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Assessing the readiness of Greek municipalities to manage bioplastics in municipal waste management streams

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Abstract
Each year citizens of the European Union (EU) generate 2.5 billion tonnes of waste; equating to five tonnes of waste per person per year. To ensure optimal material recovery, and to support the move towards a circular economy, proper separate collection of waste is necessary. The current trend of increasing collection rates, encouraged by EU legislation, is promising; however, progress is uneven both across and within EU member states. While European and national targets provide the overarching driver for better waste collection, regional and local implementation is crucial for achieving continued progress. Therefore, it is vital to consider the disparity among the different EU countries when introducing new materials, such as bioplastics (bio-based and/or biodegradable plastics), into current national waste management streams, and any new introductions should be carefully evaluated before further actions are recommended by local authorities. As a member state that is heavily reliant on tourism, proper solid waste management is of vital importance in Greece, especially during the peak summer season. Considering the rapid expansion of bioplastics in the European market, it is important to assess the readiness of municipalities in Greece to manage this new category of solid waste. Data collected from 51 Greek municipalities via questionnaire (distributed to public authorities or waste management companies) showed that the current situation and capacities for adapting waste management streams to process bio-based and/or biodegradable plastics is still limited in Greece. Therefore, the readiness of Greece to process an increasing proportion of bioplastics within the waste stream (using the current waste management systems) is very low, as a result, such innovative materials are currently seen more as a problem than a ready-to-implement solution.

Keywords Bio-based plastics · Bioplastics · Municipal waste management · Municipal waste collection · Assessment · Greece · Readiness

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1 Introduction

Plastics, which are conventionally made from petrochemical (fossil-based) sources, have shaped modern economies. Mostly used for packaging purposes, these materials are today in the spotlight due to the increasing awareness towards climate change and environmental protection [1]. Indeed, the production and use of fossil-based plastics have been associated with several environmental issues ranging from high greenhouse gas emissions to microplastics formation. Therefore, the development of alternatives is seen as a priority for many scientists and industrial players around the world [1]. One of the fastest-growing markets is represented by the biochemical industry, with a wide spectrum of applications, including bio-based fuels, chemicals and materials [2]. The market for one such application, bio-based plastics, i.e., plastics that are fully or partially made from biomass [3], is expected to increase from 2.2 thousand tonnes in 2022 to 6.3 thousand tonnes in 2027. Concurrently, global bioplastics production capacity, which includes both biodegradable and non-biodegradable bio-based plastics, is set to increase from around 2.18 million tonnes in 2023 to approximately 7.43 million tonnes in 2028 [4, 5]. However, the process of producing, consuming, and valorizing bioplastics needs to be carefully considered. The added value that these materials can provide is widely debated and the waste management system is not ready to treat these materials, especially when biodegradable and compostable [6]. While UNI EN 14995 and UNI EN 13432 define the requirements for the treatment of compostable plastic items, the waste collection schemes needed to implement these treatments are not harmonized in Europe. Depending on the country, and even region, compostable plastic waste can be collected with organic waste, source-separated plastics, or mixed waste [6]. In addition, current labelling does not adequately support citizens in making correct decisions with respect to proper disposal [7]. Furthermore, compostable waste is today incinerated, composted in composting and/or anaerobic digestion plants or landfilled. However, seen as eco-friendly materials, compostable plastics are largely used by catering services and the "on-the-go" food segment, with a huge impact on tourist cities [6].

Although tourism brings a number of socio-economic benefits to tourist areas [8], there are a number of environmental impacts that are closely related to tourist activities, especially in countries that depend strongly on it. One of the key issues is represented by the overgeneration of waste during peak seasons. The study by Murava and Korobeinykova [9] demonstrates that 69% of the municipal waste generated in the Carpathian region in Ukraine stemmed from tourism in the region [9]. Relatedly, the work done by Mateu-Sbert et al. [10] on the Spanish Island of Menorca reveals that residents collected almost 50% more separated recyclables than tourists [10]. Consequently, increasing rates of solid waste generation urge the necessity to effectively manage solid waste streams at a local level [9]. The increasing volume of waste is exacerbated by the massive use of fast-moving consumer goods, which is on the rise in the tourism industry [11] and the increasing number of tourist arrivals; multiplying the size of the problem [8]. It follows that this increasing volume of municipal waste generated by tourism can overburden local waste management systems [12]. In addition to population and tourism rate growth, another determining factor is consumer behaviour which is difficult to detect when assuming the tourist state [13].

In Greece, while efforts have been made in recent years to optimize the national waste management system and reduce the amount of solid waste going to landfill, no significant reduction has been detected. Greece generates around 5.6 million tonnes of municipal waste annually, corresponding to 524 kg/cap in 2019, where the waste generation rate increased by 6% in 2019 compared to 2015 [14]. Still, 77.7% of post-consumer waste (accounting for 100,000 tonnes in 2019) is landfilled in the country. Regarding waste management performance, around 21% of municipal solid waste is mechanically and organically recycled. However, the risk of missing the targets, especially those related to recycling (55% by 2025) and landfilling (10% by 2030), have led to the use of uncontrolled landfill operations, resulting in the application of sanctions and penalties by the European Union (EU) [15]. A major obstacle in waste management starts with the seasonality of tourism [16], where the population concentration for certain months of the year doubles [11]. At the same time, there are often misalignments in waste disposal due to differences in waste management systems from country to country, further complicating the existing waste governance [12].

Potential solutions can be provided by bioplastics (bio-based and/or biodegradable plastic materials). The newest research findings capture the current situation and the potential for adaptation of waste management streams for the treatment of bio-based and/or biodegradable, compostable plastics in general, but local data to support successful implementation processes is still lacking. Therefore, this study assesses the current state of the municipal waste management streams among different Greek municipalities. In doing so, this paper aims to scrutinize the readiness of Greek cities to manage bio-based and biodegradable, compostable plastics in the current waste management

infrastructure. Greek cities have been selected due to their reliance on tourism and the associated overconsumption of single-use packaging, combined with the increasing demand for greener solutions, which today are mainly covered by compostable alternatives.

