Plastic Pollution in Slovenia: From Plastic Waste Management to Research on Microplastics

Gabriela Kalčíková and Andreja Žgajnar Gotvajn

Contents

Abstract Despite the increasing environmental awareness, there is still an enormous amount of plastic waste generated which often ends up in the environment. Slovenia is not an exception, and in the past years, there was a lot of effort to minimize plastic pollution in terrestrial and aquatic environments. Since waste management is closely connected to plastic pollution, the first part of the chapter summarizes waste management practice and plastic waste handling in Slovenia. According to European statistical data, Slovenia belongs among countries, where a good waste management practice is well established; waste collection, recycling rate, and waste management are comparable to other developed countries. The book chapter also focuses on the plastic waste in Slovenia and how plastic pollution is treated from a governmental perspective as well as from the perspective of nonprofit organizations. The last part of the chapter is aimed to present research on plastic pollution and microplastics in Slovenia; to introduce current research efforts and trends in Slovenia; to discuss monitoring results and the impact of microplastics on the local environment; and to link these results to the global microplastic research.

G. Kalčíková (✉) and A. Žgajnar Gotvajn
Faculty of Chemistry and Chemical Technology, University of Ljubljana, Ljubljana, Slovenia
e-mail: gabriela.kalcikova@fkkt.uni-lj.si; andreja.zgajnar@fkkt.uni-lj.si

Friederike Stock, Georg Reifferscheid, Nicole Brennholt, and Evgeniia Kostianaia (eds.),
Plastics in the Aquatic Environment - Part I: Current Status and Challenges,
Hdb Env Chem (2022) 111: 307–322, DOI 10.1007/698_2019_402,

Keywords Microplastics, Plastics, Pollution, Waste management

1 Introduction

1.1 A Brief History of (Plastic) Waste

In early history, when humans roamed the Earth, there was no such thing as waste, because nature was able to recycle everything that was left on the ground or in water. Food was immediately consumed, and waste quickly disappeared by the action of natural processes of scavenging and microbial decomposition [1]. Containers for food packaging were not needed; later, some natural materials as clay or reed fibers were used to make pottery that were reused and repaired until they were broken. Already in 1500 BC, Egyptians produced glass from silica and sodium carbonate to prepare glasses, bowls, and containers for storage. In the first and second century BC in China, mulberry bark was used for the packaging of food [2]. However, due to the low human population, there was no need for a special waste management practice and problems associated with waste, i.e., diseases, air pollution, and groundwater contamination were negligible for a long time [3].

With the development of civilization and increased population density, problems connected to waste became more important, and, as a result, some rules and practices emerged to encourage some early programs of waste management. The most common way how to manage waste during the ancient time was to place it away from populated areas into large pits or rivers, while some civilizations (as, e.g., Ancient Rome) had organized waste collection workforces already in the first century AD. It would be expected that the development of waste management will go further, but with the beginning of the Middle Ages, the common practice was to discard waste directly out of the window. Increased population in medieval cities, waste crisis, and finally the plague pandemic in the fourteenth century AD helped to reinvent rudimentary rules of waste management [1, 3].

Another important milestone regarding waste management progress was the industrial revolution. It was characterized by the development of new processes, materials, and products, but it also led to the generation of an enormous amount of waste. New types of industrial wastes could not be handled by traditional ways, and thus the real breakthrough in waste management just started [3]. Engineers were challenged to develop technologies that would alleviate and solve these problems. Among other measures, this led to the construction of the first waste incinerators in 1876 [4] and construction of a sanitary landfill in 1912 [5]. During this time, there were also major changes for many ordinary consumers. In the nineteenth century, metal containers became the primary material for food storage, and their usage expanded in 1959 when they started to be used for beer and soda. At the end of the nineteenth century, the typical shopping bags were made of jute, because paper as a packaging material was still scarce and paper bags were not very strong. Several further inventions helped to make paper bags stronger and inexpensive, and soon they became an essential shopping item in every grocery store [2].

However, the real revolution in packaging, and consequently in waste generation, started at the beginning of the twentieth century with the invention of plastics. The first plastic material made was a synthetic resin called Bakelite, and the commercial success of the invention encouraged the chemical industry to start research, development, and production of many new plastic materials. Further, and mainly due to the worries about a shortage of natural resources during World War II, there was a great interest in the development of artificial materials. Although the majority of plastic materials were originally used for military purposes after the war, new commercial products burst onto the market [2, 6]. Polystyrene, a by-product of military research that was supposed to bring a new rubber material from styrene monomers, became the key material of hot cups, plates, fast food containers, and other common packaging products. Similarly, polyethylene was discovered during military research. After the war, it replaced many metal cans and paper products and became the most important material for packaging ever made [6]. Polyethylene plastic bags were patented in 1965 [7], and together with PET bottles that were introduced in 1977, they quickly became superior to other consumer packaging products [8].

In overall, since the 1950s, plastics became an absolutely indispensable part of the consumer society; they permeated to everyday life, and thereafter almost every product could be replaced by a plastic substitute [6]. The extraordinary global expansion of plastic can be seen from the dramatic increase of plastic production from less than 2 million tons manufactured in 1950 to more than 335 million tons made annually today, with Europe among the leading plastic producers (19%) [9]. As of 2015, there were 5 billion tons of plastics produced, which is enough to wrap the Earth in a layer of plastic foil [10].

