sustainability

Article

Challenges and Strategies for Bio-Based and Biodegradable Plastic Waste Management in Europe

Žaneta Stasiškienė [1], Jelena Barbir [2,*], Lina Draudvilienė [1,*], Zhi Kai Chong [3], Kerstin Kuchta [3], Viktoria Voronova [4] and Walter Leal Filho [2]

[1] Institute of Environmental Engineering, Kaunas University of Technology, Gedimino St. 50, LT-44239 Kaunas, Lithuania
[2] Research and Transfer Centre "Sustainable Development & Climate Change Management" (FTZ-NK), Faculty of Life Sciences, Hamburg University of Applied Sciences, D-21033 Hamburg, Germany
[3] Institute of Circular Resource Engineering and Management (CREM), Hamburg University of Technology, D-21073 Hamburg, Germany
[4] Department of Civil Engineering and Architecture, Tallinn University of Technology, EE-19086 Tallinn, Estonia
* Correspondence: jelena.barbir@haw-hamburg.de (J.B.); lina.draudviliene@ktu.lt (L.D.)

Abstract: In recent years, an increasing trend towards replacement of conventional fossil-based plastics with bio-based plastics was noticed, i.e., production of plastics partly or fully made from biomass is rapidly expanding. Currently, bio-based and biodegradable plastics have a very small market size, approximately only 1% of all plastics produced. However, the forecast of the global bioplastics production capacities predicts an increase from approximately 2.417 million tonnes in 2021 to approximately 7.593 million tonnes in 2026, more than three times the current capacity. Therefore, it is necessary to assess the challenges and identify the barriers for bio-based and biodegradable plastics for waste management and to evaluate the effectiveness of current plastic waste management strategies for the efficient waste management of bio-based and biodegradable plastics. The main barriers and motivators of the biodegradable and biodegradable plastics market that have been identified include macroeconomic factors, regulatory factors, technological factors, and social factors. The bio-based and biodegradable plastics have to be separately collected and treated under mostly controlled, regulated conditions. However, currently, there are no legal provisions providing for the separate collection of bio-based plastics, leading to their disposal with either hazardous waste, conventional plastics, or municipal waste. Since the effective plastic waste management strategy relates to good performance in each step of the waste management process, bio-based and biodegradable plastic waste management could, therefore, be based on an effective strategy for the management of plastic waste. However, there is a need for standardizing waste collection systems and creating a harmonized waste collection infrastructure, which would lead to effective sorting of bio-based plastic waste.

Keywords: bioplastics sector; bio-based and biodegradable plastics market; waste management strategy; bio-economy

check for updates

Citation: Stasiškienė, Ž.; Barbir, J.; Draudvilienė, L.; Chong, Z.K.; Kuchta, K.; Voronova, V.; Leal Filho, W. Challenges and Strategies for Bio-Based and Biodegradable Plastic Waste Management in Europe. *Sustainability* **2022**, *14*, 16476. https://doi.org/10.3390/su142416476

Academic Editor: Elena Cristina Rada

Received: 27 October 2022
Accepted: 6 December 2022
Published: 9 December 2022

1. Introduction

Plastics have become one of the most pervasive materials used globally, and its massive production has, on average, increased on a yearly basis by approximately 9% since 1950, reaching 359 million tonnes per annum in 2018 [1–3]. According to The European Academies' Science Advisory Council (EASAC) [4], this rapid growth has been driven by two underlying trends: (1) the continued growth in population and consumers' demand exhibited in all markets, and (2) the replacement of other materials (e.g., paper, metals, glass) due to superior costs, performance ratio of plastics, and by the addition of new applications. It is particularly relevant, given the steady increase in the proportion of oil and gas demand, which is driven by plastics production and consumption [5]. Plastic use was estimated to contribute 1.7 Gt of CO_2-equivalent emissions throughout its lifecycle in 2015 [6], and this value is predicted to quadruple by 2050 unless the current systems are improved. Another study estimated the carbon footprint of plastics in 2015 to be 2 Gt CO_2-equivalent or 4.5% of global carbon emissions [7].

