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RESEARCH ARTICLE

The road to sustainable use and waste management of plastics in Portugal

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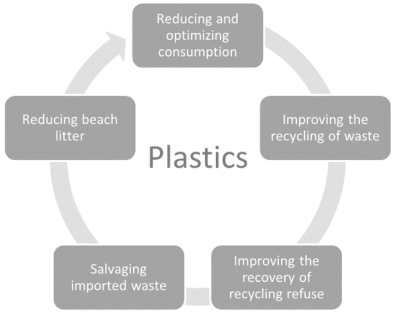
HIGHLIGHTS

- Portugal recycles 34% of the 40 kg/hab year of plastic packaging waste.
- Recycling of plastics in Portugal produces a final revenue of 167 €/t.
- Recycling and recovery must be the priority for imported wastes.
- Beach litter must be reduced from 330 to 20 items/100 m (94%) under EU goals.
- Consumption, use, and waste management of plastics need to improve.

GRAPHIC ABSTRACT



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ABSTRACT

As a European Union (EU) member, Portugal must comply with reductions in plastic waste. In Portugal, the 330 items/100 m of beach litter, comprising up to 3.9 million pieces and of which 88% is plastic, is higher than the EU median (149 items/100 m) and must be reduced to 20 items/100 m (94%). Integrative measures are needed to reduce littering and improve plastics' use and disposal under the circular economy. Of this 414 kt of plastic packaging waste, 163 kt were declared plastic packaging, 140 kt subjected to recycling, and 94 kt to energy recovery. The current recycling rate of plastic packaging (34%) should be improved to reach EU recycling averages (42%) and goals and to provide widespread benefits, considering revenues of 167 €/t. As a net importer of waste, Portugal could benefit from the valorization of imported waste. Besides increased recycling, pyrolysis and gasification could provide short-term alternatives for producing value-added substances from plastic waste, such as hydrogen, consistent with the National Plan of Hydrogen and improving ongoing regulations on single-use plastics. This manuscript provides an integrative view of plastics in Portugal, from use to disposal, providing specific recommendations under the circular economy.

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1 Introduction

Plastics have benefited humankind by providing a cheap and lightweight material that contributes to better medical care (e.g., disposable syringes) and food safety (e.g., packaging). Plastics provide other societal benefits, such as storage of clean water and improved shelf-lives of packaged foods, only considered a problem due to misuse and mismanagement (Andrady and Neal, 2009). While high durability may be beneficial for some applications (e.g., in construction materials), single-use items and packaging create problems regarding their persistence in the environment. In 2019, of the global production of 368 million ton of plastics, 39.6% were used in packaging (Plastics Europe, 2019). Most littered plastics originate from land-based sources (Jambeck et al., 2015). Despite persistent in the environment, plastics fragment under the abrasive forces and sunlight forming pieces < 5 mm known as microplastics (Andrady, 2017). Both plastics and microplastics, directly and indirectly, affect ecosystems, human health, and have socioeconomic impacts

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(e.g., decreased tourism) (Prata et al., 2021). The irreversibility and global distribution of marine plastic litter lead to its classification as a planetary boundary threat (Villarrubia-Gómez et al., 2018).

Portugal is a country with 1187 km of Atlantic coast located in the south-western part of Europe. A review of the Portuguese coast's environmental status of (micro) plastic contamination concluded that it is low to moderately contaminated (relative to other countries). However, animals already present plastics in their gastrointestinal systems. Furthermore, the highest concentrations of plastics were related to high population density areas (i.e., coastal cities) (Prata et al., 2020a). As a State Member of the European Union (EU), Portugal must comply with monitoring beach litter (European Commission, 2020c), reducing the consumption of single-use plastics (European Parliament, 2019), and improving plastic waste management (European Parliament, 1994; European Commission, 2018). Therefore, the Portuguese government is responsible for transposing EU Directives and recommendations into national laws and regulations, while the Portuguese Environmental Protection Agency (Agência Portuguesa do Ambiente, APA) is responsible for monitoring. This work aims to address current measures taken in Portugal regarding plastics' consumption and waste management of plastics, considering their success and compliance with EU objectives, and provide recommendations for improving their use and waste management.

2 Waste management of plastics in Portugal

The past five years have seen an increase in waste, with a total production of 5.2 Mt of waste in 2019, corresponding to 513 kg/hab year (Fig. S1). Citizens dispose of waste in one of the four streams in public containers available at the curbside: mixed waste, paper and cardboard, glass, and plastic and metal packaging. The collection of urban mixed waste and recyclables is provided by municipalities or by managing entities (SGRSU). SGRSU receive MSW for final disposal and sorting of recyclables. Recyclables managing entities (SIGRE, e.g., Green Dot Society), financed by the packaging industry and importers, receive recyclables and send them to the recycling industry (Magrinho et al., 2006). In 2019, there were 258 waste collection entities, 23 SGRSU, and 4 SIGRE (Agencia Portuguesa do Ambiente, 2019b). Landfilling is still the dominant treatment in Portugal, with 33% of the waste directly sent to landfills, reaching 58% when considering refuse from other operations (Fig. S2). Besides curbside collection, other collection systems are present on a smaller scale (Fig. 1). Large commercial establishments often provide drop-off containers for specific recyclable streams produced in smaller quantities (i.e., e-waste, textiles, used cooking oil, lamps, coffee capsules, batteries, caps, toners, specific plastic types), allowing for higher recycling efficiencies and providing benefits in the form of discounts (e.g., for recycling toners when buying new ones) or by donating to charity. Bottle caps that are rarely recycled are avidly collected by citizens or entities under the *Tampinhas* ("Bottle caps") project and delivered to waste management facilities, which donate their recycling value to charity cases, usually to buy medic equipment such as wheelchairs. Pay-as-you-throw (PAYT) systems are also being tested in some municipalities. For instance, Guimarães municipality sells official trash bags for mixed waste, offering trash bags for recyclables, which are then left at the citizens' doorstep at the time of collection by municipal services, leading to a 126% increase in recycling rates and a 34% decrease in mixed waste. Maia and Portimão municipalities installed curbside "intelligent" containers, which are opened with identification cards attributed to citizens, allowing to apply a fee on each use of the 30 L mixed waste container, improving recycling rates. Finally, the Portuguese government is running a pilot project on a deposit-return system on beverage containers, with large grocery stores selling products also providing collection equipment since the beginning of 2020 (Assembleia da Republica, 2018). The government will evaluate this system in the final trimester of 2021 and hopefully implement it by the 1st of January 2022. These measures can provide feasible alternatives to improve recycling rates, especially for specific waste streams. Additionally, the Waste Management Tax (Taxa de Gestão de Resíduos, TGR) paid by municipalities will be increased from 11 to 22 €/t (compared to the EU 80 €/t) (Agencia Portuguesa do Ambiente, 2021a). TGR is paid in

Fig. 1 Waste management in Portugal: (A) *Ecopoint* recyclable containers for glass (green stream), metal and plastic packaging (yellow stream) and paper (blue stream) next to two mixed waste containers; (B) Container for e-waste available in commercial spaces; (C) Containers for odd streams of recyclables available in commercial spaces.

full for landfilling, at 70% for incineration, and 25% for energy recovery, to encourage waste disposal by recycling (Agencia Portuguesa do Ambiente, 2021a). However, some municipalities already consider increasing waste taxes paid by consumers in the water bill instead of moving toward more sustainable alternatives.