1.2 From Macroplastics to Microplastics

Today's society became a plastic consumption society – low production costs, as well as the favorable properties of plastics, make them suitable for an enormously broad range of applications and easily available for consumers [11]. More products are available for purchase, and they are wrapped in packaging which is of little value to consumers. It means that the majority of packaging materials are used once and then thrown away [2]. Since plastic packaging is the major sector of the plastic industry – e.g., in 2016, 39.9% of produced plastics in the EU were used for packaging – thus, the generation of massive amounts of plastic waste is inevitable. As a consequence, plastics contaminate aquatic habitats worldwide – it occurs in coastal areas and open oceans from the poles to the equator including even the most remote habitats; they are accumulated in sediments, dispersed in the water body, or floating on the water surface [11] – making plastic the most significant part of marine litter [12]. Although plastics are considered as environmentally nondegradable materials, they are subject to environmental aging – a combination of photo- and thermal-oxidative degradation by ultraviolet (UV) radiation, mechanical weathering, and biodegradation, which results in plastic fragmentation [13]. Such fragments are called microplastics.

Although the first scientific articles that identified microplastics in the environment as an issue were published in 1972 [14], efforts of the scientific community on this subject only started in 2004, with the paper "Lost at Sea: Where Is All the Plastic?" in the *Science* journal [15]. Since then, microplastics have become a truly global issue, because they can be found practically everywhere around the world and have thus become contaminants of emerging concern [16].

In the last years, microplastics have received great attention not only in the research community but also in society. High-profile media attention has expanded the issue of microplastics to the public and, therefore, driven by concerns with respect to both ecological harm and human health, triggered calls for policy action. However, human decisions and behaviors are the reason why microplastics occur in the environment and the economy drives the production of (micro)plastics [17]. If microplastic pollution is to be reduced, the society needs to understand the overall microplastic issue and to link the production of microplastics to their behavior and decisions. Efforts should emphasize the controlling sources and inputs of plastics into the environment by better educating and by improved waste management [18].

2 Plastics and Slovenia

In line with the introduction, the aim of this book chapter is to introduce an overview of plastic waste and management in Slovenia, the role of the government and nongovernmental organizations in the plastic issue, and, in the end, research efforts regarding plastics and microplastics that have been going on in Slovenia in recent years.

Slovenia is a country located in the south of Central Europe; it lies in the eastern Alps and borders the Adriatic Sea at its northern end. Although Slovenia was part of socialistic Yugoslavia for most of the twentieth century, it managed to sidestep most of the problems associated with the breakup of Yugoslavia. Since gaining independence, Slovenia has striven quickly to attain a level of development that enabled it to become a member of the European Union. Despite the common history of Slovenia and Western Balkans, Slovenia integrated economically and politically with Western Europe, and thus it may be considered a country bridging these two "worlds" – not only geographically but also socioeconomically. Therefore, Slovenia is an exceptional example of a post-socialistic country that, in the last decade, has developed into a country with strong priorities in nature conservation and environmental protection.

2.1 Waste and Plastic Waste Generation

In the past decades, changes in lifestyle, economic and commercial growth, technological development, and other factors led to increases in waste generation in many countries [19]. Waste is regarded as an inevitable, valueless by-product of human activities [20]. Waste has many negative environmental consequences, and thus the prevention of waste generation got into forefronts of environmental strategies around the world [21].

Plastics are an important part of many waste types: they can be found in industrial, municipal, and household wastes as well as in packaging waste. Therefore, it is difficult to evaluate a total amount of generated plastic waste by a country or to compare such data among countries due to differences in data collection and management (landfilling, incineration without energy recovery, incineration with energy recovery and recovery other than energy recovery), statistical analysis, missing data, and also the definition of various types of waste. For example, statistical data in the EU define the amount of generated plastic waste by the population as the amount of plastic waste collected by recycling centers of each municipality. It means that it is the plastic waste that inhabitants brought to the recycling center and not all the plastics collected by municipalities. In Slovenia, it is 2 kg per capita, while in the EU (28) (data for 28 member states) it was 5 kg per capita in 2014 [22]. But the majority of plastic waste is found in municipal and packaging waste.

Most waste generated by the population is collected as municipal waste. The main compositional categories of municipal solid waste are paper and cardboard, organic waste, plastics, metals, glass, textiles, and other minor fractions of waste [23]. In Slovenia, the most abundant fraction of mixed municipal waste is plastics (24%), followed by organic waste (18%) and paper (14%) [24]. However, the municipal waste composition varies a lot among countries and also depends on local conditions and on the waste collection and management system. It is strongly affected by socioeconomic factors, level of industrialization, geographic location, climate, level of consumption, collection system, population density, the extent of recycling, legislative controls, and public attitudes as well as by seasons, for example, in the amount of organic yard waste [1, 25].

The amount of generated municipal waste is also very variable. Although the move toward the reduction of waste in Europe was introduced by the Waste Framework Directive already in 1975 emphasizing the importance of waste prevention and minimization [26], there is still no common trend of municipal waste reduction. For example, over the last 22 years, in Switzerland and Slovakia, the amount of municipal waste per capita increased by 18% and 28%, respectively (Fig. 1). In the EU (27) the overall generation of municipal waste is relatively stable, similar to many member states (e.g., Poland and Germany). In Slovenia, the amount of municipal waste per capita was reduced by 21% [22] (Fig. 1).

Figure 1 also shows a significant difference in the amount of waste generated by each country, and it seems that some countries within the EU generate a significantly lower amount of municipal waste than others (e.g., Germany and Poland, Fig. 1).