Mismanaged plastic waste is recognized as a threat to the environment as well as human health. Incomplete combustion of plastics can lead to a more hazardous threat to the environment, releasing substances as volatile organic carbons (VOCs), furans, polycyclic aromatic hydrocarbons, dioxins, and others, which have a negative effect on human health. These toxins can cause cancer, serious respiratory and cardiovascular diseases, and damage to immune and nervous systems [8]. In addition to macroplastics serving as a physical hazard for marine life through entanglement, smothering, or ingestion [9], micro- and nanoplastic particles resulting from the disintegration of plastic waste are proven to affect the health of freshwater and marine fauna [10]. The effects on human health are still under investigation, but risk factors exist due to the presence of plastic additives as well as plastics being potential carriers of harmful chemicals. It is recognized that the plastic problem management is a big challenge globally. As was reported by Jambeck et al. [11], the biggest plastic waste producers are middle-income countries, such as China and Indonesia, who have seen rapid economic growth, yet still lack a waste management infrastructure. This leads to the leakage of the plastic to the environment (soil, marine, and fresh water) and requires the implementation of an efficient waste management system. On the basis of the results of the studies [12,13], the world plastic production and consumption can be divided into two main flows—packaging and non-packaging plastic. Therefore, it can be stated that the majority of plastic production can be treated as "short-term" or "single-use plastic products" [14]. Therefore, one has to look for an integration of two ways for the treatment of plastics—ensure efficient fossil-fuel-based plastic waste collection for recycling and foster development of new bio-based plastics [15].

Comprehensive reviews have been published on plastic waste management and opportunities for their recycling and valorization. Zhang et al. [16] reviewed the development status of recycling technologies for plastic recycling and sub-grouped them into physical recycling (i.e., mechanical recycling), resource recovery (i.e., pyrolysis), thermal recovery, as well as biodegradation and oxo-biodegradation. Alassali et al. [17] focused on mechanical recycling, the dominant material recovery process for plastics, and highlighted the limitations due to material quality. Chemical recycling is, in turn, gaining momentum in research, reviewed, for example, by Thionne and Smith [18] as an alternative to mechanical recycling due to its limitations. For bioplastics, Lamberti et al. [19] discussed technically the recycling routes available for bioplastics. The authors concluded that reuse and mechanical recycling should be preferred for bio-based plastics, such as bio-polyethylene (bio-PE), as well as biodegradable plastics, such as polylactic acid (PLA), until the quality is no longer sufficient, after which chemical recycling methods can be applied.

From the perspective of handling the plastic waste, behavior related to recycling can be well predicted in correlation with economic compensation (for example, a deposit system), with social norms being less important. As reported in Leal Filho at al. [20], the social factor is very important in littering, and this is in close correlation with cultural differences and level of education; therefore, modifying people's behavior on consumption of plastic products and increasing the likelihood of their recycling requires more than one method of engagement [12,21]. In fact, an integrated plastic waste management system—focused on the four R's hierarchy (reduce, reuse, recycle, recover) and improving the life-cycle of plastics—should be the priority in striving toward the goal of reducing the consumption of energy and resources, avoiding harmful emissions, and reducing quantities of mismanaged plastic waste reaching the oceans.

In many countries, the overall situation shows that the problem awareness is high; however, the behavioral change does not follow the awareness trend, automatically forming a gap. Currently, an increasing trend towards replacement of conventional fossil-based plastics with bio-based plastics has been noticed, i.e., production of plastics partly or fully made from biomass is rapidly expanding [22,23]. This was triggered by several causes:

- New legislation related to single-use plastic;
- Societal pressure;
- Depletion of non-renewable resources.

However, there is a faulty practice in many countries of using the term "bioplastics" for two different things: bio-based plastics (plastics made at least partly from biological matter) and biodegradable plastics (plastics that can be completely broken down by microbes in a reasonable timeframe, given specific conditions) [22]. However, not all the bio-based plastics are biodegradable, and not all biodegradable plastics are bio-based. Special concern has been posed lately by the EU, since newest research shows that even biodegradable plastics might not fully biodegrade if not in a suitable environment [24]. Therefore, many issues still remain unsolved, even showing that bio-based plastics do not solve all of the current issues and, in fact, may create new ones. On the other hand, bio-based plastics generated from second or third generation feedstock could provide a promising solution for replacing fossil-based plastics.

Therefore, this paper has two aims: (1) to assess the challenges and identify the barriers for bio-based and biodegradable plastics for waste management and (2) to evaluate the effectiveness of current plastic waste management strategies for the efficient waste management of bio-based and biodegradable plastics.

2. Methodological Approach

The methodological approach applied in this research is described in Figure 1.

