Malta, and Slovakia [35].

Moreover, an overview of the various recycling processes can be found in the literature [7]. Some studies focus on the cost-benefit analysis of beverage packaging in a DRS [39], and others on the potential for recycling PET bottles into new food packaging [40,41].

1.4. Portuguese pilot project for PET packaging waste

In 2020, the recycling rate for plastic packaging waste in Portugal was 33.9% [42]. Consequently, Portugal needs to increase the quantity of packaging waste being sent for recycling. Moreover, the country needs to ensure that the quality of the plastic collected is sufficient for it to be incorporated into the production of new beverage bottles, promoting the maximum circularity of these materials. Considering the requirement to adhere to the circular economy principles, it is necessary to force producers to adopt clean production methods, but also to encourage consumers to deposit suitable waste products for recycling [43].

In Portugal, as a result of the Single-Use Plastics Directive, the Government published Law n.° 69/2018 of December 26th, which establishes that a mandatory deposit system had to be implemented by January 2022 for non-reusable plastic, glass, ferrous metal, and aluminium beverage packaging. The same law created a consumer incentive system, in the form of a pilot project, exclusively for the return of non-reusable PET plastic beverage packaging, through the use of 23 automatic collection machines, located in supermarkets geographically distributed throughout mainland Portugal.

This pilot project was implemented by the consortium formed by the Portuguese Association of Natural and Spring Water Industries (APIAM), the Portuguese Association of Non-Alcoholic Drinks (PROBEB), and the Portuguese Association of Distribution Companies (APED), having been financed by the Environmental Fund of the Ministry for the Environment and Climate Action (MAAC). The consortium implemented the pilot project, which began in March 2020 and ended in December 2022. NOVA School of Science and Technology – NOVA University Lisbon (FCT NOVA) was responsible for monitoring the operational component.

The DRS pilot project exclusively involved PET bottles, through the use of Reverse Vending Machines (RVM), as the Portuguese Government intended, initially, to develop knowledge and experience for the implementation of a future beverage packaging deposit system, intended to extend to other packaging materials (*e.g.* glass, ferrous metal, and aluminium) upon its nationwide implementation. Moreover, the pilot and wider projects were intended to promote the adoption of sustainable behaviours, recycling the materials collected for incorporation into the production of new beverage packaging.

1.5. Scope and main objectives

One of the objectives of monitoring this pilot scheme, which was carried out by the authors, was to determine operational indicators associated with the RVM model used in the project, and to analyse the characteristics and quality of the packaging that customers deposited in the machines. The main results presented were fundamental for the operational and logistical design of the future, national level, system and may also be useful for other countries that intend to implement DRS since this type of information is scarce in the public literature.

Furthermore, the insights from this study contributed to an understanding of the factors that affect the efficiency of the waste collection system, citizens' behaviour, and the role of financial incentives. They are also relevant to policymakers, who can use the results to refine waste collection systems and communication campaigns to further engage citizens in recycling.

2. Methods

2.1. The Portuguese case study

The choice of plastic packaging for this pilot project, particularly PET, was motivated by several favourable considerations, namely it being a material which many European policies focus on; clean and widely used by the beverage industry; the plastic packaging material with the highest market value; and the most widely used and demanded by the food industry for incorporation into new food grade packaging. In addition, it can be compacted in the RVM, which reduces storage at the store and transport costs for recycling.

The pilot project included non-reusable PET beverage packaging, with a volumetry between 0.1 and 2 l, for products such as water, juices, soft drinks, and alcoholic beverages (with the exclusion of dairy drinks), that are sold on the domestic market and destined for the final consumer. The following requirements were established for the packaging to be accepted in the machines: they should not contain liquids or be flat, should have an intact lid and label, and include a legible barcode.

In a DRS, the economic incentive applied is expected to not only reduce the amount of waste produced but also to preserve and recover resources and energy, encouraging reuse and recycling [21,44]. In pursuit of these aims, and to encourage the disposal of PET packaging in the RVM, the Portuguese Government created an incentive: for each qualifying item inserted into the machine, the user was rewarded with 0.02 € for packages with a volumetry between 0.1 and 0.5 l, and 0.05 € for packages with a volumetry greater than 0.5 and up to 2 l. In this way, the consumer does not pay any deposit amount. However, when they voluntarily place their PET packaging in the RVM, they receive the incentive for each qualifying item introduced.

Concerning the operational component, the study aimed to characterise the packaging delivered to the RVM, as well as observing and characterising the packaging delivered by consumers that was not accepted by the RVM.