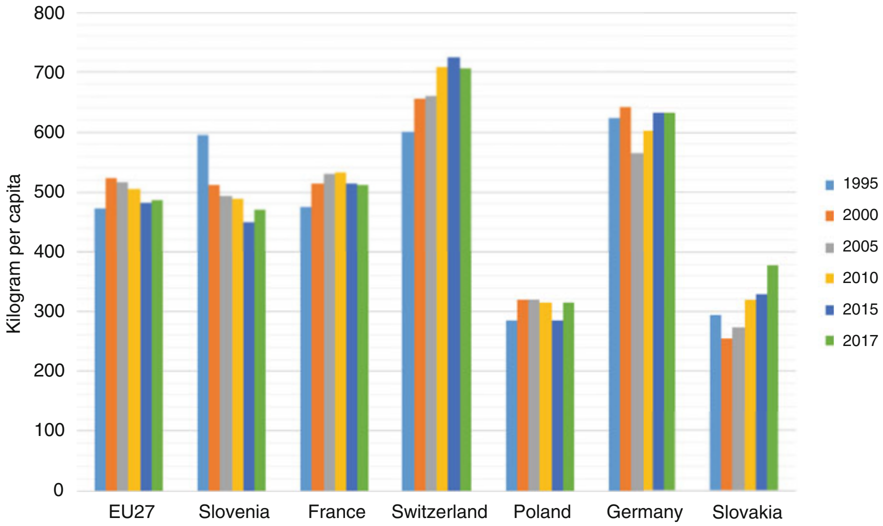

Fig. 1 The development of municipal waste generation (kg per capita) in different countries of the European Union from 1995 until 2017 [22]

However, countries define municipal waste differently; some countries also include bulky or garden waste. Then, it appears that these countries generate more municipal waste per capita than a country that excludes these waste fractions. Some countries also include only waste from households, whereas other countries also include waste from commercial activities [27].

Plastic packaging comprises about two-thirds of all the plastics put on the market [9], and most of the packaging is disposable. Thus, it can be assumed that plastic packaging waste is a relevant indicator of plastic waste generation by the population. In 2016, 170 kg of packaging waste was generated per capita in the EU, varying from 55 kg per capita in Croatia and 221 kg per capita in Germany and Slovenia with about 108 kg per capita [22]. Generation of packaging waste can also be linked to an economic situation of a country. The more the population grows, the more goods are consumed, and packaging becomes an important part of the waste. For example, when the gross domestic product (GDP) – a quantitative indication of the mean living standard of a nation – is compared to packaging waste generation in Slovenia from 2007 to 2016 (Fig. 2), there is a significant correlation. In this case, Slovenia was dragged into a deep recession by the European financial crisis from 2008, and it was quickly reflected in the package waste generation. After 2014, the financial situation stabilized, and GDP and amount of packaging waste again steeply increased (Fig. 2).

In Slovenia, the amount of plastic packaging waste generated per capita is stable with 22.66 kg per capita in 2007 and 22.45 kg per capita in 2016. Packaging plastics represent about 21% of the total packaging waste [22].

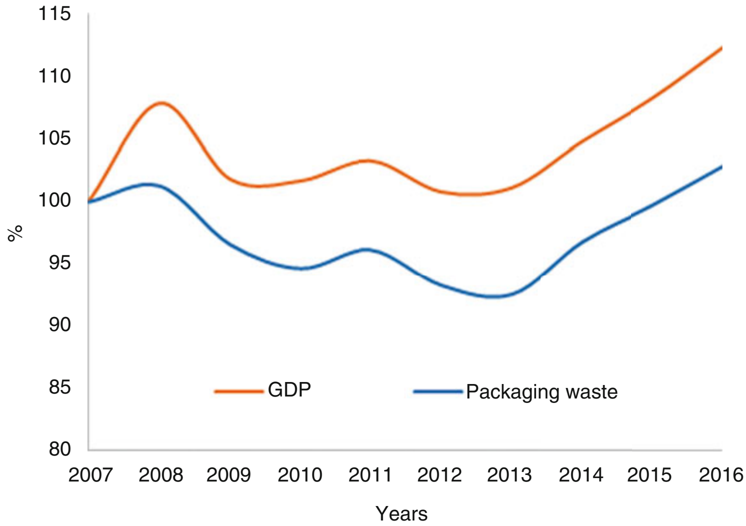

Fig. 2 Comparison of packaging waste generation in Slovenia and gross domestic product (GDP) from 2007 to 2016 (calculated from 100% in 2007 selected as a starting year) [28]

2.2 Plastic Waste Management

Solid waste management is an important tool to reduce environmental pollution caused due to the generation of plastic waste. It includes many actions such as planning, organization, administration, and financial and legal implications of various activities regarding generation, on-site storage, collection, transfer, transportation, processing, and recovery, as well as the ultimate disposal of solid waste [3, 29]. The first effort to define the priority of the EU waste management began in 1975 with the first Waste Framework Directive (1975/442/EEC, [26]), but the modern concept of waste hierarchy was introduced in 2008. The EU parliament implemented a new five-step waste hierarchy to the legislation (Directive 2008/98/EC, [30]): the priority of waste management is the waste prevention, reuse, recycling, and another recovery (e.g., energy recovery), and the last option is disposal.