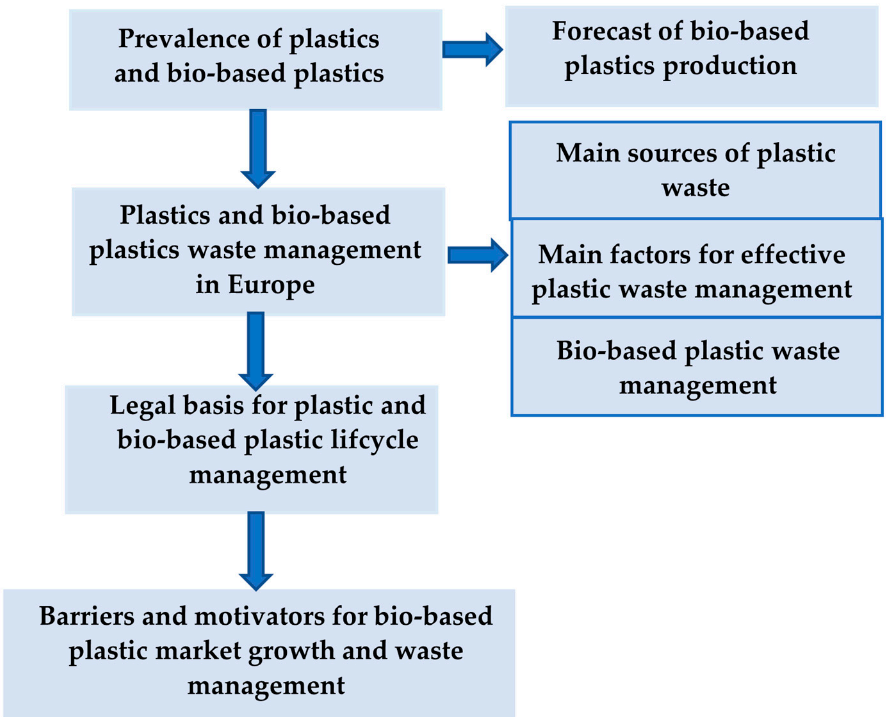
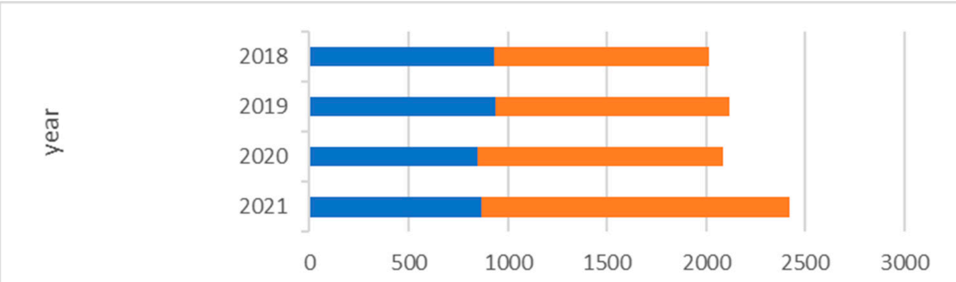


Figure 1. Methodological approach.

To achieve the aims of this paper, the paper is structured into analysis covering the production of bio-based and biodegradable plastics, their end-of-life management, as well framework legal conditions. In the first two sections, published statistics on production and waste management were reviewed to identify trends and insights on the main challenges for bio-based and biodegradable plastics implementation. Legal landscape focuses on mapping out relevant policies and legislations that regulate biodegradable and compostable plastics. This helps in identifying relevant policies and legislation and how they affect responsibilities, impacts, and consequences to key stakeholder groups, including producers, consumers, and waste managers. Special attention is given to analyzing the barriers and motivators for bio-based and biodegradable plastics market growth and effective waste management and how an increased presence of bio-based biodegradable plastics will impact waste management.

3. Prevalence of Plastics and Bio-Based Plastics

Plastic production and use continue to grow. It is, thus, unreasonable to imagine a near-term scenario where all of the current plastic production is replaced by bio-based or biodegradable plastics. Currently, bioplastics production has a very low share in the total production of plastics, with bioplastics representing only approximately 1% of the about 368 million tonnes of plastic produced annually [24]. Analysis of the bio-based plastic production volumes by regions revealed the correlation between countries' leadership in plastic production and prevalence in bio-based plastics production, as well as in the total amount produced. In 2019, Asia remains the major production hub with more than 45% of bio-based plastics currently being produced there; the second is Europe with 25%, third is North America with 18%, then South America with 12%. Thus, approximately one-quarter of the production capacity is located in Europe. This share is predicted to grow, reaching 30% by 2024 [24]. The global production capacities of biodegradable bio-based and non-biodegradable bio-based plastic in 2018–2021, in 1000 tonnes, is presented in Figure 2 [25].



	2021	2020	2019	2018
Bio-based/non-biodegradable	864	848	941	934
Bio-based/biodegradable	1553	1239	1174	1077

Figure 2. Global production capacities of bio-based plastic in tonnes.