In order to investigate and assess the current situation of municipal waste management among Greek municipalities, as well as to estimate their capacities to adapt waste management systems to process bio-based and biodegradable, compostable plastic materials, this study collected data directly from municipalities across Greece via survey. The paper is structured as follows: Sect. 2 introduces present and future trends of bioplastics; Sect. 3 explains current waste management practices in Greece while Sect. 4 introduces the methodology used. Results are reported in Sect. 5 and discussed in Sect. 6. Section 7 presents the concluding findings and further research agenda.

2 Bioplastics: present and future trends

Bioplastics can be bio-based and/or biodegradable [3]. Bio-based plastic materials are made from bio-based feedstock such as sugar cane, corn, soy, hemp or agro-industrial residues. Biodegradable plastics are degraded by microorganisms to produce CO_2, methane, water, and biomass [17]. When compostable, biomass can be industrially converted into compost. Conversely, non-biodegradable plastics, like bio-PE and bio-PET, are characterized by the same properties as their fossil-based counterparts. While the latter benefit from the use of bio-based feedstock only, biodegradable, and compostable plastics may create added value because of their influence on the end-of-life stage of products [3]. Indeed, even if bio-based, biodegradable and compostable materials aspire to be used in the same way as conventional plastics, their usage is common in single-use packaging and disposable goods. Specifically, compostable plastics may be helpful in food packaging where food contamination is one of the key issues of mechanical recycling [18]. Likewise, different types of bio-based plastics have distinguishing biodegradability and compostability properties at specific environmental conditions, all characterized by a significantly shorter time for natural degradation in contrast to conventional plastics. This enables the opportunity to address global plastic waste pollution, which is mainly caused by the long duration of degradation required for fossil-based plastics [16]. Still, plastics that are both bio-based and biodegradable contribute to the biological cycle of the butterfly diagram of the Ellen MacArthur Foundation. However, these materials are far from being considered valid alternatives to conventional plastics for their impacts on biodiversity, land and water usage [3]. Although many LCA studies [19, 20] confirm that the environmental impact of bio-based plastics is lower compared to the impact of conventional (fossil-based) plastics, the variability of LCA results in the specific environmental categories makes the transition challenging [21]. Moreover, the effect on single-use products may be lower compared with more durable products where carbon content may remain for longer, according to the lifetime of the product itself [22]. Furthermore, another distinction needs to be made between collectable and non-collectable items. As pointed out by Paul-Pont et al. [23], the destination should be well-detected to assess the potential of these materials to push circularity at the end of their life. That said, only Italy has today implemented a dedicated waste governance for compostable plastics while it is still fragmenting in the rest of Europe. Consequently, because of the lack of harmonized waste management, assessment methods and degradation protocols [4], bio-based and biodegradable plastics cannot yet be seen as the proven solution to the global plastic waste problem, but we may assume them as part of the long-term New Plastics Economy framework [24, 25].

3 Background information on current plastic waste management practices across Greece

3.1 Municipal solid waste management in Europe

In 2018, over 2.337 million tonnes of waste was generated within the EU [26]. Out of this waste, 61.6 million tonnes is plastic produced by EU member states [1]. Most plastic items in the EU are used by the plastic packaging sector, with 39.6% of all used plastic goods belonging to this sector, followed by plastic used for constructional purposes (9.6%) [1].

Regarding general waste production, on average 5 tonnes of waste was produced in the EU per person in 2018, of which approximately 33.45 kg was plastic packaging waste [1].

To ensure high-quality recycling, separate collection of waste is preconditional as it increases resource efficiency, helping to close the loop in a circular economy, and leading to a reduction of greenhouse gas emissions [27]. To address

this, the EU Commission has revised the Waste Framework Directive to ensure the rise in recycling rates all over Europe. However, again progress regarding this topic is uneven among EU countries [28].

Out of the overall post-consumer plastic waste in the EU in 2020, 35% is recycled. Highest recycling rates are reported in the Netherlands (45%) followed by Norway (44%) and Spain (43%). The lowest recycling rates can be found in Finland (21%), Hungary (22%) and Bulgaria (23%). For Greece, the recycling level is 25%, and from the remaining plastic waste, 2% in 2018 was used for energy recovery while 73% was landfilled [28].

The concern with the impact of conventional plastics, when landfilled, is that the degradation process takes many years. During the degradation process, plastics may break into microplastics, which are high-risk for both the environment and humans, since they can easily contaminate the food chain and lead to bio-accumulation [29]. Since landfilling is still used across the EU, and especially by Eastern and Southern European countries (e.g., Malta, Cyprus, and Greece), where more than 80% of the municipal waste is landfilled, this leads to impacts that can be harmful to the environment and people [30].

Concerning the environmental impacts of plastics, bio-based and/or biodegradable plastics seem to have some advantages compared to conventional plastics. For example, bio-based and/or biodegradable plastics seem to be environmentally friendlier than conventional plastics while their toxicity level is lower compared to conventional plastics [31, 32]. These advantages of bio-based and/or biodegradable plastic alternatives raise the need for extended research into the usage and production of renewable alternatives for conventional plastics. It is crucial in circular economy context where circularity strongly depends on the systems in which materials and products circulate [33].

3.2 Municipal solid waste management system in Greece

An integrated framework for waste management have been adopted in Greece. Consequently, reducing the operation of landfills, as well as restoring all Uncontrolled Waste Disposal Sites (UWDS) are the main priorities. According to the Organization for Economic Cooperation and Development (OECD) environmental performance assessment report [34], Greece has taken significant steps in the last decade to close illegal landfills. However, around 80% of municipal waste is still disposed of in landfills, and Greece's 50% reuse/recycling target have not been met by 2020. In addition, more than 50 landfills did not meet the requirements by mid-2018. At the same time, there are significant gaps in hazardous waste management [34]. Yet, the government invested mainly in the mixed waste management, undermining the potential for recycling. Indeed, 15 Mechanical Biological Treatment plants exist in the countries, with investments allocated for an additional 36 plants. No incineration facilities are located in the country while six plants are allocated for bio-waste treatment [35].