2.2. Operational criteria for the pilot project

For the pilot project, 23 RVM were installed at large commercial retail sites (supermarkets), located throughout mainland Portugal, locating one RVM within the jurisdiction of each of the country's 23 municipal waste management systems. A uniform model of RVM was distributed, chosen because it was developed by its manufacturer specifically for stores where the anticipated volumes of packaging collection are moderate and where space for its installation is limited. These RVM have two containers inside with external dimensions of 600 mm in width, 800 mm in length, and 1000 mm in height (each container having a volume of 0.48 m^3), which are lined with plastic bags to facilitate the packaging and handling of the collected packages and to avoid a run-off.

According to the supplier, the machines have instant 360 degree recognition, detecting all barcodes and security marks, allowing the containers to be inserted in a fast and continuous flow. Their compaction rate varies according to the composition and volumetry of the packaging.

All machines are connected to the supplier's network via a router or the store's Wi-Fi network. In this way, it is possible to remotely monitor its operating status, collect operating data and provide software updates or repairs. They also have a management system, with a mobile application, which communicates maintenance alerts to the person responsible for the RVM at each store, as well as making the daily statistics available for each machine, such as: container volume, cleaning history, and operating time.

2.3. Methodological approach for the pilot project

For monitoring the operational indicators of the RVM, data was recorded for a period of approximately seven months by the 23 machines installed, from March 2020 until September 2020. This included data such as the number of packages deposited, the average time per transaction, the percentage of rejects, the availability of the RVM, and the number of bag changes carried out, amongst others.

Moreover, a physical characterisation campaign on a sample of packaging deposited in the RVM was executed, conducted six months after the start of the pilot project, in September 2020. For this characterisation, a random sample of 46 RVM collection bags full of packaging waste was collected (2 bags per RVM) with a useable volume of 0.48 m^3 each, which were separated and quantified, in number and weight, by volumetry, type of beverage, package colour, presence of caps, and state of cleanliness. At this stage, the choice of sample size was based solely on logistical limitations; the human and financial resources necessary for its transportation and characterisation; and the lack of knowledge of the expected variability of the packaging composition, as it was the first characterisation campaign carried out for RMV collections in Portugal.

At the same time, visual observations were made of the packaging delivered by consumers but not accepted by the RVM, to understand whether the cause of the rejection was consumer error (*e.g.,* introducing types of packaging excluded from the trial or illegible labels) or RVM problems in packaging identification. Also, at each supermarket, nominated employees oversaw the operation and maintenance of the RVM. Some of these employees were asked questions to understand their perception, to ascertain the type of tasks they were required to undertake, the main difficulties they experienced, and any possible suggestions they may have had for improving such systems.

2.4. *Representativeness of sample size*

Because it is important to ensure that the sample is representative for future RVM packaging characterisation campaigns, the size of the sample (N) was determined by the number of RVM bags to be characterised. Two confidence intervals were assumed (90% and 95%), using Eq. (1) [45], based on the percentage distribution of packages obtained in the present research project, by weight, by volumetry and type of beverage.

$$N = \left(\frac{Z_{\left(1-\frac{\alpha}{2}\right)} \times S}{\Delta} \right)^2 \quad \text{(Eq. 1)}$$

N – sample size; $Z_{\left(1-\frac{\alpha}{2}\right)}$ *– confidence coefficient (tabulated); S – standard deviation;* Δ *– precision*

3. Results and discussion

3.1. *Indicators related to the pilot project's RVM model*

During the monitoring period, the performance of the pilot project registered continuous growth. Fig. 1 shows the evolution of the number of PET packages deposited in the 23 RVM from their start in March 2020 until September 2020.

Some contextual factors help explain this evolution. Firstly, the project started in March 2020, which coincided with the day when the first state of emergency was declared by the Portuguese Government due to Covid-19, which enforced total confinement of citizens for almost three months. Some of the stores with RVM were closed and those that remained open recorded a significant reduction in customers. From that date until June 2021 several other contingency periods and restrictive measures were taken by the Government to control the pandemic. Secondly, as this was a pilot project, the communication campaigns carried out were very localised, only targeting the consumers in the 23 establishments with the RVM. This evolution also reflects the growth of the number of consumers at these locations, demonstrating how the system can effectively increase the rate of selective packaging collection, as in other countries, and as reported by Plastic Recyclers Europe (2022).

Based on the records of the 23 RVM and the results of the physical characterisation performed on a sample of 17,677 packages (476.6 kg), it was possible to determine the operational indicators presented in Table 1, relating to the model of machines used in the pilot project.

During the 202 days of operation of the pilot project, a total of 5,949,423 PET packages (corresponding to 151,285 kg) were deposited by customers of the supermarkets where the 23 RVM were located, which represents an average of 29,453 packages/day (748.9 kg/day), and 1,281 packages/RVM.day (32.6 kg/RVM.day).