Over the last decade, Slovenia has successfully implemented the EU waste legislation that helped in diverting waste from landfills and has established a recycling system throughout the country, achieving a high recycling rate. Slovenia has a high number of waste management facilities: 386 for recycling, 10 for energy recovery, and 14 landfills for municipal waste disposal; the number of waste treatment facilities increased by 3% from 2014 to 2016 [31]. In 2010, only 22.4% of municipal waste was recycled in Slovenia, while in 2017 it was 57.7%. On the other hand, landfilling of municipal waste significantly decreased over the last decade, from 72.0% in 2010 to 16.4% in 2017 [22, 31]. 69.4% of all packaging waste and 62% of plastic packaging waste were recycled in Slovenia in 2016; it is one of the highest recycling rates in the EU (Fig. 3). The transition from landfilling to recycling was strongly supported by the modernization of waste management facilities in Slovenia. In 2015, the most modern and one of the largest waste management centers in Europe was opened in Ljubljana. This Regional Waste Management Center (RCERO) collects waste from 50 municipalities, which represents one-third of the Slovenian population. It is aimed to treat mixed municipal waste that does not contain paper and cardboard, plastics, and organic waste, because they are collected and treated separately. The treatment results in 95% of mixed municipal waste being utilized and only 5% of municipal waste being disposed in a landfill [32].

However, the positive trend in the implementation of the hierarchy of waste management in Slovenia can be linked also to other aspects. For example, social aspects play an important role in successful waste management [33]. These social aspects include communication and acceptance of waste treatment methods (e.g., a large campaign about the new waste management facility – the example of RCERO), public participation in planning and implementation (e.g., sorting of waste, separation of plastics), and consumer behavior (e.g., their own decision not using single-use plastics). In Slovenia, sorting of waste and separation of plastics are strongly supported by legislation. For example, in the capital city of Ljubljana, individuals who do not separate waste properly face a fine of 200–800 euros [34].

Another very important factor is early education. The Slovenian government has been supporting many projects regarding waste management education since the modern history of Slovenia. For example, in 1996, a program was launched, which was called "Eco-Schools," designed to implement sustainable development education in schools by encouraging children and youth to take an active role in how their school can be run for the benefit of the environment [35]. The Ministry of the

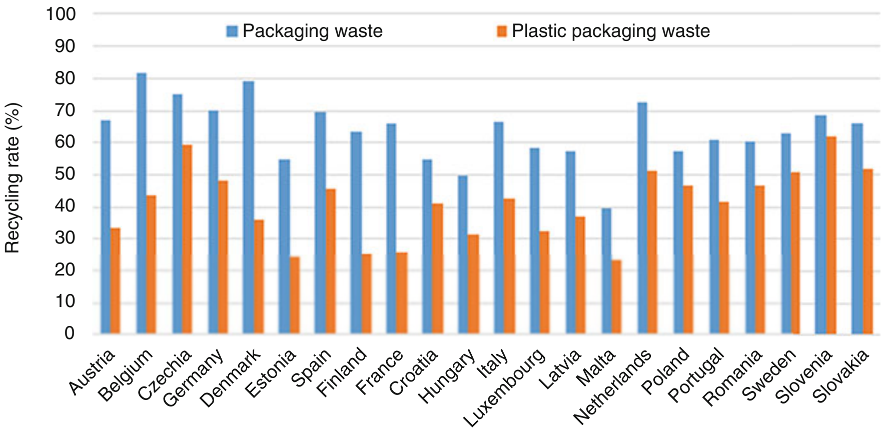

Fig. 3 Comparison of the recycling rate of packaging waste and plastic packaging waste in selected European countries in 2016 [22]

Environment and Spatial Planning ran a large campaign on the impact of lightweight plastic carrier bags on the environment in 2018. The aim of this campaign was to increase knowledge about single-use plastics and generation of microplastics in the environment as well as to reduce consumption of lightweight plastic carrier bags [36].

There are also many nonprofit and nongovernmental organizations spreading the awareness of waste and waste plastic generation. The largest action against waste in Slovenia was organized by the environmental organization "Ecologists Without Borders." They have organized several events; one of them is "Let's Clean Slovenia in One Day!" targeting illegal dumps and collecting waste around the country. During the last event in 2018, about 28,000 volunteers removed 77 tons of waste from the environment [37]. Before the event, various promotional and organizational activities were offered and aimed to educate about waste, plastics, and appropriate waste handling [38]. The same organization supports Slovenian municipalities to join the initiative "Zero Waste Slovenija." There are nine municipalities in the network (17% of the population) that have adopted the Zero Waste strategy and limited the generation of mixed municipal waste. Together, they prevented of at least 15,750 tons of mixed municipal waste, thus saving about three million euros avoiding waste management costs [39].

The successful story of plastic waste management and handling in Slovenia is related to a combination of many factors including advanced technological development, adaptation of new legislations, and participation of people as well as constantly increasing awareness regarding environmental issues. All these aspects are crucial to ensure the success of proper waste management systems. However, there is still a lot of work to do to prevent plastics from entering the environment. Most of these efforts are conducted by scientists, and therefore the last part of the book chapter is aimed to introduce their work on the plastic and microplastic issues.

3 Plastics and Microplastics Research in Slovenia

In the last years, there has been a strong interest in the development of strategies to prevent plastics from entering the environment and to understand the ecological consequences of their presence in various ecosystems. The interest in plastics research basically follows the line of the waste hierarchy: (1) to search for new materials to prevent generation of plastic waste (*prevention*), (2) to develop new methods for plastic waste reuse and recycling (*recycling*, *reuse*), and (3) to describe impacts of plastics that already entered the environment (*disposal*).