Regarding waste management by management category for 2018, "Disposal on or within the ground" constitutes 81.6% of the total, while "Recovery other than energy recovery—except landfill" is 10.7%. [36].

According to the independent Ombudsman's Special Report 2020 on waste management, Greece ranks last among EU member states in terms of recycling targets for municipal, construction/demolition, hazardous, packaging, and electronic waste. The main problems identified on the national level are listed below [37].

- Poor performance in separate collection and achievement of recycling targets are the primary issues.
- The operation of UWDS spaces and their non-restoration.
- Installation of balers for temporary waste management.
- Incompatibility of municipal solid waste management project location with urban, spatial, and environmental legislation commitments.
- Operating existing municipal solid waste management projects without legal permits, thereby violating environmental legislation.
- The administration's inability or delay in inspecting these facilities.
- Failure to impose the prescribed sanctions, as well as the incorporation of financial incentives into the waste management system.

3.3 Post-consumer plastic packaging waste management performance in Greece

Greece produces approximately 869,500 tonnes of packaging waste annually, or 81 kg per person. For plastic packaging, 21 kg/cap were produced in 2019. Yet 649,967 tonnes of plastic packaging are found in the residual waste steam while only 86,663 tonnes are separately collected, accounting for 11% of the total post-consumer plastic packaging waste

generated in the country [35]. Tourists increase waste production by up to 26% in Greece's coastal areas during peak season. It is difficult to recover plastics from mixed waste streams and Greece has limited recycling infrastructure. Most waste (84%) is dumped in landfills. Nearly 40,000 tonnes of plastic waste are released into the environment each year, with 11,500 tonnes ending up in the Mediterranean (28% coming from abandoned or dumped fishing nets and other gear). Every year, nearly 70% of this waste pollutes Greek coastlines. Plastic pollution affects tourism, shipping, and fishing industries, costing Greece around 26 million euros per year [38].

Furthermore, to prevent the spread of COVID-19 disease in modern daily life, the use of plastic products, personal protection, and general disposable items was deemed necessary. This has raised fears that plastic pollution will worsen not only as a result of increased production and consumption of plastic products, but also as a result of the suspension of plastic pollution reduction policies. The pandemic's environmental challenge occurred at the same time as efforts to combat disposable plastics were launched. This effort, however, was halted. While environmental abuse on land, water, and air continues unabated, the need for environmental awareness is growing [39].

4 Methodology

In order to assess current waste management streams among Greek municipalities and evaluate their readiness to process bio-based and/or biodegradable materials, an analysis was performed through a survey in the form of a questionnaire [2]. A questionnaire of 23 questions was created as part of the BIO-PLASTICS EUROPE project (www.bioplasticseurope.eu) and was organized into five different sections:

Part A: Background information about the municipality (number of inhabitants, number of tourists per year, annual months of tourist season).

Part B: Assessing current waste management strategies.

Part C: Assessing the readiness of the municipalities for "bioplastics" waste management.

Part D: Experience-based perceptions and opinions about measures fostering the reduction of plastic pollution.

Part E: Future targets.

The study focuses on the types of bioplastics that are bio-based and biodegradable, compostable. Preliminary conversations with intended participants of the survey, clarified that they would feel more comfortable using the term "bioplastics" instead of "bio-based and biodegradable, compostable plastics". As such the questionnaire was developed using this term, but with clarification of the term such that its meaning was clearly described and communicated to the participants.

In addition, as the purpose was to obtain well-structured answers as well as to formulate easily understandable questions, the questionnaire consisted of different question types: open-answer, Likert scale, multiple-answer and yes or no answers. Specifically, the Likert scales were based on 5 levels, from "Strongly agree" to" Strongly disagree" [40].

The survey was launched in 2022 within municipalities located in Greece and characterized by different size and ubication. Olya and Gavilyan's [41] sampling technique was adopted to administer the questionnaire, since it has previously been shown as an effective method for achieving a high response rate. As in Olya and Gavilyan [41], we were helped by local connections from universities, NGOs and their connections with municipalities, as well as previously established connections of Greek municipalities with the BIO-PLASTICS EUROPE project, within the initiative of Historic Cities against Plastic Waste (HISCAP) network [41].

The questionnaire was delivered using Google Forms and followed data protection requirements. The final version of the questionnaire was validated by selected partners of the BIO-PLASTICS EUROPE project. After collecting valuable feedback from experts on European solid waste management, the questionnaire was successively adapted in terms of conciseness and clarity.

The first communication with the Greek municipalities took place via email and telephone. Subsequently, some municipalities that expressed interest joined the HISCAP network and were asked to respond to the questionnaire entitled "Assessing readiness of Greek municipalities to manage bioplastics in municipal waste management streams". The target participants to the questionnaire were representatives of Greek municipalities (e.g., such as mayors, special deputy mayors, or the head of the respective office) with the aim of evaluating the existing waste management strategies (specifically plastics) and assessing the readiness of Greek municipalities for the management of waste from bio-based and biodegradable, compostable plastics. Since the target recipients of the questionnaire were only Greek municipalities, the questionnaire was translated into Greek to facilitate answering the questions.

Responses were collected for 2 months, from April 2022 to May 2022. Different municipalities were mapped across Greece, in order to gather inputs from municipalities of different sizes (small, medium and large) and geographical distribution (islands or mainland). The questionnaire has been filled out once per municipality by the mayor or the relevant person in charge of municipal waste. Of originally mapped municipalities, the questionnaire was answered by 51 Greek municipalities with a final response rate of 56%. After translating the survey results into English, an analysis was performed. Due to confidentiality on the individual scale, the answers have been anonymized and consequently, the data was processed only by using the size of the municipality and avoiding the name. The data were analyzed using descriptive statistics, with frequency tables. The additional value of this study is the capacity to collect data from 51 Greek municipalities considering that this sort of data is extremely difficult to obtain.