The days of the week when more packages were deposited at the RVM were Saturdays, Sundays, and Mondays, which coincides with the days with the greatest influx of customers at these stores. This information is useful for planning the frequency of collections of this waste stream in the future DRS.

The average number of packages deposited in each visit to the RVM was 21, and the average time for each transaction was 1 min and 29 s. On several occasions, consumers were observed carrying many bags full of PET packaging to introduce into the machines,

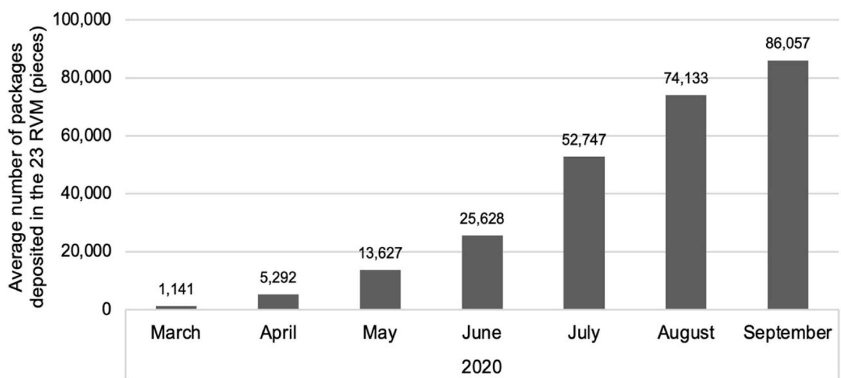

Fig. 1. Number of packages deposited in the 23 RVM, by month, between March and September of 2020.

Table 1
RVM Operational indicators for the pilot project.

Indicator	Average	Minimum	Maximum	Standard deviation
Number of packages deposited, per RVM and per day (packages/RVM.day)	1,281	60	2,869	1,035
Number of packages, per transaction (packages/transaction)	21.1	5.3	24.1	6.0
Average time, per transaction	1min 29 s	40 s	2 min 15 s	16 s
Percentage of rejects, per RVM (%)	16	12	23	2
Availability of the RVM (%)	88	39	99	8
Average number of bag changes, per month (bag/month)	2,512	228	5,402	1,835
Packaging weight, per bag (kg/bag)	9.9	9.4	10.4	0.4
Number of packages, per bag (packages/bag)	395	366	534	55
Specific weight of packages in RVM bags (kg/m^3)	20.6	19.7	21.7	0.8

which sometimes led to queues and for some of those waiting to choose to leave rather than continue waiting to make use of the RVM. From the conversations established with some of these high-quantity users, it was understood that they were either cafe workers that brought the packaging that their customers had consumed, or they were people who had asked family and friends or cafes for their packaging, in order to receive the shopping voucher.

According to the RVM records, the percentage of rejected packages that consumers tried to introduce in the machines was 16%. Through visual observation of the packages that were not accepted by the RVM, consumers deposited these in a specific container located beside or near these machines, it was possible to conclude that the main causes for this were: the state of the label or its absence; the condition of the package (*e.g.,* crumpled); packages that ought to have been accepted, but were not yet registered in the system; packages that were not in the collection portfolio of the DRS (*e.g.,* oil packaging, olive oil, detergent, or packaging from abroad); the volume of the packaging was outside the set limits (*e.g.,* higher than 2 l); and packages that were not fed into the RVM despite being on the collection portfolio of the DRS, perhaps as a result of customers giving up (*e.g.,* due to machine stoppage or queues).

The machines were available for 88% of the time during the store's opening hours, the downtime corresponded to the stops required for cleaning (maintenance representing about 1% of the stops, with an average of 83 transactions required per RVM before a complete cleaning cycle), changing the bag (about 2,512 bags/month), replacing the voucher printing paper, and other occurrences.

Operational parameters such as the number of packages deposited per RVM per day (packages/RVM.day) and the average number of bag changes per month (bags/month) do not have a normal distribution. However, this is because the data relates to the start-up phase of the DRS system.

According to statements made by some users, the RVM have some limitations, including: not recognising foreign brands (particularly relevant in areas closely bordering Spain); the non-acceptance of packages larger than 2 l; the packages having to be deposited in the RVM one by one; the incentive (*i.e.,* voucher) not being virtual, because it was always printed on paper, and was only allowed to be used for in-store purchases at the location of the RVM; and the location and visibility of machines not always being ideal for consumers. Regarding the space occupied on site for the pilot project system, the RVM itself needs 1.34 m^2 [46]. However, some supermarkets also had a bin for non-accepted bottles, and marketing objects advertising the project. The space required for filled bags depends on the type of place (supermarket) and availability of outside space.