Most important is the prevention of plastic waste generation. Thus researchers have been looking for other materials that could become an appropriate replacement of petroleum-based plastics. They have designed many plastic materials that could have a potentially lower impact on the environment. One of such examples is the so-called oxo-plastics or oxo-degradable plastics, which are conventional plastics that contain additives which promote oxidation of the material under certain conditions. It has been designed and implemented to increase the rate of natural removal of plastic waste disposed in the environment. They were claimed to degrade rapidly into harmless products under common environmental conditions. However, they will break down into smaller parts, potentially contributing to environmental contamination by microplastics [40]. Therefore, many research efforts rather focused on biodegradable plastics produced from natural materials [41]. Biodegradable plastics are degraded under natural conditions, and they represent a source of carbon and energy for microorganisms [42]. They can be prepared from several sources, including animal and plant materials. Currently, starch-based bioplastics are the most commonly manufactured on an industrial scale [43]. Similarly, in Slovenia, research on biodegradable polymers was included in schemes of many research groups. Pepic et al. [44] worked for example on synthesis and characterization of biodegradable aliphatic copolyesters with poly(ethylene oxide) soft segments being one of the most promising biodegradable materials due to their susceptibility to biological attacks and their degradation products being soluble, biodegradable, and nontoxic. A further step toward the commercial application of biodegradable polymers proceeds in the framework of the EU project BioApp (Interreg Europe), where Slovenia is one of the project partners. The project focused on the utilization of waste biomass; shells and exoskeletons from shellfish production are used for the production of biopolymers that are a base for the development of a product for commercialization (e.g., biopolymer packaging materials) [45].

In order to tackle the problem of already generated plastic waste, researchers are looking for alternative innovative applications for reuse or recycling of waste plastics [46]. In Slovenia, this part of the research is covered by various projects, e.g., MOVECO – Mobilizing Institutional Learning for Better Exploitation of Research and Innovation for the Circular Economy in the framework of the Interreg Danube Transnational Program. The aim of the program is to minimize waste generation and to keep products and resources in the economy as long as possible so that both the economy and the environment can benefit from it [47]. Another project led by a Slovenian partner (TECOS, the Slovenian Tool and Die Development Centre) is a new circular economy through the valorization of postconsumer plastic waste and reclaimed pulp fiber (CEPLAFIB). The project is heading toward the development of new materials out of plastic packaging waste and waste newspaper that could be used for high-tech products in the automotive, construction, and packaging industries [48].

The last aspects of plastic research in Slovenia are monitoring and impact studies that are carried out in several Slovenian institutions. One of the first and largest projects focusing on monitoring of (micro)plastics was the DeFishGear Project (IPA Adriatic Cross-border Cooperation Programme) in 2013. The aim of the project was to improve knowledge on the occurrence, amounts, sources, and impacts of marine litter in the Adriatic Sea and to address the emerging threat of microplastics [49]. Results of visual observation of floating macroplastics (items > 2.5 cm) showed that the average number of floating macroplastics in Adriatic waters is 251 ± 601 per km^2. The majority of macroplastics were plastic bags (29%) followed by plastic pieces (22%) and sheets (15%) [50]. The results are one or two orders of magnitude higher than most of previously reported in the Mediterranean and the Adriatic Sea, e.g., 15 items/km^2 [51], but the difference can be related to variations in the methodology for macroplastic observation, e.g., oceanographic vessel speed or observation height. Microplastics (particles > 330 μm) were also very abundant at the sea surface of the Adriatic Sea. The average number was 315,009 ± 568,578 per km^2, and the majority of microplastics were made of polyethylene (67%) and polypropylene (18%). Such results are in accordance with many authors that use a similar sampling technology, i.e., manta net (330 or 333 μm) towing (Table 1). The abundance of microplastics related to the Slovenian part of the Adriatic Sea can be derived from the data of Gajšt et al. [59]. The authors sampled microplastics (manta net, with mesh size 300 μm) at the sea surface of the Gulf of Trieste close to the Slovenian cities Piran, Portorož, and Koper. The average number of microplastic particles was 472,000 ± 210,000 per km^2. Viršek et al. [60] also sampled microplastics (manta net, with mesh size 308 μm) around the Slovenian coast. The results of the first sampling (August 2014) showed 259,310 ± 57,096 microplastic particles per km^2, while during the second sampling (May 2015), 1,304,811 ± 609,426 microplastic particles per km^2 were found. Such results reveal one of the highest microplastic abundances among similar studies conducted around the world (Table 1). The authors determined also bacterial community drifting on the microplastic surface and among many bacterial species found invasive fish pathogen *Aeromonas salmonicida* [60].