5 Results

5.1 Background information about the sample

The results showed that of the 51 municipalities surveyed, 20 were islands, while 31 were located on the mainland. Although it was complicated to get information from the municipalities, the sample was distributed across all geographical regions. The range of the population was wide-ranging, including smallest municipalities of 492 inhabitants and largest over of 660,000 inhabitants. Due to the anonymization of the data, municipalities are not listed, but instead were grouped as small (1,200–10,000 inhabitants), medium (10,001–50,000 inhabitants), and large (over 50,000 inhabitants). Overall, the study sample consists of 11 small, 26 medium and 14 large municipalities (Appendix 1).

In two medium municipalities, the number of tourists reported was zero. However, in some other small and medium municipalities, the number of tourists reached high numbers; this was especially the case with tourist islands. The tourist season is communicated as 4–8 months long during the year, and always in summer.

5.2 Assessing current waste management strategies in Greek cities

Section 1 of the questionnaire investigates the perception of respondents on current waste management practices. More than half of the sample (85%) reported that current waste management runs with many problems (44%) or it is very problematic (41%). Only 4% of the sample answered that it is efficient, but could be improved, as shown in Fig. 1. Within the sample of 51 municipalities, none reported very efficient waste management, reflecting again on the fact that current waste management should be improved.

The second section examines existing waste management strategies, including landfills, incineration with or without energy recovery, organic recycling and biological treatment, material reuse and mechanical recycling, and

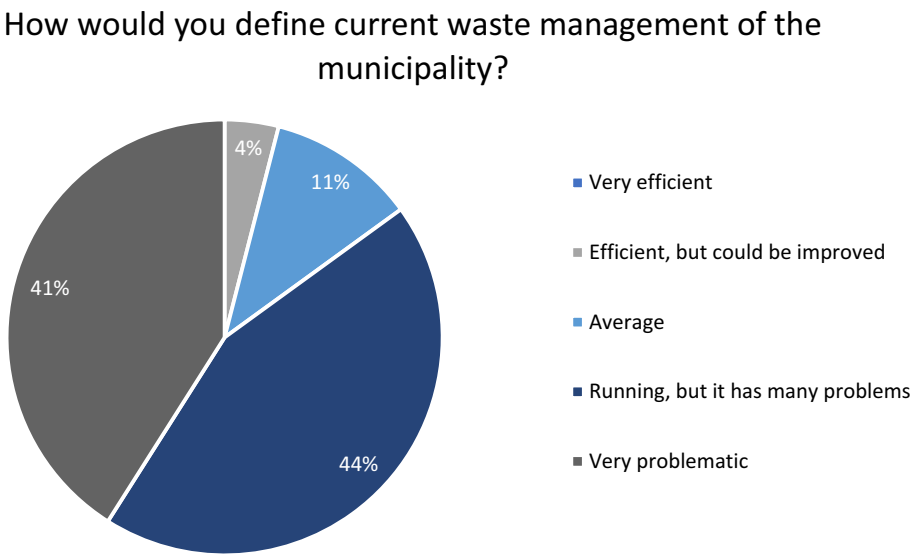

Fig. 1 Effectiveness of the current waste management in Greek municipalities

potential waste minimization practices. For waste minimization, a highly recommended treatment is one that prevents waste generation [42], such as product reuse, repair, refurbishment, etc.

Figure 2 represents the key waste management strategies implemented by municipalities. Landfilling is the most common management option (92%), followed by mechanical (40%) and organic (39%) recycling. Only 11% of the sample performs incineration with or without energy recovery, while waste minimization practices account for 14% (Fig. 2).

Regarding plastic waste management, 98% of the participating municipalities responded that plastic waste is a problem, while all the municipalities surveyed stated that the recycling system exists and operates to a certain level. Since the accumulation of plastic bottles is considered one of the major problems in Greece, especially during the tourist season, the municipalities were asked if the promotion of tap water could be a possible solution to reduce plastic waste. Unfortunately, it seems that 83% of municipalities responded that the promotion of tap water is not suitable since water is not potable in their territory, and usage of water beverage bottles is still the only option.

In addition, when analyzing the waste management strategies implemented for the plastic waste stream, the most common management option was segregation/sorting (72%), followed by contributory recycling, since the deposit-refund system is implemented (Fig. 3).

5.3 Assessing the readiness of municipalities for "bioplastics" waste management

Bio-based and biodegradable, compostable plastics are seen as a good solution to replace currently existing conventional plastics. However, among surveyed Greek municipalities, none stated that a functional waste management system devoted to valorizing these materials has been developed. Furthermore, when asked whether bioplastics are found in current plastic waste streams or in organic waste streams, 52% said they did not know, while 24% said no. Only 24% answered positively for organic or plastic waste or both.

Regarding the collection of biodegradable, compostable plastics, 60% of the municipalities collect them in traditional recycling bins for plastic waste, 24% in mixed waste bins, 10% in plastic bins and only 6% in organic waste bins (Fig. 4).

Regarding the benefits of encouraging the wider use of bio-based, biodegradable and compostable plastics at the municipal level, the majority of the sample (63%) answered that the usage influences on the reduction of plastic waste and 10% of the questioned municipalities stated that it contributes to the reduction of the carbon footprint. Similarly, 19% listed the high functionality of the product as a benefit, while the remaining 8% noted faster biodegradation of these materials as a benefit. (Fig. 5).