It was also found that the proper functioning of the RVM and their operational availability for customers was very dependent on the commitment and skills of the employees responsible for their maintenance and operation. However, it was understood that for the supermarket employees, this system created extra work. Another obstacle mentioned concerned the space needed in the supermarket to store the full bags until they were collected for transport to their final destination. Sometimes, especially at the beginning of the project, collection took a long time. However, in general, the operation and maintenance of these RVM was deemed straightforward and it was easy for customers to use them.

3.2. Characteristics and composition of packages deposited in RVM

The packages contained in the sample of 46 bags were separated by type of beverage, volumetry, and colour (Table 2). In terms of the types of drinks, water bottles were the majority (68.7%, by weight, and 81.4%, by number), followed by soft drinks (29.1%, by weight, and 17.2%, by number). The percentage of juice bottles was low compared to the other categories, and this is relevant in terms of the contamination of the bags (and other bottles collected).

Regarding the volumetry of packaging (Table 3), 1.5 l was the most commonly observed (53.9%, by weight, and 44.9%, by

Table 2
Total number and percentage of packages, by type of beverage.

Beverage group	Total number of packages (n.°)	Percentage, by number (%)	Percentage, by weight (%)
Water	14,385	81.4	68.7
Soft drinks	3,045	17.2	29.1
Alcoholic beverages	139	0.8	1.2
Fruit juices	108	0.6	1.0
Total	17,677	100	100

Table 3
Total number and percentage of packages, by volumetry.

Volumetry (l)	Total number of packages (n.°)	Percentage, by number (%)	Percentage, by weight (%)
1.50	7,937	44.9	53.9
0.50	4,521	25.6	15.7
2.00	885	5.0	9.1
0.33	2,879	16.3	8.8
1.00	724	4.1	6.0
1.75	461	2.6	4.9
1.25	84	0.5	0.8
0.75	80	0.4	0.6
0.25	53	0.3	0.2
0.20	8	0.1	<0.1
Unknown	45	0.2	–
Total	17,677	100	100

number), followed by 0.5 l (15.7%, by weight, and 25.6%, by number). It was not possible to identify the volumetry of some packages (45, in total, corresponding to 0.3%), due to their labels being missing or them having been sliced by the compression performed in the RVM.

Concerning the colour of the packaging body's material (Table 4), transparent blue was the dominant colour (58.4%, by weight, and 69.7%, by number), followed by non-coloured (31.0%, by weight, and 22.3%, by number) and finally green (10.4%, by weight, and 7.6%, by number). The low share of coloured bottles indicates that most bottles are transparent, which is in agreement with the Recyclass design-for recycling guidelines [23].

On average, the caps represented between 4 and 5% of the total weight of the packages deposited in the bags. However, about 25-33% of packages were returned without the caps. One possible explanation for this is that in some supermarkets, a collection of bottle caps for social purposes exists. It was also found that most caps and rings were loose in the bags, due to the compacting process inside the machine, only 0.2% of packages had their caps and rings attached to the body of the package, and 1.2% contained only the caps. Moreover, no packages with a fixed cap were found.

The analysis of the labels showed that 46.7% of packages had paper labels, and 52.3% had plastic labels. In about 2.8% of the packages, the label was on the upper part of the package body (curve), and 1% covered more than 50% of the package body. However, according to Recyclass [23] and Alsewailem & Alrefaie [48], paper labels are not deemed to be compatible with PET bottle recycling. It was verified that 6.9% of packages already mentioned the incorporation of recycled material on the label, with the proportions being between 25% and 100% of the total packaging material. All these aspects, such as the colours, lost caps and the labels, are important for informing packaging design and the need to recycle the material again, according to Recyclass [23] and EPBP [24].

On average, in the sample analysed, a full RVM bag weighs 10.4 kg and contains 466 packages. Considering the volumetry of the bags, the specific weight of packaging in RVM bags is 21.6 kg/m^3. This value is within the range indicated by Rodrigues et al. [47] and in the case of packaging waste deposited in plastic/metal containers. However, given that only the PET plastic material is accepted by the RMV, it would be expected that the rate of compaction of the machines would result in a higher specific weight. Furthermore, although the RVM bags all had the same volume, and full bags were requested for the physical characterisation of the packaging, in some cases store employees compacted the deposits to a greater extent than in others, to make the most of the volume available, so this indicator reflects variation dependent upon how employees engaged with the technology. This may relate to another problem also reported at the beginning of the campaign, which indicated that not all the bags were being filled according to the initial instructions and that methods differed at the various locations.

3.3. Representative sample size

Considering the volumetry (Table 5), the sample size used in this research is representative for 1.5 l packages (the most commonly deposited packages) and for the lids that were weighed separately (because they were loose), to both confidence intervals.