Plastic comprises 11.3% of total waste weight (Fig. 2(A)). Plastic packaging represents 8% of the waste produced in Portugal, corresponding to 414.5 kt, or 40.3 kg/hab year (17% above the European Union average), in 2018 (Figs. 2(B) and 2(C)). Packaging or importing entities declared 163.0 kt of plastic packaging in 2018, with 72.3 kt (57.7%) being collected in urban waste by SIGRE, of which consumers separate 84.0% and the remaining 16.0% is separated from mixed waste (Sociedade Ponto Verde, 2019). These plastics were mostly comprised of mixed plastics, films, and polyethylene terephthalate (PET). In addition to urban waste, producers

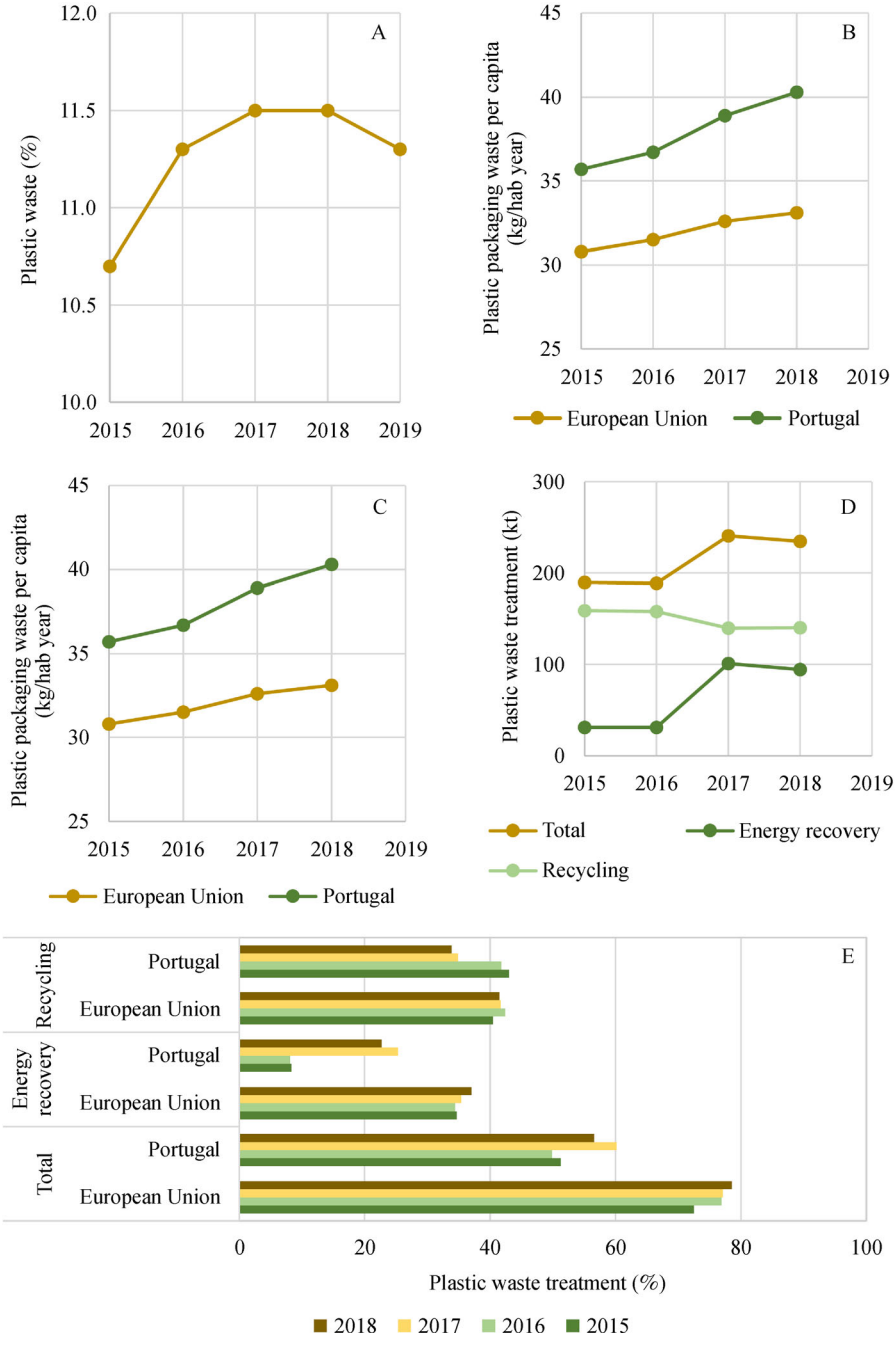

Fig. 2 Percentage of plastic in municipal solid waste (A), plastic packaging waste production per capita (B), total plastic packaging waste produced (C), recovery treatment of plastic waste by weight (D) and percentage (E). Data collected from (Agencia Portuguesa do Ambiente, 2019b; Sociedade Ponto Verde, 2019; Agencia Portuguesa do Ambiente, 2020; Eurostat, 2021a).