Slovenian beaches are also affected by microplastics. Laglbauer et al. [61] found 178 microplastic particles per kg of sediment at Slovenia beaches (>250 μm). However, it is difficult to compare these results with other studies due to a significant variation in sampling methods (Table 1). The authors suggested that most of the microplastics originated from outflows and untreated wastewaters that flow through the river into the sea [61]. It is in agreement with Kalčikova et al. [62] who evaluated

Table 1 Occurrence of microplastics in the marine environment – water surface and beach sediments

Location	Sample	Sampling size (μm)	Number of microplastic particles	Reference
Northwestern Mediterranean Basin	Water surface	>333	116,000 per km^2	[52]
Ligurian Sea	Water surface	>333	2,100–578,000 per km^2	[53]
South Pacific Gyre	Water surface	>333	26,898 per km^2	[54]
North Pacific Gyre	Water surface	>333	334,271 per km^2	[55]
Baltic beaches of Kaliningrad region	Beach sediment	>500	1.3–36.3 per kg	[56]
Belgium coast	Beach sediment	>38	92.8 per kg	[57]
Islands Kachelotplate and Spiekeroog	Beach sediment	>1.2	210 per kg (granular) 461 per kg (fibers)	[58]

a high amount of polyethylene microbeads entering waterways with treated wastewater from the largest Slovenian municipal wastewater treatment plant. According to their calculations, about 1 kg of polyethylene microbeads (about 112,500,000 particles) is daily released into the Ljubljanica River with treated wastewaters. Similarly, many other authors have considered wastewater treatment plant effluents as an important route for microplastics into the environment (e.g., [63]). However, the presence and abundance of microplastics in Slovenian freshwaters have not been systematically investigated yet.

Besides monitoring studies, Slovenian researchers also focus on the impact of microplastics on various freshwater and terrestrial organisms. Jemec et al. [64] investigated the ingestion and effects of polyethylene terephthalate microfibers on the water flea *Daphnia magna*. The results showed that water fleas are able to ingest very long fibers up to 1,400 μm and confirmed that fibers have a significant impact on the mortality of daphnids if they are not pre-fed with algae. Further, Kokalj et al. [65] extended their work to various types of microplastics that are commonly found in the environment (microplastics from two facial cleansers, a plastic bag, and textile fleece) and tested their uptake by water flea *Daphnia magna* and brine shrimp *Artemia franciscana*. The results showed that both organisms are able to ingest microplastics. Daphnids preferably ingested smaller particles. The most abundant particles in a gut were up to 100 μm, while brine shrimps did not show any preference toward microplastic sizes. The results of the study also showed that these microplastics do not represent an acute hazard for tested organisms, as over the duration of the study, no significant mortality was observed. Similarly, no effect of microplastics from a facial cleanser and a plastic bag was observed on feeding and energy reserves of terrestrial isopods [66]. Kalčikova et al. [67] exposed freshwater floating plants duckweed *Lemna minor* to microplastics from two facial cleansers and observed impact of microplastics on plants' root and fronds. The growth of fronds was not affected, while microplastics significantly reduced the growth of plants' roots and caused mechanical abrasion of roots. This study also showed that microplastics are highly adsorbed onto plant surfaces.

4 Conclusions

Slovenia is one of the EU member states where an environmentally sustainable structure has been successfully implemented and adopted. The significance of plastic pollution is well recognized and understood by the population and the politicians, and thus waste generated by the population has decreased. At the same time, the recycling rate has significantly increased in the last years. Although good waste management practice can be directly linked to the reduction of plastic items and consequently microplastics in the environment, there are many more possible routes to the environment. Despite the good waste management strategy, research results showed that Slovenia's coast is significantly polluted by microplastics. Their occurrence can be linked to several sources, but the most important ones seem to be wastewater treatment plant effluents acting as a point source of microplastic pollution. A significant amount of fibers, microbeads, and disintegrated consumer products originate from these effluents and consequently pollute freshwater and marine ecosystems. Therefore, more efforts should be undertaken to reduce plastic pollution not only by implementation of appropriate solid waste management but also by improving wastewater treatment in order to reduce the plastic stream from the society into the environment.

Acknowledgments The authors are grateful to the Slovenian Research Agency (Research program Chemical Engineering – P2-0191) for supporting their research and to Mr. Predrag Korica for help with statistical data about plastic waste and plastic waste management.

References

1. Letcher TM, Vallero DA (2011) Waste: a handbook for managers. Academic Press, Burlington
2. Vaughn J (2009) Waste management: a reference handbook. Abc-Clio, Santa Barbara
3. Pichtel J (2005) Waste management practices: municipal, hazardous, and industrial. Taylor & Francis, Boca Raton
4. Bilitewski B, Hardtle G, Marek K (1997) Waste management. Springer, New York
5. Pipkin BW (2014) Geology and the environment. Brooks/Cole, Cengage Learning/National Geographic Learning, Pacific Grove/Boston
6. Miller C (2013) The atlas of U.S. and Canadian environmental history. Routledge, New York
7. United Nation Environment (2018) From birth to ban: a history of the plastic shopping bag. https://www.unenvironment.org/news-and-stories/story/birth-ban-history-plastic-shopping-bag. Accessed 16 Feb 2019
8. Smith AF (2013) Food and drink in American history: a "full course" encyclopedia. Santa Barbara, Abc-Clio
9. Plasticseurope (2018) Plastics – the facts 2017 – an analysis of European plastics production, demand and waste data. Plasticseurope, Brussels
10. Zalasiewicz J, Waters CN, Ivar Do Sul JA, Corcoran PL, Barnosky AD, Cearreta A, Edgeworth M, Gałuszka A, Jeandel C, Leinfelder R, Mcneill JR, Steffen W, Summerhayes C, Wagreich M, Williams M, Wolfe AP, Yonan Y (2016) The geological cycle of plastics and their use as a stratigraphic indicator of the anthropocene. Anthropocene 13:4–17
11. Derraik JGB (2002) The pollution of the marine environment by plastic debris: a review. Mar Pollut Bull 44:842–852
12. Andrady AL (2011) Microplastics in the marine environment. Mar Pollut Bull 62:1596–1605
13. Driedger AGJ, Dürr HH, Mitchell K, van Cappellen P (2015) Plastic debris in the Laurentian Great Lakes: a review. J Great Lakes Res 41:9–19
14. Carpenter EJ, Smith Jr KL (1972) Plastics on the sargasso sea surface. Science 175:1240–1241
15. Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AWG, Mcgonigle D, Russell AE (2004) Lost at sea: where is all the plastic? Science 304:838
16. Avio CG, Gorbi S, Regoli F (2017) Plastics and microplastics in the oceans: from emerging pollutants to emerged threat. Mar Environ Res 128:2–11
17. SAPEA (2019) A scientific perspective on microplastics in nature and society. SAPEA, Berlin
18. Peng J, Wang J, Cai L (2017) Current understanding of microplastics in the environment: occurrence, fate, risks, and what we should do. Integr Environ Assess Manag 13:476–482
19. Renou S, Givaudan JG, Poulain S, Dirassouyan F, Moulin P (2008) Landfill leachate treatment: review and opportunity. J Hazard Mater 150:468–493