The non-acceptance of bottles with a volumetry greater than 2 l is a weakness of these RVM since many Portuguese consumers buy larger bottles of water and soft drinks. High capacity bottles have a smaller ecological footprint than smaller bottles, and by not allowing for the disposal of higher capacity bottles it is feared that this may incentivise a change in consumer habits, increasing the consumption of smaller bottles.

Table 4
Percentage of packages, by colour.

Colour of packages	Percentage, by number (%)	Percentage, by weight (%)
Transparent blue	69.9	58.4
Non-coloured	22.3	30.9
Transparent green	7.5	10.4
Other (transparent purple)	0.3	0.3
Total	100	100

Table 5
Analysis of the representativeness of the sample, by volumetry.

Volumetry (l)	Statistical data (%, by weight)							
	Minimum	Maximum	Mean	Median	SD	Delta	N (95%)	N (90%)
0.20	0.0	1.2	0.0	0.0	0.2	0.0	13,812	9,729
0.25	0.0	4.9	0.2	0.0	0.8	0.0	5,157	3,633
0.33	0.0	47.9	7.8	4.1	9.7	0.8	592	417
0.50	1.9	57.4	15.0	12.3	11.7	1.5	234	165
0.75	0.0	5.7	0.6	0.1	1.2	0.1	1,476	1,039
1.00	0.0	25.6	5.4	3.9	4.7	0.5	285	201
1.25	0.0	3.2	0.8	0.5	0.9	0.1	526	370
1.50	22.3	80.3	52.3	53.5	14.5	5.2	29	21
1.75	0.0	14.0	4.6	4.4	3.4	0.5	210	148
2.00	0.0	23.8	8.6	9.0	5.4	0.9	153	108

Legend: SD - sample standard deviation; Delta - precision; N - sample size (number of RVM filled bags).

Considering packages by type of beverage, the sample used is representative for water (the predominant type of beverage), for both confidence intervals (Table 6).

Given the results obtained in this statistical treatment, and because physical characterisations of waste require considerable human and financial resources, in future characterisation campaigns, the sample size can be reduced to 30 RVM bags, which is sufficient for the representativeness of the dominant type of packages observed (water in 1.5 l packaging).

3.4. *Quality of packaging collected from RVM for bottle-to-bottle recycling*

According to the analyses performed by the two consulted recycling companies on the collected PET bottle feedstock, it is concluded that the material delivered to the recyclers was of a good quality (*i.e.,* quite clean, without many of the caps and their rings, or labels). The collection of clean material, providing better-quality PET upon recycling, represents around 78%, and coloured PET bottles (particularly green) represent 12%. One problem with this material was the presence of some bottles made of complex materials, which present a barrier to the recyclability of these materials, as mentioned by Antonopoulos et al. [25]. It was also possible to detect some lower quality packaging in the bags (that which was collected from the street, from collective recycling sites, and from unsorted waste), which may contaminate the remaining packages.

These results reveal the importance of adapting, articulating the ecological design of packaging, reducing the amount of coloured PET packaging, as well as complex materials, to accomplish a higher circularity of PET beverage packaging.

4. Conclusion

Despite the fact that the monitoring period occurred during the Covid-19 pandemic, the DRS proved to be innovative in the Portuguese context. The results of the DRS pilot suggest that implementing a DRS will help to increase the quantity and quality of packaging waste collected in Portugal, contributing to efforts to meet the mandatory recycling targets for European Union Member States. Furthermore, although the pilot research project was focused solely on PET bottles, it is an important contribution to packaging recycling targets and circularity, with the incorporation of secondary quality recycled material in the production of new packaging.

Throughout the research project, information was gathered about the functioning of the RVM and the characteristics of the PET containers collected, namely through the operational indicators assessed. Specifically, the results of the physical characterisation of the packages contained in the sample of 46 collection bags allow for the following conclusions: in terms of types of drinks, water bottles are the most commonly deposited; 1.5 l packages were the most frequently observed volumetry; and transparent blue was the dominant colour of the material deposited, which has a high level of recyclability.

The indicators studied include the average time for each transaction (1min 29s), the percentage of rejected packages (16%), the availability of the RVM (88%) and the quality of the material delivered to the recyclers; all of which show that the material has good quality and the DRS could contribute towards meeting packaging recycling targets and circularity, and towards the incorporation of secondary quality recycled material in new packaging.

This project also demonstrated the need for manual packaging drop-off locations, for situations when, for instance, the packaging has eligibility problems due to the condition of the label. It is also important to adapt, and articulate to producers, the ecological design of packaging, reducing the use of loose caps, reducing the amount of coloured PET packaging, as well as reducing the use of complex materials. On the other hand, the implementation of a wider DRS is associated with costs, especially the investment in RVM, their maintenance, and the collection operations, to ensure functional logistics and avoid delays in the collection of the bags stored in supermarkets by the managing entities.