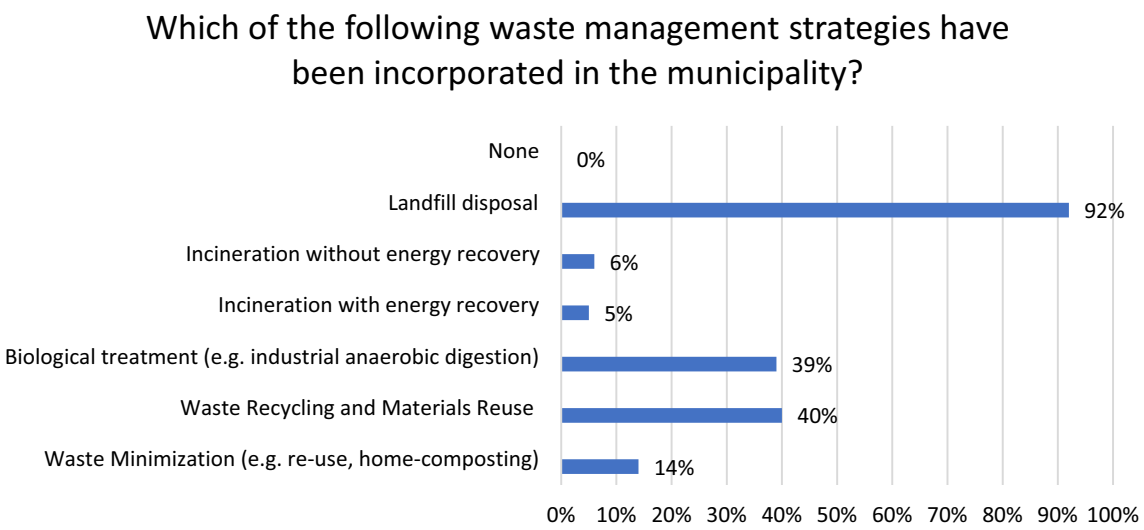

Fig. 2 Waste management strategies in Greek municipalities

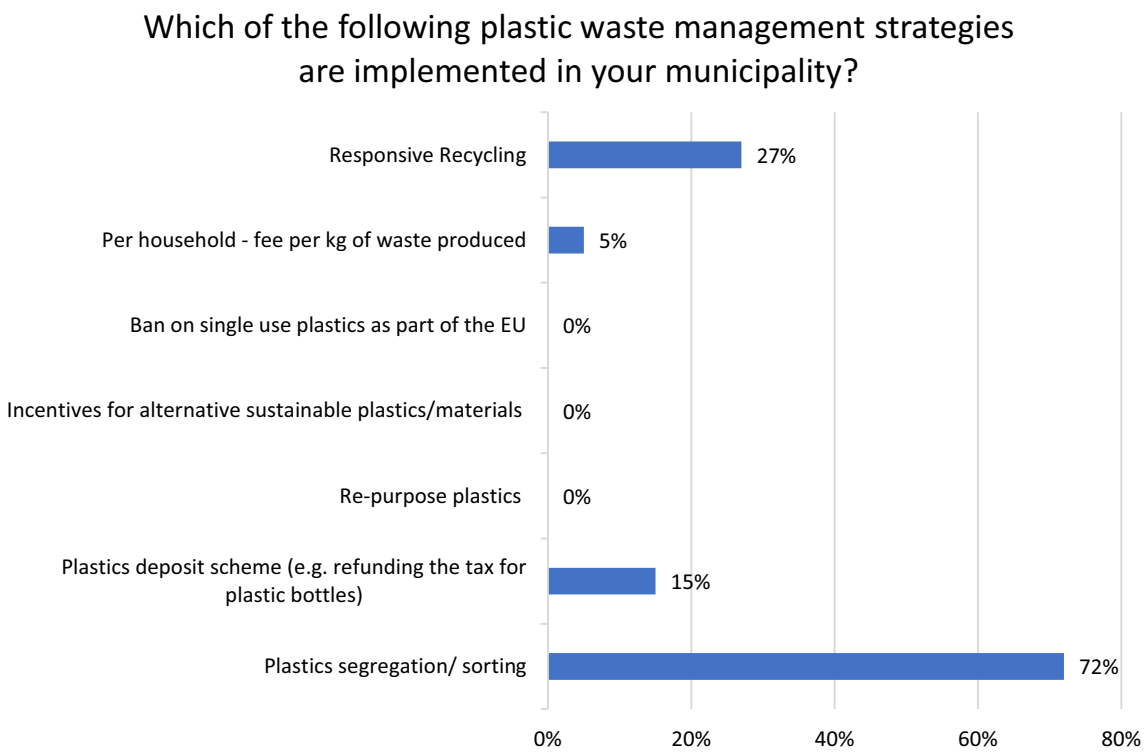

Fig. 3 Plastic waste management strategies in Greek municipalities

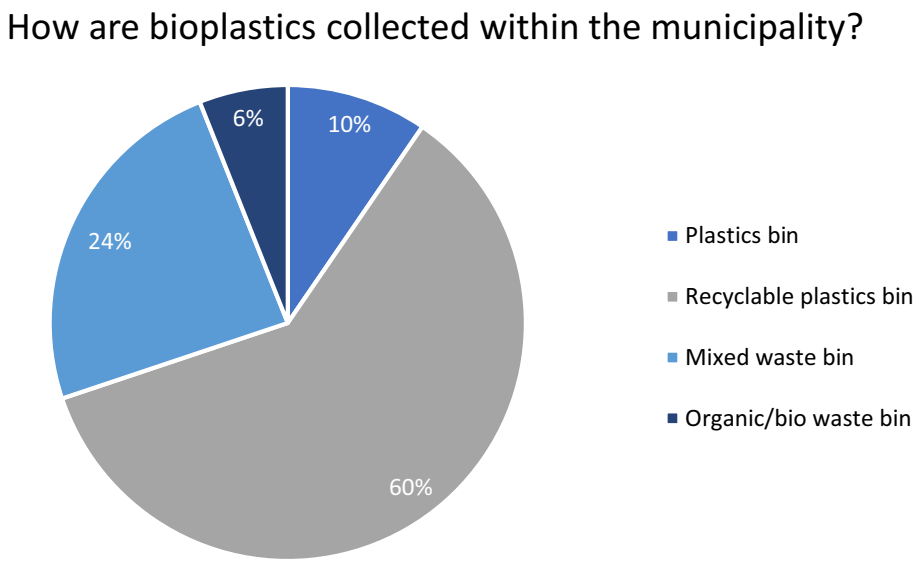

Fig. 4 Collection practices for bioplastics in Greek municipalities. Bioplastics here refer to bio-based, biodegradable and compostable plastics

According to the municipalities' responses, the biggest limitation of the use of bio-based, biodegradable, compostable plastics is the lack of user awareness (55%), followed by the high cost (33%) and finally, the fact that currently it is competing with the food chain (12%).