20. Pariatamby A (2014) Msw management in Malaysia-changes for sustainability. In: Pariatamby A, Tanaka M (eds) Municipal solid waste management in Asia and the Pacific Islands: challenges and strategic solutions. Springer, Singapore
21. Minelgaitė A, Liobikienė G (2019) Waste problem in European Union and its influence on waste management behaviours. Sci Total Environ 667:86–93
22. Eurostat (2019) Waste statistics. https://ec.europa.eu/eurostat/web/waste/overview. Accessed 11 Feb 2019
23. Malinauskaite J, Jouhara H, Czajczyńska D, Stanchev P, Katsou E, Rostkowski P, Thorne RJ, Colón J, Ponsá S, Al-Mansour F, Anguilano L, Krzyżyńska R, López IC, Vlasopoulos A, Spencer N (2017) Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe. Energy 141:2013–2044
24. Mol (2016) The environmental report on waste. http://www.mop.gov.si/fileadmin/mop.gov.si/pageuploads/podrocja/cpvo/okoljsko_porocilo_op_odpadki_priloga1.pdf. Accessed 16 Feb 2019
25. Williams PT (2005) Waste treatment and disposal. Wiley, Chichester
26. Waste Framework Directive (1975) Council Directive 75/442/EEC of 15 July 1975 on waste
27. European Environmental Agency (2013) Managing municipal solid waste – a review of achievements in 32 European countries. https://www.eea.europa.eu/publications/managing-municipal-solid-waste. Accessed 28 Feb 2019
28. Republic of Slovenia Statistical Office (2019) Waste and GDP statistics. https://www.stat.si/statweb/en. Accessed 17 Feb 2019
29. Subramanian MN (2016) Plastics waste management: processing and disposal. Smithers Rapra Technology, Akron
30. Waste Framework Directive (2008) Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives
31. Republic of Slovenia Statistical Office (2016) Seventeen operating landfill sites in Slovenia in 2016. https://www.stat.si/statweb/en/news/index/7501. Accessed 27 Feb 2019
32. Rcero (2019) Regional waste management center. http://www.rcero-ljubljana.eu/. Accessed 21 Feb 2019
33. Kaplan Mintz K, Henn L, Park J, Kurman J (2019) What predicts household waste management behaviors? Culture and type of behavior as moderators. Resour Conserv Recycl 145:11–18
34. Official Gazette of Republic of Slovenia (2008) 72/2008
35. Ekošola (2019). https://ekosola.si/. Accessed 28 Feb 2019
36. Mop (2018) I have a chice: so i bring my own bag. http://www.mop.gov.si/si/delovna_podrocja/odpadki/akcije_ozavescanja_javnosti/. Accessed 16 Feb 2019
37. STA (2018) Let's clean Slovenia in one day! 2018: 28,000 people removed 77 tonnes of waste. https://www.sta.si/2555227/ocistimo-slovenijo-2018-28-000-ljudi-odstranilo-77-ton-odpadkov?q=o%c4%8dist,sloven. Accessed 28 Feb 2019
38. Ecologists without Borders (2018) Let's clean Slovenia in one day! http://www.ocistimo.si/o-projektu/ocistimo-slovenijo-2018. Accessed 15 Feb 2019
39. Ecologists without Borders (2018) Zero waste municipalities. https://ebm.si/zw/obcine/. Accessed 16 Feb 2019
40. European Commission (2018) Report from the commission to the European Parliament and the Council on the impact of the use of oxo-degradable plastic, including oxo-degradable plastic carrier bags, on the environment
41. Luyt AS, Malik SS (2019) Can biodegradable plastics solve plastic solid waste accumulation? In: Al-Salem SM (ed) Plastics to energy. William Andrew, Norwich
42. Chinaglia S, Tosin M, Degli-Innocenti F (2018) Biodegradation rate of biodegradable plastics at molecular level. Polym Degrad Stab 147:237–244
43. Harding KG, Gounden T, Pretorius S (2017) "Biodegradable" plastics: a myth of marketing? Procedia Manuf 7:106–110
44. Pepic D, Zagar E, Zigon M, Krzan A, Kunaver M, Djonlagic J (2008) Synthesis and characterization of biodegradable aliphatic copolyesters with poly(ethylene oxide) soft segments. Eur Polym J 44:904–917