of non-urban waste must ensure the dispatching of waste to a licensed waste management entity. From the 414.5 kt of total plastic packaging collected (urban and non-urban), 140.4 kt were recycled, and 94.2 kt were subjected to energy recovery (Fig. 2(D); Agencia Portuguesa do Ambiente, 2020; Eurostat, 2021a). This corresponds to recycling of 33.9% and energy recovery of 22.7% of plastic packaging, below the EU averages of 41.5% and 37.0%, respectively (Figs. 2(E) and S3). The current recycling rate of 33.9% for plastic packaging in Portugal is already above the national objective of 22.5% set in Decree-Law n. 152-D/2017 (Assembleia da Republica, 2017) and above the EU targets of 25% (European Parliament, 1994). EU targets increase to 50% and 55% by 2025 and 2030, respectively (European Parliament, 1994). Thus, rapid investment in recycling infrastructures is needed in the coming decade to achieve these goals. Recycling in Portugal, including recycling plastics, generally benefits the environment, although differences in Life Cycle Assessment (LCA) result from different assumptions (Table 1). In addition to environmental benefits, recycling is beneficial for the society and economy. In 2011, SIGRE created 2300 direct jobs, and for each 1 € of value-added generated in SIGRE's activity, 1.3 € were additionally added to the economy, amounting to 391 million € in total revenue (Ferrão et al., 2014). Similarly, the high value of plastic (732 €/t) and mixed plastic (245 €/t) waste, and avoided alternative treatments (e.g., landfilling), allow offsetting costs with collection and sorting, resulting in a final revenue from the recycling of 167.2 €/t or 31.7 €/hab year (Pires et al., 2017). In addition to revenues directly related to the waste management system, recycling activities in Portugal also produce benefits in terms of environmental costs in the range of 3.3 to 8.2 million € (Ferreira et al., 2014). While recycling should be prioritized considering the benefits for society (e.g., saving of raw materials, energy, environmental and societal benefits), energy recovery should be preferred to landfilling of recycling refuse (e.g., degraded or contaminated plastics) (Prata et al., 2019). Waste-to-energy, in the form of incineration, also has a beneficial environmental impact (Table 1), with an ecological footprint of -0.78 global m^2/kg of combustible waste (i.e., saving space required to provide the resources and absorb wastes of an activity) (Herva et al., 2014) and an additional positive outcome in terms of ecotoxicity (freshwater: -267×10^{-3} $kg_{DCB\text{-}eq}$; seawater: -26×10^{-3} $kg_{DCB\text{-}eq}$; terrestrial: -59×10^{-3} $kg_{DCB\text{-}eq}$), and human toxicity potential (-7.45 $kg_{DCB\text{-}eq}$), mostly offset by resources and emissions saved in alternative energy production and avoided landfilling (Ramos et al., 2018). As for all recoveries, including waste-to-energy, the national objective for all packaging materials is 60% (Assembleia da Republica, 2017). Energy recovery is currently 22.7% for plastic packaging, and increasing it would help achieve the objectives, especially for plastics with low recyclability. Energy recovery is a viable solution for plastics when considering energy contents of 43.3 MJ/kg in polyethylene (Baytekin et al., 2013) or 19–28 MJ/kg in plastics recovered by landfill mining (Quaghebeur et al., 2013). Only two incinerators for MSW exist in Portugal (i.e., in Porto and Lisbon), requiring investment in infrastructures to increase energy recovery from packaging waste, including plastic waste. Building incineration facilities can be controversial, as they are not easily accepted by the Portuguese public, requiring additional awareness campaigns. An alternative solution would be to produce feedstock from plastic waste- chemicals used to produce fuels, lubricants, or new plastics (Prata et al., 2019). Pyrolysis produces value-added oil, gas and char, from plastics subjected to an anaerobic thermal process (Sharuddin et al., 2016), while gasification produces synthetic gas with a lower infrastructure cost and rapid return of the investment (as low as 1.4 years) (Eriksen et al., 2018). Gasification and pyrolysis coupled with catalytic steam reforming produce H_2, with the latter being able to convert over 30% of plastic weight to H_2 (Lopez et al., 2018). Green hydrogen production must be increased following the National Plan of Hydrogen, one of the decarbonization measures, including 10%–15% consumption by injection in natural gas systems, 1%–5% consumption in road transport, 1.5%–2% in total energy consumption by 2030 (Assembleia da Republica, 2020). Thus, sustainable waste management for plastic contributes to waste management goals and green hydrogen goals (if sustainably treated). Ideally, these options should be considered under an integrated waste management system (IWMS). In Portugal, an existing IWMS, which includes recyclables, incineration, composting, and landfill of residual wastes (e.g., ashes), provided a beneficial ecological footprint of -0.49 global m^2/kg of waste (i.e., saving 0.49 m^2 per kg of waste) (Herva et al., 2014). Therefore, IWMS should be expanded to all municipalities.

3 Waste trade in Portugal

As plastic waste contains valuable raw materials, trading such wastes can have a positive impact when treated under the circular economy. Waste transportation within and beyond EU borders (OECD and non-OECD) is regulated by the EU waste shipment regulation EC 1013/2006 and the recent amendment through Delegated Regulation (EU) 2020/2174 (European Commission, 2021). Such amendment, which entered into force on the 1st of January 2021, restricts waste trade on certain plastics. For instance, it bans the export of hazardous plastic waste (i.e., plastics that contain hazardous constituents or are in contact with hazardous substances such as flammable, poisonous, infectious, corrosive substances) and non-hazardous plastic waste hard to recycle from EU to non-OECD countries

Table 1 Life cycle assessment of waste in Portugal regarding recycling, plastic recycling, and waste-to-energy in incineration

Reference	Type of waste reatment	Year	Climate change (kg $CO_{2\text{-eq}}$)	Acidification (mol H + eq)	Photochemical ozone formation (kg NMVOC-eq)	Abiotic depletion (kg Sb-eq)	Water resource depletion (m^3 H_2O)
Ferrão et al., 2014	Recycling	2011	-3.3×10^{8}	-3.1×10^{6}	-1.7×10^{6}	-3.7×10^{1}	-7.3×10^{5}
Ferreira et al., 2014	Recycling	2010	5.6×10^{6}	-9.5×10^{3}	-7.9×10^{3}	2.4×10^{3}	n.a.
Ferrão et al., 2014	Plastic Recycling	2011	4.9×10^{7}	-2.4×10^{5}	-1.9×10^{5}	2.6×10^{-3}	-2.7×10^{4}
Ferreira et al., 2014	Plastic Recycling	2010	-3.0×10^{6}	-4.2×10^{3}	-1.1×10^{4}	-4.2×10^{3}	n.a.
Ramos et al., 2018	Incineration	2015	-1.7×10^{2}	n.a.	n.a.	-50.1×10^{-6}	n.a.

that often lack the capacity and standards to manage it sustainably. Additionally, it limits import into the EU or intra-EU, requiring a prior notification and consent procedure. In 2018, Portugal was among the top-15 countries of the EU for imports of plastic waste from other EU members (Statistica, 2019). Most Portuguese waste import originates from the EU market, corresponding to 70.7% for total waste and 75.0% for plastic waste in 2019 (Eurostat, 2021a). In the same year, total waste import in Portugal by weight corresponded to 18.0% for total waste and 17.2% for plastic waste imported in the EU. However, it only corresponded to 4.0% and 10.3% of income traded, respectively. Indeed, revenue from waste import is 77.9% lower for total waste and 40.2% lower for plastic waste in Portugal, compared to the EU average. Portuguese waste export also takes place in the EU market, corresponding to 83.1% and 68.6% for total waste and plastic waste exported, respectively, by weight in 2019. Portugal's total waste export corresponded to 3.8% and 2.7% of the weight of total waste and plastics waste exported by the EU, corresponding to 3.5% and 4.4% of currency traded, corresponding to 10% lower pay for total waste, and 64% higher pay for plastic waste. In 2019 Portugal exported 64.0 kt and imported 140.9 kt of plastic waste, a ratio of 0.45. Conversely, the European Union exported 2.4 Mt and imported 0.9 Mt of plastic waste, a ratio of 2.89. Thus, Portugal is a net plastic waste importer, while the European Union is a plastic waste exporter (Fig. 3). In 2020, Portugal imported plastic waste (by weight) mainly from Spain and the USA and mainly exported to Spain, Cyprus, and Belgium (Code 391590; UN Comtrade, 2021).