Furthermore, the following factors are relevant when the DRS is implemented at full scale: the commitment and skills of the employees responsible for RVM maintenance and operation are crucial elements for the more effective operation of the pilot project; the condition of the material being sent for recycling is impacted by the RVM compacting systems, thereby directly influencing material loss due to the formation of small, compacted pieces, like caps and rings found loose in the bags; the location of the machines, in terms of visibility; and the non-acceptance of foreign bottles (in the context of the pilot project this was particularly relevant in areas

Table 6
Analysis of the representativeness of the sample, by type of beverage.

Beverage group	Statistical data (%, by weight)							
	Minimum	Maximum	Mean	Median	SD	Delta	N (95%)	N (90%)
Water	36.9	91.0	66.5	68.1	13.1	6.7	15	11
Fruit juices	0.0	9.3	1.0	0.0	1.9	0.1	1,412	995
Soft drinks	4.1	50.4	26.6	25.1	12.4	2.7	83	59
Alcoholic beverages	0.0	30.0	1.2	0.0	4.4	0.1	5,160	3,634

Legend: SD - sample standard deviation; Delta - precision; N - sample size (number of RVM filled bags).

closely bordering Spain).

Future research should include an economic analysis of the DRS to facilitate a comparison with the costs of the current collective collection system. Technological developments in the RVM can improve the behaviour of users, particularly in terms of their operation. It is crucial to establish clear requirements for the acceptance of packages in the RVM and to enhance the user experience by accommodating a higher volume of packages within a shorter timeframe. This helps to prevent the disposal of potentially recyclable packages and encourages bottle-to-bottle recycling, while also addressing fraud prevention requirements. Regular machine maintenance, including thorough interior cleaning, is vital to ensure proper packaging acceptance. These efforts aim to improve system efficiency in any future DRS. Apart from the operational component, it is important to further explore the social component of a DRS, to study the changes in consumer behaviour, and consider how behaviours change with alterations in the economic incentives applied to pilot projects.

To enable future benchmarking with other DRS, it is essential to consider the specifications and compaction systems of the range of RVM that are available in the market.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Graça Martinho: Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Pedro Santos:** Methodology, Formal analysis, Investigation, Writing – Original Draft, Writing – Review & Editing, Project administration.. **Ana Alves:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Mário Ramos:** Writing – review & editing, Writing – original draft, Validation, Supervision.

Declaration of competing interest

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

Acknowledgments

The pilot project was funded by the Environmental Fund, of the Ministry of Environment and Climate Action (MAAC), within the scope of the Action Plan for the Circular Economy. This work was also funded by Fundação para a Ciência e a Tecnologia (FCT, Portugal), through the strategic projects UIDB/04292/2020 and UIDP/04292/2020 granted to MARE - Marine and Environmental Sciences Centre, and the project LA/P/0069/2020 granted to the Associate Laboratory ARNET - Aquatic Research Network.

The authors are grateful to Cristina Costa, from the Portuguese Association of Non-Alcoholic Refreshing Drinks, and Cristina Câmara, from the Portuguese Association of Distribution Companies, for their support in the planning of the monitoring campaign of the packages deposited in the RVM, and to the managers and employees of the 23 commercial establishments directly involved in the pilot project, for their support in the monitoring work.

References

[1] R. Abejón, J. Laso, M. Margallo, R. Aldaco, G. Blanca-Alcubilla, A. Bala, P. Fullana-i-Palmer, Environmental impact assessment of the implementation of a Deposit-Refund System for packaging waste in Spain: a solution or an additional problem? Sci. Total Environ. 721 (2020) 137744 https://doi.org/10.1016/j.scitotenv.2020.137744.
[2] Y. Wang, Y. Gu, Y. Wu, G. Zhou, H. Wang, H. Han, T. Chang, Performance simulation and policy optimization of waste polyethylene terephthalate bottle recycling system in China, Resour. Conserv. Recycl. 162 (2020) 105014, https://doi.org/10.1016/j.resconrec.2020.105014.
[3] W. Leal Filho, U. Saari, M. Fedoruk, A. Iital, H. Moora, M. Klöga, V. Voronova, An overview of the problems posed by plastic products and the role of extended producer responsibility in Europe, J. Clean. Prod. 214 (2019) 550–558, https://doi.org/10.1016/j.jclepro.2018.12.256.
[4] Plastics Europe, Plastics - the facts 2022. https://plasticseurope.org/knowledge-hub/plastics-the-facts-2022/, 2022.
[5] Eunomia, PET market in Europe - state of play, Production, Collection and Recycling 48 (2022).