45. Bioapp (2019) A trans-regional platform for the transfer of technological biopolymers from the research sector to the market. https://www.ita-slo.eu/en/bioapp#objectives. Accessed 27 Feb 2019
46. Mohammadinia A, Wong YC, Arulrajah A, Horpibulsuk S (2019) Strength evaluation of utilizing recycled plastic waste and recycled crushed glass in concrete footpaths. Constr Build Mater 197:489–496
47. Moveco (2019) Mobilising institutional learning for better exploitation of research and innovation for the circular economy. http://www.interreg-danube.eu/approved-projects/moveco. Accessed 28 Feb 2019
48. Ceplafib (2019) Implementation of a new circular economy through the valorisation of postconsumer plastic waste and reclaimed pulp. https://www.tecos.si/index.php/en/applied-research/running-projects/item/631-life-ceplafib-predelava-odpadne-plasticne-embalaze-in-casopisnega-papirja-v-nove-kompozitne-materiale-za-proizvodnjo-embalaznih-avtomobilskih-in-gradbenih-komponent. Accessed 1 Mar 2019
49. Defishgear (2019) Towards litter-free adriatic and ionian coasts and seas. http://www.defishgear.net/project/objectives. Accessed 23 Feb 2019
50. Zeri C, Adamopoulou A, Bojanić Varezić D, Fortibuoni T, Kovač Viršek M, Kržan A, Mandic M, Mazziotti C, Palatinus A, Peterlin M, Prvan M, Ronchi F, Siljic J, Tutman P, Vlachogianni T (2018) Floating plastics in adriatic waters (Mediterranean Sea): from the macro- to the micro-scale. Mar Pollut Bull 136:341–350
51. Di-Méglio N, Campana I (2017) Floating macro-litter along the Mediterranean French coast: composition, density, distribution and overlap with cetacean range. Mar Pollut Bull 118:155–166
52. Collignon A, Hecq J-H, Glagani F, Voisin P, Collard F, Goffart A (2012) Neustonic microplastic and zooplankton in the North Western Mediterranean Sea. Mar Pollut Bull 64:861–864
53. Pedrotti ML, Petit S, Elineau A, Bruzaud S, Crebassa J-C, Dumontet B, Martí E, Gorsky G, Cózar A (2016) Changes in the floating plastic pollution of the Mediterranean sea in relation to the distance to land. PLoS One 11:1–14
54. Eriksen M, Maximenko N, Thiel M, Cummins A, Lattin G, Wilson S, Hafner J, Zellers A, Rifman S (2013) Plastic pollution in the south pacific subtropical gyre. Mar Pollut Bull 68:71–76
55. Moore CJ, Moore SL, Leecaster MK, Weisberg SB (2001) A comparison of plastic and plankton in the North Pacific central gyre. Mar Pollut Bull 42:1297–1300
56. Esiukova E (2017) Plastic pollution on the Baltic beaches of Kaliningrad region, Russia. Mar Pollut Bull 114:1072–1080
57. Claessens M, Meester SD, Landuyt LV, Clerck KD, Janssen CR (2011) Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar Pollut Bull 62:2199–2204
58. Liebezeit G, Dubaish F (2012) Microplastics in beaches of the east frisian islands spiekeroog and Kachelotplate. Bull Environ Contam Toxicol 89:213–217
59. Gajšt T, Bizjak T, Palatinus A, Liubartseva S, Kržan A (2016) Sea surface microplastics in Slovenian part of the Northern Adriatic. Mar Pollut Bull 113:392–399
60. Viršek MK, Lovšin MN, Koren Š, Kržan A, Peterlin M (2017) Microplastics as a vector for the transport of the bacterial fish pathogen species *Aeromonas salmonicida*. Mar Pollut Bull 125:301–309
61. Laglbauer BJL, Franco-Santos RM, Andreu-Cazenave M, Brunelli L, Papadatou M, Palatinus A, Grego M, Deprez T (2014) Macrodebris and microplastics from beaches in Slovenia. Mar Pollut Bull 89:356–366
62. Kalčíková G, Alič B, Skalar T, Bundschuh M, Gotvajn AŽ (2017) Wastewater treatment plant effluents as source of cosmetic polyethylene microbeads to freshwater. Chemosphere 188:25–31

63. Murphy F, Ewins C, Carbonnier F, Quinn B (2016) Wastewater treatment works (Wwtw) as a source of microplastics in the aquatic environment. Environ Sci Technol 50:5800–5808
64. Jemec A, Horvat P, Kunej U, Bele M, Kržan A (2016) Uptake and effects of microplastic textile fibers on freshwater crustacean *Daphnia magna*. Environ Pollut 219:201–209
65. Jemec Kokalj A, Kunej U, Skalar T (2018) Screening study of four environmentally relevant microplastic pollutants: uptake and effects on *Daphnia magna* and *Artemia franciscana*. Chemosphere 208:522–529
66. Jemec Kokalj A, Horvat P, Skalar T, Kržan A (2018) Plastic bag and facial cleanser derived microplastic do not affect feeding behaviour and energy reserves of terrestrial isopods. Sci Total Environ 615:761–766
67. Kalčíková G, Žgajnar Gotvajn A, Kladnik A, Jemec A (2017) Impact of polyethylene microbeads on the floating freshwater plant duckweed *Lemna minor*. Environ Pollut 230:1108–1115