Based on "Green" List Waste (including wastes covered by the Basel Convention) in APA's waste trade report for 2018, all imported and exported plastics in this category were used in recovery operations (European Parliament, 2006; Agencia Portuguesa do Ambiente, 2019a). Imported plastic waste was treated by mechanical recycling (30.8%), waste-to-energy (27.3%), preparatory activities (26.5%, e.g., sorting, shredding), and temporary storage (15.3%). Imported plastics mainly were comprised of plastics and rubbers from mechanical treatment of wastes (63.5%, e.g., sorted), plastic packaging (35.3%), plastics from end-of-life vehicles (0.6%), plastics from MSW including selectively separated (0.5%), and plastic shavings and turnings (0.1%). Treatment varies with the type of plastic waste, with all plastic shavings and turnings being sent for preparatory activities (e.g., sorting, shredding) and all plastic from end-of-life vehicles being temporarily stored. Conversely, most imported plastic packaging waste was mechanically recycled (87.0%), most plastics and rubbers from mechanical treatment of wastes incinerated with energy recovery (42.9%), and most plastic from MSW including selectively separated subjected to preparatory activities (90.6%, e.g., sorting, shredding). Exported plastic waste was treated by mechanical recycling (54.8%), followed by reclamation of other inorganic matter (26.6%, e.g., construction waste, or incorporation in cement or asphalt), temporary storage (11.5%), and preparatory activities (5.8%, e.g., sorting, shredding). Exported plastics were comprised of plastic packaging (47.3%), plastic and rubbers from mechanical treatment of waste (36.0%), plastics from MSW including selectively separated (8.7%), plastic waste from primary industry (2.7%, e.g., from agriculture, forestry, fishing), plastic from organic chemical processes (2.5%), plastic shavings and turnings (1.9%), and plastics from end-of-life vehicles (1.0%). Plastic waste from primary industry was mainly stored (54.0%). Mechanical recycling was the main treatment for waste plastics from organic chemical processes (53.9%), plastic shavings and turnings (95.2%), plastic packaging (64.8%), plastic from end-of-life vehicles (75.6%), plastic and rubbers from mechanical treatment of waste (48.0%), and plastics from MSW including selectively separated (32.5%). When comparing exports and imports for specific plastic types in 2018, plastic and rubbers from mechanical treatment of waste were mainly imported, while the remaining categories were mainly exported. Waste plastics from primary industry and organic chemical processes were only exported. Due to the prevalence of large amounts of imported plastic shavings and turnings in 2018, Portugal imported more plastics than exported (Fig. S4). However, the combined effects of changes in EU regulations and the COVID-19 pandemic led to a suspension of waste trade between May and December 2020 (Euroactiv, 2020), critically changing the waste trade dynamics in Portugal. Nonetheless, Portugal should maintain a preference for recovery treatments for exported and imported plastic waste under a circular economy.

Fig. 3 Plastic waste import in Portugal (A), import percentage by total waste by weight (B), export in Portugal (C), export percentage by total waste by weight (D), ratio export/import (E). Data collected from Agencia Portuguesa do Ambiente, 2019b; Sociedade Ponto Verde, 2019; Agencia Portuguesa do Ambiente, 2020; Eurostat, 2021a.

4 Littered plastics in Portugal

Littered waste does not enter proper waste management streams. Therefore, the most common plastic items present in the Portuguese environment across time must determine the needed solutions. Two data sets are available online and were used to assess littered waste- beach survey reports from APA and citizen science entries in a smartphone app named Litterati.

Litterati (Litterati, 2021) is an APP in which users photograph and classify littered items in all types of environments (e.g., urban, beach), taking advantage of

citizen science. The free online database was downloaded on the 3rd of February 2021 and further formatted following OSPAR classifications for marine litter, also used by APA, based on the description tags (OSPAR, 2007). Only plastic items and cigarette butts were classified following the objective of the work. Limitations in classification based on the lack of details required combining some categories (e.g., small plastic bags and plastic bags, plastics and polystyrene pieces) and classifying ambiguous descriptions as unidentified. A total of 14188 items, corresponding to 1325 plastic items (9.3%) and 2003 cigarette butts (14.1%), were reported from 2015 to early February 2021. It is worth considering that many entries did not present a description (10.2%), possibly influencing results. Cigarette butts corresponded to 60.2% of classified entries. Most entries on plastics and cigarette butts (n = 3061) were concentrated in 2020, with 65.4% corresponding to cigarette butts. For plastics, the ten most frequent items found were plastic and polystyrene pieces (24.6%), unidentified plastics (23.9%), crisp or sweet packets and lollipop sticks (9.0%), other plastics/polystyrene items (7.9%), caps and lids (3.9%), other medical waste: masks (3.7%), bottles, containers, and drums: drinks (3.3%), plastic bags (3.3%), packaging (3.0%), and cutlery, trays, straws and stirrers (2.9%). If considered together, pandemic related items (masks, gloves, wet wipes) contributed to 5.7% of plastic waste. It should be considered that these results might be influenced by the number of data entries and public perception of the problem of littering some items.

APA is the Portuguese entity responsible for monitoring beach litter, following the Marine Strategies Framework Directive (European Commission, 2020c) recommendations and classifying litter in 100 m stretches of multiple beaches following the OSPAR system (Agencia Portuguesa do Ambiente, 2021b). Reports are available from 2013 to 2020, with varying data analysis criteria requiring uniformization (e.g., calculations of the percentage of plastic items based on total items from 2015–2017) (Agencia Portuguesa do Ambiente, 2021b). Sampled beaches increased from 7 to 15 in 2014 and 2020, respectively, with the highest number of campaigns (60) achieved in 2019 (Fig. S5). The number of surveys per country should be at least 40 (European Commission, 2020a), which has been achieved since 2018. The total amount of items in beaches varied from 349 to 943 items/100 m, with a mean of 588 items/100 m from 2013 to 2020 (Fig. 4(A)). The mean amount of beach litter in 1470 surveys in the European Union from 2015 to 2016 was 504 items/100 m, with a threshold set on a median of 20 items/100 m (European Commission, 2020a). The amount of beach litter in Portugal is considerably higher than the objective and closer to the European average. It is also worth considering that values are reported as means, while the threshold value is a median. According to APA reports, for 2015–2016, a median of 330 items/100 m was registered for Portugal, compared to 149 items/100 m in the European Union. While all European countries are still above the threshold value, Portugal must take swift action to reduce beach litter. The percentage of plastic items has increased, reaching 88% in 2020 (Fig. 4(B)), close to the reported 90% European value (European Commission, 2020a). Although data is not always available, the percentage of most common plastic items and cigarette butts across years is presented in Fig. 4(C). The percentage of each category has remained relatively stable over the years, with some exceptions (e.g., a peak of 12% in caps and lids in 2017). Harmonizing data by combining categories and calculating the percentages by total items reveal that the most common items were comparable between Litterati and APA for 2020 (Fig. 4(D)). It is worth considering that Litterati data is spread across the Portuguese territory, while APA's monitoring is focused on beach litter. Cigarette butts and plastic or polystyrene pieces are present in relatively similar percentages, dominating both databases. Foam sponge is more frequently found in beaches, possibly by originating from fishing or boating activities (e.g., buoys) or being transported and accumulating in marine environments. Drinking containers (e.g., bottles, cups), disposable tableware (e.g., cutlery, straws), and packaging for snacks (e.g., crisps, sweet packets, lollipop sticks) are more dominant in Litterati than in beach litter. This results from citizens being more aware and reporting these items more frequently or from their predominance in urban areas.