[6] R. Geyer, J.R. Jambeck, K.L. Law, Production, use, and fate of all plastics ever made, Sci. Adv. 3 (7) (2017), https://doi.org/10.1126/sciadv.1700782.
[7] F. Welle, Twenty years of PET bottle to bottle recycling - an overview, Resour. Conserv. Recycl. 55 (11) (2011) 865–875, https://doi.org/10.1016/j.resconrec.2011.04.009.
[8] Resolve, Reuse is the way out of the plastics mess. https://www.resolve.ngo/pr3.htm?mc_cid=a9704e29e9&mc_eid=6cc227745e, 2022.
[9] PAEC, Circular economy action agenda: plastics. Platform for accelerating the circular economy. https://pacecircular.org/sites/default/files/2021-02/circular-agenda-plastics-feb2021_FINAL.pdf, 2021.
[10] G. Zhou, Y. Gu, Y. Wu, Y. Gong, X. Mu, H. Han, T. Chang, A systematic review of the deposit-refund system for beverage packaging: operating mode, key parameter and development trend, J. Clean. Prod. 251 (2020) 119660, https://doi.org/10.1016/j.jclepro.2019.119660.
[11] Ocean Conservancy, The Beach and beyond, vols. 1–30, International Costal Cleanup, 2019. https://oceanconservancy.org/wp-content/uploads/2019/09/Final-2019-ICC-Report.pdf.
[12] Eunomia, Plastics in the marine environment. June, 13. www.eunomia.co.uk, 2016.
[13] E. Van Sebille, A. Gilbert, C. Spathi, The ocean plastic pollution challenge: towards solutions in the UK, Grantham Instit. Breifing Pap. 19 (19) (2016) 3–4. www.imperial.ac.uk/grantham/publications.
[14] J. Hänninen, M. Weckström, J. Pawłowska, N. Szymańska, E. Uurasjärvi, M. Zajaczkowski, S. Hartikainen, I. Vuorinen, Plastic debris composition and concentration in the arctic ocean, the north sea and the baltic sea, Mar. Pollut. Bull. 165 (2021) 112150, https://doi.org/10.1016/j.marpolbul.2021.112150.
[15] M. Guan, H. Jin, W. Wei, M. Yan, Degradation of polyethylene terephthalate (PET) and polypropylene (PP) plastics in seawater, DeCarbon 1 (2023) 100006, https://doi.org/10.1016/j.decarb.2023.100006.
[16] European Commission, A European strategy for plastics in a circular economy. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions, Brussels, January 16th 2018 COM (2018). Available online: https://ec.europa.eu/environment/circular-economy/pdf/plastics-strategy.pdf, 2018. (Accessed 22 August 2022).
[17] D.R. Schneider, T. Tomić, R. Raal, 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), https://doi.org/10.13044/j.sdewes.d8.0386.
[18] A. Oke, O. Osobajo, L. Obi, T. Omotayo, Rethinking and optimising post-consumer packaging waste: a sentiment analysis of consumers' perceptions towards the introduction of a deposit refund scheme in Scotland, Waste Manag. 118 (2020) 463–470, https://doi.org/10.1016/j.wasman.2020.09.008.
[19] Ellen Macarthur Foundation, The European plastics Pact. https://ellenmacarthurfoundation.org/the-plastics-pact-networkon, 2022. (Accessed 28 October 2022).
[20] Plastics Recyclers Europe, PET market in Europe. State of play production, collection and recycling data (2022) 22.
[21] M. Malindzakova, J. Štofková, M. Majernik, Economic–environmental performance of Reverse logistics of disposable beverage packaging, Sustainability (2022), https://doi.org/10.3390/su14137544.
[22] R. Cremiato, M.L. Mastellone, C. Tagliaferri, L. Zaccariello, P. Lettieri, Environmental impact of municipal solid waste management using Life Cycle Assessment: the effect of anaerobic digestion, materials recovery and secondary fuels production, Renew. Energy 124 (2018) 180–188, https://doi.org/10.1016/j.renene.2017.06.033.
[23] Recyclass, Design for recycling guidelines. https://recyclass.eu/guidelines/coloured-pet-bottles/, 2023.
[24] Epbp, European PET bottle platform - design guidelines, Available online: https://www.epbp.org/design-guidelines on, 2022. (Accessed 28 October 2022).
[25] I. Antonopoulos, G. Faraca, D. Tonini, Recycling of post-consumer plastic packaging waste in EU: process efficiencies, material flows, and barriers, Waste Manag. 126 (2021) 694–705, https://doi.org/10.1016/j.wasman.2021.04.002.
[26] Plastics Recyclers Europe, Guidance on Quality Sorting of Plastic Packaging 1–7 (2018). January 2018.