5.4 Investigating experience-based perceptions and opinions

Deepening the analysis to public awareness strategies, the final section of the survey aimed to reflect on measures fostering the reduction of plastic pollution (Table 1). The participating municipalities consider financial compensation for recycling or reusing plastic items as the best strategy to raise public awareness, where 71% strongly agree. They also choose campaigns

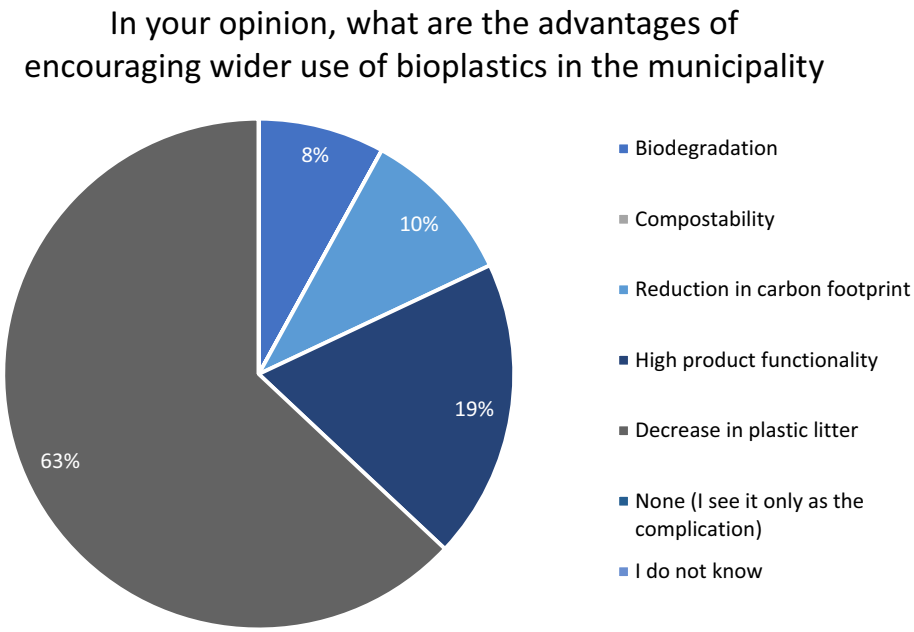

Fig. 5 Advantages of encouraging the wider use of bioplastics in Greek municipalities. Bioplastics here refer to bio-based, biodegradable and compostable plastics

Table 1 Public awareness strategies that could help in reduction of plastic pollution

Questions/answers	Strongly disagree (%)	Disagree (%)	Neutral (%)	Agree (%)	Strongly agree (%)
Media coverage of NGOs/organization promoting beach cleaning campaigns, plastic free July, etc	0	14	34	12	40
Taxes on single use plastics	17	0	9	45	29
Community based waste management (organised by inhabitants)	10	0	14	25	51
Using sustainable alternatives for plastics	0	4	18	26	52
Market based instruments and/ or legislative measures	0	0	32	10	58
Campaigns on reducing plastic pollution	0	0	0	32	68
Economic reimbursement for recycling or re-use of plastic items (return plastic bottles, reuse cups, etc.)	0	0	3	26	71

and market-based instruments and/or legislative measures and media coverage of NGOs/organization promoting beach cleaning campaigns. Plastic Free July initiative has been identified as the next good strategy. In contrast, the application of market restriction measures on single-use plastics (introduced by the European Commission within the Single-Use Plastics Directive) is a less attractive strategy (Table 1).

As reflected in the survey, 36% of the sampled municipalities strongly agree with a total ban on single-use plastics, while 16% are totally opposed to such a measure. The remaining 48% are neutral and perhaps positive. Regarding the feasibility of banning single-use plastics in Greek municipalities, only 30% responded positively, while the rest (70%) found such a measure more or less unfeasible. Environmental education awareness is the main factor to be considered when integrating bioplastics into waste recycling streams (56%), cost was identified as the next factor (31%), while 13% did not know the answer.

In regard to what are their strategies for the promotion of circular economy and waste management by the year 2030, 71% answered the promotion of environmental education and awareness while another 17% answered the adaptation of a fine policy, and finally 10% again did not know the answer.

6 Discussion

Overcoming the initial barrier of the study to gather the data directly from the Greek municipalities and considering the limitations of the study, the overall findings showed an additional value to the understanding of issues regarding solid waste locally and nationally. The survey interrogated various Greek municipalities with the aim to evaluate the proficiency of existing waste management strategies (with a specific focus on plastics), and to assess their readiness for dealing with an increased proportion of bio-based, biodegradable, compostable plastics within existing municipal waste streams. Overall, this study found that the current waste management performance across the many different Greek municipalities does not reach a high level of efficiency to the point of risking the achievement of EU waste management targets established within the EU Waste Framework Directive in 2018. This finding is based on the fact that most of the waste across Greece is still landfilled (ca. 80% in 2019). Furthermore, as revealed by the survey respondents, Greek waste management does not operate effectively, with 85% of those surveyed reporting the waste management system to have difficulties ("running but with some problems") or to be "very problematic". This reflects the national waste management situation where most of the separable post-consumer packaging waste are found in mixed waste streams. None of the respondents agreed that the waste management system was "very effective", with only 4% agreeing that it was effective, but with room for further improvement.