5 Reducing the consumption of plastics in Portugal

Lightweight plastic bags (thickness < 50 μm) were among the top ten littered items in the EU (Kasidoni et al., 2015). Thus, economic instruments (e.g., fees) or restrictions (e.g., bans) were implemented to reduce their consumption from an average of 200 bags per capita (Kasidoni et al., 2015). Directive 94/62/EC (European Parliament, 1994), updated by Directive (EU) 2015/720 (European Parliament, 2015), establishes that thin plastic bags should not be free of charge from the 31st of December 2018 onwards, and yearly consumption should be reduced to 90 bags per capita by the 31st of December 2019 and 40 bags by the 31st of December 2025. To achieve this goal, Portugal instituted a fee on thin plastics bags of 0.10 € (Assembleia da Republica, 2014). In 2011, thin plastic bag consumption in Portugal was estimated at 466 bags/hab year, with around four bags littered per capita year (corresponding to 44 million plastic bags littered every year) (Kasidoni et al., 2015). In 2018, lightweight plastic bag consumption was 5.7 bags/hab year, a 99% reduction and already complying with the EU objectives for the end of 2025 (Fig. 5; Agencia Portuguesa do Ambiente, 2020).

A survey on Portuguese restaurants, pastry shops and

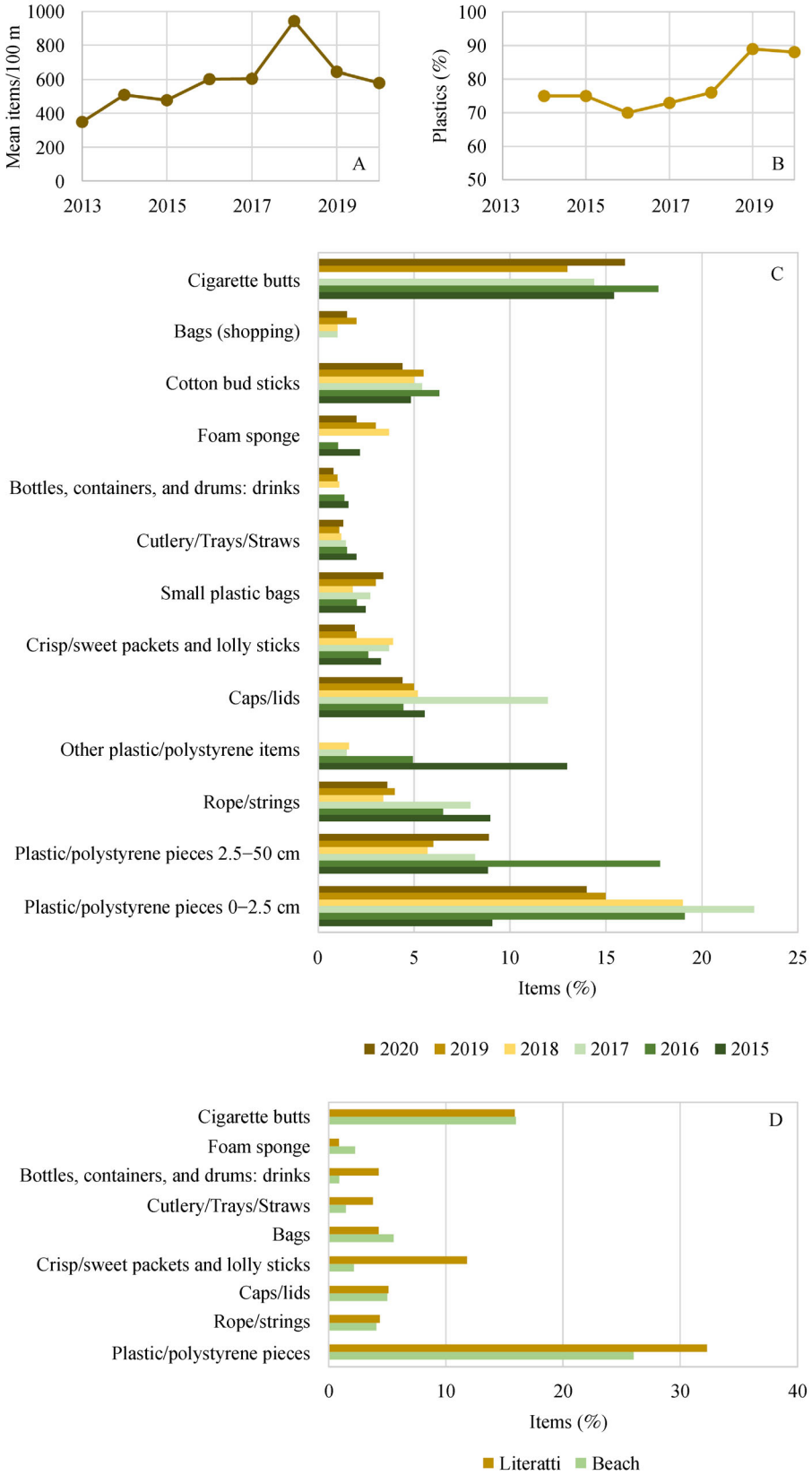

Fig. 4 Distribution over the years of total beach litter items (A) and percentage of plastic items (B). Details on the percentage of most common plastic items and cigarette butts across years (C). Comparison between Litterati data and APA beach litter data on percentages of combined categories from total items for 2020 (D). Data collected from Agencia Portuguesa do Ambiente, 2021b; Litterati, 2021.

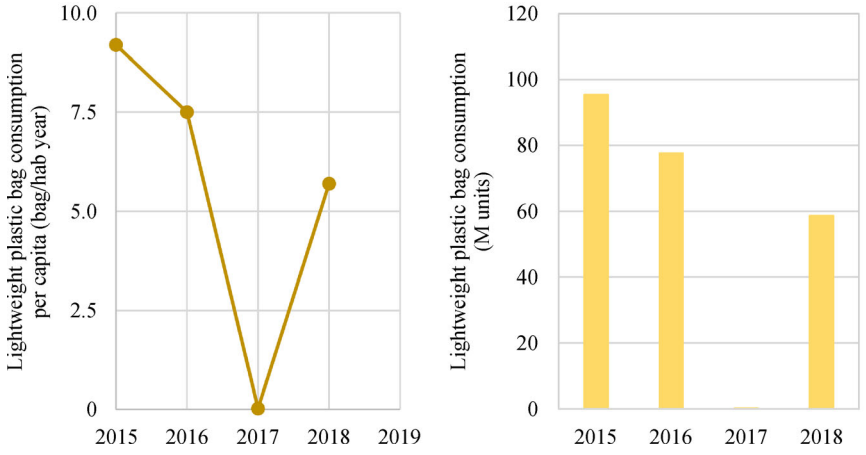

Fig. 5 Lightweight plastic bag consumption per capita (left) and total amount introduced in the market (right). The drop in 2017 corresponds to missing data relative to the amount of lightweight plastic bags used to contain ice or foodstuff. Data collected from Agencia Portuguesa do Ambiente 2020.