[27] M. Kawai, J. Nakatani, K. Kurisu, Y. Moriguchi, Quantity- and quality-oriented scenario optimizations for the material recycling of plastic packaging in Japan, Resour. Conserv. Recycl. 180 (2022) 106162, https://doi.org/10.1016/j.resconrec.2022.106162.
[28] Ellen Macarthur Foundation, The New Plastics Economy - Rethinking the future of plastics (2016). Available at: http://www.ellenmacarthurfoundation.org/publications.
[29] EFSA, About us. https://www.efsa.europa.eu/en/aboutefsa, 2020.
[30] C. Matthews, F. Moran, A.K. Jaiswal, A review on European Union's strategy for plastics in a circular economy and its impact on food safety, J. Clean. Prod. 283 (2021) 125263, https://doi.org/10.1016/j.jclepro.2020.125263.
[31] M. Niaounakis, Recycling of Flexible Plastic Packaging || Legislation and Regulatory Framework (2020) 369–393, https://doi.org/10.1016/B978-0-12-816335-1.00010-4.
[32] M.T. Brouwer, F. Alvarado Chacon, E.U. Thoden van Velzen, Effect of recycled content and rPET quality on the properties of PET bottles, part III: modelling of repetitive recycling, Packag. Technol. Sci. 33 (9) (2020) 373–383, https://doi.org/10.1002/pts.2489.
[33] R. Franz, F. Welle, Contamination levels in recollected PET bottles from non-food applications and their impact on the safety of recycled PET for food contact, Molecules 25 (2020) 4998, https://doi.org/10.3390/molecules25214998.
[34] European Commission, Plastics own resource, Available online: https://ec.europa.eu/info/strategy/eu-budget/long-term-eu-budget/2021-2027/revenue/own-resources/plastics-own-resource_en, 2022. (Accessed 22 August 2022).
[35] Reloop, Global Deposit Book 2022. An overview of deposit systems for single-way beverage containers. https://www.reloopplatform.org/wp-content/uploads/2022/11/RELOOP_Global_Deposit_Book_11I2022_P1.pdf, 2022.
[36] UNEP. Single-use plastics: a roadmap for sustainability, Rev ed., 2018, p. 6.
[37] F. Laubinger, et al., Deposit-refund systems and the interplay with additional mandatory extended producer responsibility policies, in: OECD Environment Working Papers, OECD Publishing, Paris, 2022, https://doi.org/10.1787/a80f4b26-en. No. 208.
[38] A. Calabrese, R. Costa, N. Levialdi Ghiron, T. Menichini, V. Miscoli, L. Tiburzi, Operating modes and cost burdens for the European deposit-refund systems: a systematic approach for their analysis and design, J. Clean. Prod. 288 (2021) 125600, https://doi.org/10.1016/j.jclepro.2020.125600.
[39] D. Lavee, A cost-benefit analysis of a deposit-refund program for beverage containers in Israel, Waste Manag. 30 (2) (2010) 338–345, https://doi.org/10.1016/j.wasman.2009.09.026.
[40] F. Welle, Is PET bottle-to-bottle recycling safe? Evaluation of post-consumer recycling processes according to the EFSA guidelines, Resour. Conserv. Recycl. 73 (2013) 41–45, https://doi.org/10.1016/j.resconrec.2013.01.012.
[41] T.H. Begley, T.P. McNeal, J.E. Biles, K.E. Paquette, Evaluating the potential for recycling all PET bottles into new food packaging, Food Addit. Contam. 19 (Suppl) (2002) 135–143, https://doi.org/10.1080/02652030110083720.
[42] Eurostat, Recycling rates of packaging waste for monitoring compliance with policy targets, by type of packaging, Available online: https://ec.europa.eu/eurostat/databrowser/view/ENV_WASPACR_custom_5772405/default/table?lang=en, 2023.
[43] OECD, Deposit-refund system. https://stats.oecd.org/glossary/detail.asp?ID=594, 2001.
[44] M.G. Martinho, M.G. Gonçalves, Gestão de Resíduos, Edição Da Universidade Aberta, 2000.
[45] P. Newbold, Statistics for Business and Economics, Prentice-Hall, 1995.
[46] TOMRA, TOMRA T70 dual. https://www.tomra.com/en/reverse-vending/our-offering/reverse-vending-machines/tomra-t70-dual, 2023.
[47] S. Rodrigues, G. Martinho, A. Pires, Waste collection systems. Part B: benchmarking indicators. Benchmarking of the great Lisbon area, Portugal, J. Clean. Prod. 139 (2016) 230–241, https://doi.org/10.1016/j.jclepro.2016.07.146.
[48] F.D. Alsewailem, J.K. Alrefaie, Effect of contaminants and processing regime on the mechanical properties and moldability of postconsumer polyethylene terephthalate bottles, Waste Manag. 81 (2018) 88–93, https://doi.org/10.1016/j.wasman.2018.09.052.