This reliance on landfilling, and the continued use of ineffective waste management systems, will have implications for the achievement of national targets set by the EU. By setting legally binding performance targets, the Landfill Directive [43] and the Waste Framework Directive [44] have driven significant changes in municipal waste management across Europe. In recent years, both directives have been amended by the Circular Economy Package to include more stringent targets [3]. As an EU member state, Greece is obligated to meet relevant limits and targets imposed by EU directives such as the Waste Framework Directive, where current limits/targets include; a ban on the landfilling of biodegradable municipal waste which has been collected separately, a target of reducing landfill to a maximum of 10% of municipal waste by 2035; where concurrently, 55% of municipal waste should be prepared for re-use or recycling by 2025 (increasing to 60% by 2030, and 65% by 2035). As legally bound performance targets, member states found not to comply will be subjected to financial penalties. As previously noted, Greece did not meet the previous target of preparing at least 50% of their waste for reuse or recycling by 2020, and thus were subjected to financial ramifications. This study indicates that unless the waste management system across Greece were to change substantially, then it is very unlikely that Greece will be able to meet the increasingly stringent targets put forward by the Circular Economy Action Plan, and again be subject to further financial penalties in the future.

In order to improve its overall waste management strategy, Greece must also consider the impact that consumer behavior and tourism may have on waste generation. For example, the collection of plastic packaging (which represents a significant waste stream in post-consumer packaging waste volumes) by local residents is strongly linked to the local water supply, whereas in Greece (and many other Mediterranean countries) the high hardness or brackishness of tap water has led to the high consumption of bottled water. Indeed, Greek citizens regularly buy bottled water, due to concerns over the drinkability of tap water. Even in areas where tap water quality is quite satisfactory, such as Athens, a large proportion of the population still prefers bottled water, indicating that this form of consumption has become a fully embedded habit within the modern Greek lifestyle [45]. This pattern of behavior is further exacerbated during the tourist season, where the survey results indicate that transient populations can increase by up to 500 × the resident population. For most of Greece, the tourist season covers the summer period and lasts between 4 and 8 months, as noted by 87% of the survey respondents. Tourism, therefore, has a substantial (albeit time-focused) impact on local plastic consumption and waste generation rates, a trend also reported by Leka et al. [13], McDowall [12], and Oblak [11]. Given that Greece is one of the most important tourist destinations worldwide and continues to grow at a strong pace, solid waste management should be one of the highest priorities in order to contribute to the strengthening of the economy [46].

The preference for bottled water by local people and tourists, combined with the ineffective separate waste collection scheme, is one of the important reasons why Greece has failed to achieve current waste recycling targets. Municipalities have stressed that they are unable to address the issue of water quality sufficiently, as improving and managing the current potable water supply system is a complex task. This points to the need for the exploration of other simpler options, such as the use of water houses to purify (through ultrafiltration) tap water in order to reduce plastic waste and increase the usage of filtered water, as a more sustainable solution. However, such a solution may not provide an immediate resolution; therefore, focus should be placed on managing waste streams as currently generated.

With respect to plastic waste, the 2019 Directive [47] on Single Use Plastics (SUP) sought to address the top ten plastic items most commonly found on European Beaches, which have the greatest impact on the marine ecosystem [47]. This has direct relevance for Greece, as a country which boasts a coastline of 13,676 km, the impact of plastic pollution on the marine ecosystem can have a huge impact across many industry sectors, namely tourism, shipping, and fishing [38]. Therefore, this directive not only has huge implications for the waste management strategies employed across the different municipalities (i.e., to meet targets), but also could have a significant impact of its reputation and industrial activities were it to be a success. Measures introduced by the SUP include [47]; a ban on specific plastic items where a more sustainable alternative is readily available and attempts to limit use of SUPs through awareness-raising campaigns, design/labelling requirements, and the introduction of Extended Producer Responsibility (EPR) schemes. In addition, the SUP has set specific targets with regards to plastic bottles, where by 2025 at least 77% of plastic bottles should be collected separately (increasing to 90% by 2029), and by 2025 PET beverage bottles should incorporate at least 25% recycled material (increasing to 30% in all plastic bottles by 2030). With regards to the separate collection of plastic bottles, the survey results are encouraging, whereby 72% of the municipalities reported that segregation/sorting was the most common waste management strategy for waste plastics, followed by responsive recycling (27%) which includes the use of deposit-refund systems. However, these solutions are fragmented and not exploited in all the cities.

One trend that may have further ramifications for Greek waste management strategy is the increasing use of bio-based and biodegradable, compostable plastic packaging, which, as previously noted, may have added value for food/beverage packaging. To date, and considering the objectives of the European Green Deal, Circular Economy Action Plan and EU Plastics Strategy, only the 'Policy framework on the sourcing, labelling and use of biobased plastics, and the use of biodegradable and compostable plastics' has been developed [48]. While acknowledging that bio-based, biodegradable, and compostable plastics may become a sustainable alternative to conventional plastics for some specific applications, the framework concedes that certain sustainability challenges and trade-offs must be carefully assessed and considered. Thus, improving the understanding of these materials from a consumer, public authority and business point of view is paramount. The survey results agree with this statement, whereby 55% of the survey respondents said that the lack of user awareness is the biggest limitation for [bioplastics]. Beyond this, there are currently no EU policies or laws in place that apply to bio-based, biodegradable, and compostable plastics in a comprehensive manner. However, they are considered in-part by the SUP, which states *"Plastics manufactured […] manufactured from bio-based, […] are not naturally occurring and should therefore be addressed by this Directive. The adapted definition of plastics should therefore cover […] bio-based and biodegradable plastics regardless of whether they are derived from biomass or are intended to biodegrade over time."*—e.g., a plastic bottle made from bio-based plastic will need to have at least 30% recycled content by 2030.