bars ($n = 489$) in 2018 revealed that 70.3% used disposable plastic materials, corresponding 52.5% to straws and 28.2% to plastic cups (Associação da Hotelaria and Restauração e Similares de Portugal, 2019). The preponderance of single-use plastics in eateries must be quickly reversed, as Law n. 76/2019 predicts the banning of plastic tableware, cutlery, and straws in restaurants and retail (Assembleia da Republica, 2019a). Concomitantly, Law n. 77/2019 predicts banning ultralight plastic bags and plastic packaging for bread, fruit, and vegetables, with a mandatory availability of alternatives, after the 1st of June 2023 (Assembleia da Republica, 2019b). These laws have been reviewed to harmonize terms better and avoid greenwashing alternative products, with Law n. 76/2016 being postponed from January 2021 to the 31st of March 2021 and again to the 1st of July 2021, due to the pandemic (Assembleia da Republica, 2021a). Nonetheless, many brands are already implementing plastic reduction strategies due to the consumers' interest in sustainability (Jornal de Noticias, 2021). Law n. 88/2019 regulates the prohibition of littering of cigarette butts, the mandatory placement of ashtrays (build to avoid scattering of litter) outside commercial or public establishments, which are responsible for the cleaning of ashtrays and an influence radius of 5 m, and in boarding platforms of bus stops where smoking is permitted (Assembleia da Republica, 2019c). An approved law proposal also accounts for the banning of microbeads in cosmetic and hygiene products until the 1st of July 2021 and the creation of "Eco-islands" (waste collection containers) in all harbors and ports until the end of 2021 to promote proper disposal of waste and reduce littering of plastic (Assembleia da Republica, 2021b). Over the last years, several initiatives and awareness campaigns regarding marine litter have become popular in Portugal. All entities responsible for urban waste management are also responsible for awareness campaigns (Marques et al., 2012), but these are usually aimed at increasing recycling participation. Additional initiatives are conducted by other entities dedicated to environmental preservation, conducting awareness and beach cleanup campaigns (Fig. 6).

6 Status and potential improvements on the use and disposal of plastics in Portugal

Portugal presented a median of 330 items/100 m of beach litter reported by APA in 2015–2016 (Agencia Portuguesa do Ambiente, 2021b). Considering a coastline length of 1187 km (Martinez et al., 2020), the total number of littered items found on the Portuguese coast could reach 3.9 million pieces. This median is 45% higher than the EU median (i.e., 149 items/m) and would require a decrease of 94% to achieve the EU objective of 20 items/100 m (European Commission, 2020a). Portugal's most abundant litter categories include cigarette butts, plastic and polystyrene pieces, and plastic packaging waste (e.g., crisps or sweet packets and lollipop sticks). Plastics and polystyrene pieces possibly originate from fragmentation under environmental conditions, such as under physical forces and exposure to sunlight (Andrady, 2017). Accordingly, the categories of identifiable items are covered by the Directive (EU) 2019/904 on reducing the impact of certain plastic products in the environment (European Parliament, 2019). According to this Directive, from July 2021 onwards, EU Member States must describe the measures to reduce the consumption of single-use plastics (cups, beverages, covers, lids, food containers for takeaway and prepared foods) by 2026 compared to 2022. Other products (cotton bud sticks, cutlery, plates, straws, stirrers, balloon sticks, food or drinking containers of expanded polystyrene) shall be banned, including oxo-degradable plastics. Lids and caps must remain attached to the containers or bottles, while beverage bottles must incorporate a minimum of recycled plastics (e.g., 25% of recycled plastics in

Fig. 6 Initiatives and awareness campaigns on marine litter conducted in Portugal.

PET bottled by 2025). Separate collection for recycling some single-use plastics (food containers for takeaway and prepared foods, packets and wrappers, beverage containers up to 3 L, cups for beverages, lightweight plastic bags) must reach 77% of weight by 2025 and 90% by 2029. The Member States must implement measures to reduce littering of cigarette butts through public waste receptacles, labeling, extended product responsibility, and awareness campaigns. The Directive also covers labeling, extended producer responsibility, and awareness for plastics. Laws n. 76/2019 (Assembleia da Republica, 2019a) and 77/2019 (Assembleia da Republica, 2019b) on single-use plastics and packaging, and Law n. 88/2019 (Assembleia da Republica, 2019c) on cigarette butts address the majority of items on the Directive (EU) 2019/904. However, some items remain unaddressed by Portuguese law, such as the banning of plastic cotton bud sticks or balloon sticks. Simultaneously, Law n. 76/2019 was postponed to the 1st of July 2021 due to the pandemic, the deadline imposed by the European Union. Conversely, the implementation of fees on lightweight plastic bags, following Directive 94/62/EC (European Parliament, 1994) and Directive (EU) 2015/720 (European Parliament, 2015) has been widely successful with a 99% reduction in consumption (Agencia Portuguesa do Ambiente, 2020). Mandatory inclusion of a minimum of recycled plastics in some plastic items has also not been legislated, so far relying on voluntary action. The Portuguese Pact for Plastics is a collaboration platform involving over 80 entities, including government, manufacturers, waste management entities, universities, and NGOs, establishing ambitious goals by 2025, including incorporating 30% recycled plastics in new packaging (Pacto Portugues para os Plasticos, 2021). The EU Waste Framework Directive sets a target of 55% for recycling MSW by 2025, 60% by 2030, and 65% by 2035 (European Commission, 2018). These targets are far from the 13% of MSW sent for recycling in 2019 (Agencia Portuguesa do Ambiente, 2019a). Conversely, the current recycling rate of plastic packaging of 33.9% is still behind the EU target of 50% for 2025 (European Commission, 2015). It may

also compromise the recycling of specific single-use plastics, which should reach 77% by 2025 (European Parliament, 2019). In December 2020, the EU released the Council Decision (EU, Euratom) 202/2053 on the management of resources. This Council Decision predicts Member States pay 0.80 €/kg for non-recycled plastic waste, which will be adjusted based on the gross national income (GNI) per capita in 2017 for countries below the EU average, corresponding to a reduction of 3.8 kg per capita in 2017 (European Commission, 2020b). The Portuguese GNI per capita (standardized by purchasing power standards) was 22.2 k€ compared to the EU average of 29.3 k€ (Eurostat, 2021b) in 2017. In the same year, Portugal presented 10.3 million inhabitants (Instituto Nacional de Estatistica, 2018), corresponding to an allowed reduction of 39.1 kt of non-recycled plastic waste. In 2017, 400.2 kt of total plastic packaging were declared, with 139.6 kt being recycled, leaving 260.6 kt of non-recycled plastics (Agencia Portuguesa do Ambiente, 2020). With a reduction of 39.1 kt, 221.5 kt should pay a fee to the EU, corresponding to 177 M€, similar to the expected contribution of 153 M€ in Belgium (EY, 2020). Conversely, based on the revenue of recycling plastics (Pires et al., 2017), fully recycling 221.5 kt could generate a revenue of 4 M€ while preventing the previously mentioned contribution to the EU (a summed benefit of 181 M€), not accounting for indirect benefits (e.g., environmental costs). Therefore, a strategy based on the prevention and recycling of plastic packaging must urgently be adopted by Portugal. This profit could be increased through preferential recycling of imported wastes as well. Based on these needs, the following recommendations can be followed to improve plastics consumption and waste management:

- Reduction of consumption of plastics and other products is the preferred strategy in avoiding waste production. Results of various bans or levies on single-use plastics taking place at a global level are encouraging (Xanthos and Walker, 2017). A market regulation approach has been applied to lightweight plastic bags and single-use plastics following EU Directives, despite an improved transposition into national law still being required (i.e., the inclusion of plastic cotton bud sticks). In addition to being widely successful, implementing a 0.10 € fee on lightweight plastic bags in Portugal did not significantly harm the economy and has gathered wide public support, sympathetic with the implementation of similar measures to other plastic items (Luís et al., 2020). Additional regulations are required regarding the qualities expected in plastics entering the market, such as chemical composition, recyclability, and inclusion of a recycled fraction. The EU already mandates the inclusion of recycled plastics in some items (i.e., in Directive (EU) 2019/904; European Parliament, 2019), creating a market for recycled plastics, and is currently studying plastic additives through the European Chemical Agency (European Chemical Agency, 2018). An alternative is to classify and handle certain types of problematic plastics as hazardous waste based on their potential toxicity and low recyclability, such as polyvinyl chloride, polystyrene, polyurethane, and polycarbonate (Rochman et al., 2013). Improvements in recycling could be achieved at the design and production level (e.g., avoiding plastic mixtures), while less demanding products could be produced from recycled products. Recyclability is affected by multiple factors and should account for: 1) polymer type, recycling of some polymer types is easier and cost-effective (e.g., polyethylene terephthalate); 2) size, shape, color, which can influence if an item is identified as a recyclable by optical sorters or manual sorting; 3) liners, labels, and components which must be segregated before recycling; 4) additives, which can have adverse effects on human health and the environment; 5) available infrastructure, determining if the item can indeed be recycled; 6) economics and markets, which determine if there is demand for the recycled material (Consumers International, 2021). For instance, high-density polyethylene trash bags could be fully made from recycled materials, producing solely 52% of the abiotic depletion of virgin plastics (Fernández-Braña et al., 2019). Continente, one of the supermarkets' chains in Portugal, is already implementing plastic reduction strategies. These include using transparent cellulose films in the packaging of bread, banning microbeads from cosmetics and plastic straws from drinks (replaced by paper straws), and testing reusable containers for takeaway and charcuterie (Continente, 2021). Besides Continente, many other Portuguese brands and retailers are involved in the "Pacto Português para os Plásticos" (Portuguese Plastic Pact) focused on transitioning plastics to a circular economy (Pacto Portugues para os Plasticos, 2021). Awareness and consumer choices are other factors shaping the consumption of plastics. For instance, consumers who were made aware of microbeads (small plastic spheres used as exfoliants) in a cosmetic would choose not to purchase or discontinue their use (Chang, 2015). In a 2010 survey, 35% of Portuguese consumers were identified as highly sensitive to environmental issues, including ecofriendly products and recycling (Finisterra do Paço and Raposo, 2010). Therefore, consumers in Portugal may be receptive to changes toward sustainability and the circular economy. However, effective implementation of sustainable consumption needs to overcome misinterpretations by consumers (e.g., considering a product or material more sustainable than others, despite LCA evidence on the contrary) and misleading claims by companies (i.e., "greenwashing") (Boz et al., 2020). Improvements in plastics production must account for applications where it is advantageous to use biodegradable plastics (i.e., plastics capable of breaking down under specific conditions, such

as during composting) or the use of bio-based plastics (i.e., produced from renewable resources, decoupled from the oil industry) (Patrício Silva, 2021). Portugal has a large potential for the valorization of agroforestry residues (Gaspar et al., 2019) and marine resources (Prabha et al., 2020) through biorefineries, which could then be used in the production of bio-based or biodegradable plastics (Patrício Silva, 2021). Therefore, Portugal could have an important contribution to the production of more sustainable plastics. In addition to bio-based polymers, next-generation polymers with high recyclability can provide benefits. For instance, polydiketoenamines (PDKs) are costly to produce but are easily depolymerized in strong acids through chemical recycling at a low cost and high recoveries (Vora et al., 2021).

• Integrated Waste Management Systems (IWMS) should be expanded to all municipalities, with a preference for recycling, followed by waste-to-energy or feedstock production in the form of incineration, gasification, or pyrolysis. These operations are known to generate environmental benefits and promote jobs and wealth in the country. In France, recycling plastics can create 300 k jobs and avoid releasing 8 Mt of CO_2 annually (European Environmental Agency, 2019). Only refuse from these operations should be landfilled. Landfilling of valuable wastes could be banned, as exemplified by Finland, where landfilling of plastics is banned, which will be extended to all recyclable wastes from 2025 onwards (European Environmental Agency, 2019). Products and byproducts of these operations can be used to benefit the economy further and contribute to national goals, such as the production of hydrogen from syngas in the light of the National Plan of Hydrogen (Assembleia da Republica, 2020) or value-added carbon nanotubes (Zhuo and Levendis, 2014). Considering that individualized plastic types have a higher market value than mixed plastics (732 vs 245 €/t; Pires et al., 2017), Portugal should improve plastic waste separation, such as by effectively implementing deposit-return systems. Having targets and contingency plans could help achieve these goals. For instance, deposit-return systems will be enforced in Switzerland if polyethylene terephthalate, aluminum, and glass recycling fall below 75% (European Environmental Agency, 2019). Sorting and recycling losses (e.g., due to loss of material qualities) vary with between 67%–93% (polystyrene and polyethylene terephthalate, respectively) and should be considered when implementing mandatory inclusion of recycled materials in products, with refuse being preferentially used in other recovery operations (e.g., waste-to-energy) (Tallentire and Steubing, 2020). Environmental impacts and higher costs originate from waste collection and separation. In Portugal, the cost of selective collection is 117 €/t and of sorting is 72 €/t (da Cruz et al., 2012). Collection routes can be improved by optimizing the collection frequency and using transportation based on renewable energy (e.g., electric waste trucks). Lusagua, responsible for waste collection in Caminha and Albufeira municipalities, recently implemented the "Resíduos Smart +" project, which intends to increase the efficiency of waste collection routes using real-time readings of the loading of waste containers using sensors (Lusagua, 2021). In Germany, improvements in the sorting or separation system based on technological advancements (e.g., automated sorting of mixed plastics) has dramatically increased treatment capacity (Cimpan et al., 2015). Automated waste sorting techniques, such as based on imaging (e.g., Laser-Induced Breakdown Spectroscopy), could increase volume and separation efficiency to comply with greater recycling goals, improving workers safety and productivity (Gundupalli et al., 2017). Developments in all waste management stages could increase benefits by reducing economic and environmental costs, inspiring increased incorporation of waste in the circular economy. These benefits could extend to other EU countries through the import and valorization of their wastes.

• The increase in TGR for non-recycled wastes from 11 €/t to 22 €/t is insufficient to motivate sustainable waste management practices, as municipalities can shift costs to consumers through water taxes. The lack of recycling of wastes is detrimental because it does not generate economic and social benefits. The cost of 22 €/t for landfilling plastic packaging poorly translates the 800 €/t of non-recycled waste to be paid to the EU, in addition to the costs of the operation. Thus, the Portuguese government must find firmer strategies to enforce the preferential recycling of wastes. Strategies include reducing waste production and successfully diverting residues from landfilling (e.g., by increasing recycling). For instance, overall reductions in MSW were observed in Portuguese municipalities following pay-as-you-throw schemes. Pay-by-the-bag systems (i.e., by paying for mandatory official trash bags or stickers), curbside collection of organic waste, curbside collection of recyclables covering a wide range of materials, and collection of mixed household waste every other week, can reduce residual (mixed) household waste to 150 kg/hab year as observed in the Flanders, Belgium (Gellynck et al., 2011). A survey in EU countries revealed that consumers' separation of recyclables is influenced by convenience (e.g., accessible location of containers), awareness of environmental issues, and confidence that waste is effectively recycled (Minelgaitė and Liobikienė, 2019). Many questions and misconceptions remain in the Portuguese public regarding the recycling process (e.g., how to sort waste, if the waste is effectively recycled) despite the herculean effort of awareness campaigns. One of the most popular awareness campaigns involved a shocking television commercial featuring a chimpanzee separating wastes with the slogan "Gervasio [chimpanzee] has taken exactly 1 hour and 12 minutes to learn how to separate packaging waste. And you, how much more time do you need"? (Sociedade Ponto Verde, 2012). This ad campaign, aired in 2000, was the first promoted by the

recently founded Portuguese Green Dot Society (a SIGRE), and the first contact of many Portuguese citizens with the concept of separating packaging waste. New shocking and effective awareness campaigns may be required to clarify the need for the separation of recyclables. By producing high-quality materials through the household separation of recyclables, these can then be used more efficiently in recycling. Parameters influencing recycling include: 1) high separation of recyclables, benefiting from combined collection systems (e.g., curb-side, drop-off); 2) implementation of Extended Producer Responsibility (EPR), based on a sustainable financial scheme; 3) pay-as-you-throw schemes combined with curbside collection including more than three waste streams (i.e., to produce high-value recyclables) and deposit-refund systems; 4) regulations such as landfill or incineration bans and non-recyclable product bans (e.g., plastic bag bans); 5) implementation of ambitious goals through Zero Waste strategies; and 6) community outreach and awareness campaigns (Xevgenos et al., 2015). In the case of Portugal, much of the recycling of packaging waste is supported by public money (Ferreira et al., 2017), which could benefit from an increasing EPR of packaging manufacturers. Additionally, the review found that landfill taxes generally have a weak effect on adopting sustainable waste management options and reducing waste production (Xevgenos et al., 2015). Therefore, Portugal must implement other strategies beyond a simple increase of TGR, such as stricter regulation over what types of waste can be landfilled (e.g., only residual waste from recycling or other recovery operations).

- Portugal needs to reduce beach litter by 94% (from 330 to 20 items/100 m) to comply with EU objectives, of which 88% is plastics. As a touristic country, Portugal is prone to be affected by high densities of beach litter, leading to economic losses. In Brazilian beaches, 85% of beach users would avoid the beach if littered by>15 items/m, which could originate loss in tourism income by 31% or US$ 8.5 million per year (Krelling et al., 2017). A sampling of five Portuguese beaches in 2010 revealed average densities of 185 plastic items/m (Martins and Sobral, 2011). Therefore, urgent measures must be implemented to reduce the amount of litter present on Portuguese beaches. An extensive literature review on the effectiveness of measures to reduce marine litter include: 1) taxes and charges such as those applied to plastic bags, which can be expanded to fishing equipment and plastic food containers at a low implementation cost; 2) pay-as-you-throw systems for MSW to support waste reduction, as well as tourism taxes to support waste management further; 3) deposit-and-refund schemes which achieve high return rates, at a higher implementation cost; and 4) rewarding the fishing industry to return waste to shore (Oosterhuis et al., 2014). In Australia, councils that invested in coastal waste management presented fewer littered items on their coastline (Willis et al., 2018). Remediation strategies should be coupled with preventive measures. Beach cleaning could help maintain cleaner beaches but can have ecological impacts if based on mechanical methods and have high costs (Zielinski et al., 2019). During the bathing season in Azores, Portugal, the cost of beach cleaning varied between 11–51 k € for each local authority (Rodríguez et al., 2020). Beach cleaning should be conducted even outside the bathing season to avoid the fragmentation and further dispersion of litter, with a frequency adapted to local necessities. For instance, a higher number of plastic items was found during the wet season on a beach in Aveiro, Portugal, suggesting that storm events could cause backwashing and accumulation on shore (Prata et al., 2020b). Many of the actions needed to reduce marine litter on the Portuguese coast are already being implemented by campaigns focused on awareness, beach cleaning, and even encouraging the collection of litter by fishermen (e.g., “A Pesca por um Mar Sem Lixo”). These actions, primarily based on volunteer work, could be supported by municipalities and the government, reducing the costs of increasing the frequency of beach cleaning. Similarly, street cleaning services could provide a remediation strategy upstream.

7 Conclusions

With waste management based on open dumps, Portugal revolutionized its waste management system in the 1990s and early 2000s under the guidance and support of the European Union, investing in controlled landfills and incinerators (Magrinho et al., 2006). The evolution of the waste management system in Portugal is remarkable despite being behind in many areas compared to other EU countries. The 2020s require a similarly challenging revolution in waste management, focusing on reducing consumption and consequently waste production, followed by multiple recovery alternatives (e.g., recycling, waste-to-energy, feedstock production), and only landfilling of refuse. Plastic waste is at the core of this revolution due to its ubiquity in modern life and environmental persistence. Portugal is currently at the crossroads between resisting or embracing the circular economy. As widely presented in previous sections, sustainable waste management (including plastic waste) produces multiple economic, societal, and environmental benefits. Portugal could be at the front and benefit the most from this revolution by leveraging sustainability concerns of its inhabitants (e.g., supporting market measures), its natural resources (e.g., through biorefineries), its role as a net waste importer (e.g., by producing value-added products), and the economic boost produced by sustainable waste management strategies (e.g., revenue from plastic recycling).

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