With respect to future waste management strategies and the accommodation of increased volumes of biodegradable and compostable plastic waste, the survey results highlight a lack of harmonization across municipalities regarding collection schemes. Depending on the area, bio-based and biodegradable, compostable plastics are currently managed together with plastic, mixed or organic waste, and in some cases may be contaminating existing clean streams. In the first case, the presence of biodegradable plastics strongly affects the recycling process efficiency, thus reducing the quality of secondary plastics. In the second case, the added value of any biodegradable and compostable material is lost, especially if there is no valuable waste treatment. On this point, although national waste infrastructure includes six biowaste treatment plants, the missing separation of this waste stream does not allow the proper valorization. With regard to this, it is encouraging that almost two-fifths of the municipalities surveyed reported to already employ some variation of biological treatments (e.g., industrial AD or home composting). However, there is still scope for further improvement.

Finally, looking at waste prevention strategies, results reveal that most of the attention is still oriented to waste sorting and recycling while bans or market-based instruments were not considered crucial enough. Despite this being a common trend among the cities investigated, there are success stories linked to the zero-waste mission as represented by Tilos, which was officially proclaimed a Zero Waste Certified City in 2023 by achieving a nearly 90% recycling and composting rate. This finding calls upon a huge revision of the local waste management plan since upcoming EU policies, including the EU Regulation for Packaging and Packaging Waste, are boosting the waste hierarchy by introducing restrictive measures on reuse and reduction. Still, success stories should be properly valorized to be source of inspiration for other cities.

Overall, this study has indicated that the current waste management system is not ready to receive an influx of bio-based and biodegradable, compostable plastics, and if the current system were to continue as is then Greece would be unlikely to meet (even) the current EU targets on plastics, recycling and landfill diversion. However, the information provided in this study has its limitations. First of all, the sample of the study is too small in order to extract exact conclusions, and there is a recommendation for broader data availability that would facilitate the detailed assessment. That being said, the additional value of this study is in understanding the current state and importance of gathering information

from responsible authorities on small-scale level (municipalities) instead of relying on data from national databases only. Where for example, this study was able to highlight the disparity in waste management attitudes and strategies across the different municipalities of one country.

7 Conclusion

Assessing the current situation of solid waste management among Greek municipalities highlighted the many obstacles to collecting data, which in turn affected the final results. Nevertheless, this study is an important contribution to the overall understanding of the current solid waste management in Greece and shows a clear direction in which future actions should be directed. Regarding the future targets of Greek municipalities in relation to solid waste management, the majority have not yet clearly established specific quantitative targets for 2030. This situation is probably due to the fact that solid waste management has not been harmonized with the EU requirements in a large number of municipalities in Greece. To improve solid waste management, the study recommends increasing recycling rates, reducing solid plastic waste reaching landfills, and implementing an integrated strategy involving multi-stakeholders, including tourists who play an important role in this field. Policymakers should recognize the benefits of bio-based and biodegradable, compostable plastics and actively engage citizens and industries in the process of implementing end-of-life scenarios. Overall, the study emphasizes the need for a strong focus on implementing innovative solutions to benefit municipalities and meet EU requirements.

It follows that an integrated strategy should be envisioned, engaging multi-stakeholders, from policymakers to community industrial stakeholders in order to make each party responsible for value retention as the circular economy aspires to. In this way, the implementation of innovative solutions has a great chance to succeed and benefit municipalities. Therefore, the study recommends strong focus on future actions to be pointed in this direction by both Greece and the EU.

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Data availability Data is provided within the manuscript or supplementary information files.

Declarations

Ethics approval and consent to participate Obtained.

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Appendix

See Table 2.

Table 2 Characteristics of the municipalities participating in the survey

Type	Size	Population	Number of tourists
Mainland	Large	660,000	2,000,000
Mainland	Large	325,182	940,000
Mainland	Large	213,984	300,000
Mainland	Large	144,449	800,000
Mainland	Large	85,851	11,200
Mainland	Large	81,355	570,500
Mainland	Large	75,315	4,000
Mainland	Large	72,959	70,000
Mainland	Large	56,747	605,000
Mainland	Large	53,041	200,000
Mainland	Medium	47,000	0
Mainland	Medium	42,000	100,000
Mainland	Medium	35,847	10,000
Mainland	Medium	35,000	500,000
Mainland	Medium	32,881	5,500
Mainland	Medium	31,315	54,000
Mainland	Medium	30,000	0
Mainland	Medium	29,000	80,000
Mainland	Medium	27,800	540,050
Mainland	Medium	26,716	8,008,500
Mainland	Medium	26,389	100,000
Mainland	Medium	25,668	70,000
Mainland	Medium	19,493	6,000
Mainland	Medium	14,941	15,000
Mainland	Medium	13,105	670,000
Mainland	Medium	12,394	150,000
Mainland	Medium	11,866	55,000
Mainland	Medium	11,802	5,000
Mainland	Medium	10,063	7,000
Mainland	Small	8,304	100,000
Mainland	Small	7,710	3,500
Island	Small	492	12,000
Island	Large	173,993	6,500,000
Island	Large	115,490	5,000,000
Island	Large	108,600	8,000,000
Island	Large	70,000	2,000,000
Island	Large	55,500	2,250,000
Island	Medium	40,759	2,050,000
Island	Medium	36,196	18,000
Island	Medium	22,652	480,000
Island	Medium	18,318	55,600
Island	Medium	13,710	315,600
Island	Medium	10,113	5,000,000
Island	Small	6,100	500,000
Island	Small	3,231	300,000
Island	Small	2,750	78,050
Island	Small	2,600	100,000
Island	Small	2,450	10,000
Island	Small	1,889	780,000
Island	Small	1,200	100,000
Island	Small	1,000	78,000

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