Thus, according to the "European Bioplastics" [25], global bioplastics production capacity has increased from 2.087 million tonnes in 2020 to 2.417 million tonnes in 2021, representing a 13.65% increase (Figure 2), and they provide the opportunity for the use of non-fossil feedstocks. Based on the analysis of the types of raw materials for production of bio-based polymers in 2018, biogenic by-products (46%) (mainly glycerol from biodiesel production, used for epoxy resin production) are in the lead, followed by starches (20%) and sugars (17%). Nine percent is cellulose for cellulose acetate production, and 7% is non-edible vegetable oils, such as castor oil for the production of polyamides [13,26]. Bio-based polymers can be used in almost all the market segments and applications: textiles, automotive and transport, building and construction, consumer goods, flexible and rigid packaging, and in other sectors [13]. Four main areas of the worldwide biomass demand in 2018 were identified as: feed 60%, bioenergy 16%, food 12%, and material 10% [26]. There are also niche applications where biodegradability might offer an advantage (particularly in agricultural and related industries), and these plastics can otherwise offer interesting material properties. This leads to the conclusion that plastic producers tend to consider innovations and substitution of fossil-fuel-based plastics with a more environmentally friendly material. It is important to note that the forecasted increase of bio-based biodegradable plastic use highlights the need for research on and scaling up of production from alternative feedstocks so as not to increase competition with food sources. The production of prevalent bio-based biodegradable polymers, such as PBAT and PLA, is reliant on food-crop-based sugars and starches [27].

The innovations implemented in practice are fostering more efficient plastic waste management, with application of the circular economy concept, i.e., ensure high percentage of collection and recycling of plastic waste [28]. It is important to point out that the annual production of biodegradable plastics is increasing in various fields and becoming an alternative for different sectors, such as packaging, agriculture, gastronomy, consumer electronics, automotive, and many more [29,30]. Therefore, it can be expected that bio-based plastics will play some role in the future plastics system, especially in the packaging industrial, as the largest field for bioplastics application is in the packaging industry, with almost 47% (0.99 million tonnes) of the total bioplastics market in 2020 [31].

The Forecast of Bio-Based Plastics Production

The comparison of the global bioplastics production in 2018 versus 2021 shows an increase of only 17% (Figure 2). Thus, the forecast of the global bioplastics production capacities, according to the "European Bioplastics" in cooperation with the "Nova-Institute", should increase from approximately 2.417 million tonnes in 2021 to approximately 7.593 million tonnes in 2026, an increase of more than threefold [25]. It is expected that the share of bioplastics in the total global production of plastics will surpass the two percent mark [32]. However, it is important to note that the presented forecast by the "European Bioplastics" does not contain information on the methodology used. This means that it is unclear which model was used to calculate the forecasts and which data and impact factors were considered [33]. However, according to [34], it is very important to choose the system dynamics (SD) model, which is useful for decision-makers to design strategies. Therefore, on the basis of the presented comparisons of the global bioplastics production in 2018–2021 or 2019–2021 (Figure 2), reasonable doubts are raised. Meanwhile, three different growth paths of global demand for bio-based plastics up to 2030 using a system dynamics model are presented [15]. Three simulation scenarios are presented: baseline, the high oil prices, and the "de-risking". Two main criteria were chosen to model these different scenarios, namely oil price developments and policy measures taken [15,35]. According to the baseline scenario, the global demand for bio-based plastics should double between 2015 and 2030. In the case of the high oil price scenario, the demand should increase by 150%. Based on the "de-risking" scenario, the demand for bio-based plastics should increase to more than 6 million tonnes in 2030; when compared with the demand in 2015, it is more than six times higher. Thus, in summary, the demand for bio-based plastics will increase in all three scenarios [15,35]. The affective development of the bioplastics sector depends on a number of policies and policy instruments that are applied in agricultural, R&D support, trade, industry, and elsewhere. Thus, it can be argued that bioplastics will be an important alternative in the future plastics system; however, it should be noted that they will not play a major role in the near future. The use of the bio-based plastic in the global world plastic context is also faced with barriers which highly impact the bio-based plastics market growth and its waste management effectiveness.

4. Waste Management of Fossil-Based and Bio-Based Plastics in Europe

4.1. Plastic Waste Main Sources and Management

The major source of plastic waste comes from packaging due to its short lifespan compared with non-packaging applications, such as in the construction or automotive sector, although the total consumption in all non-packaging sectors is higher. In Europe, plastic demand from plastic converters was the highest in the packaging sector (39.6%) in 2020, followed by building and construction (20.4%), automotive (9.6%), and electrical and electronics (6.2%) [36]. Major polymer types include polypropylene, polyethylene, polyvinyl chloride, polyurethane, and polyethene terephthalate [2].

Figure 3 shows the estimated amount of plastic consumed in Europe during 2018 compared with the amount of plastic waste generated and collected for treatment [12]. Plastic packaging waste generated was 83% of consumption in 2018, compared with 35% for non-packaging. Plastic packaging, thus, made up 61% of the total plastic waste generated in Europe.

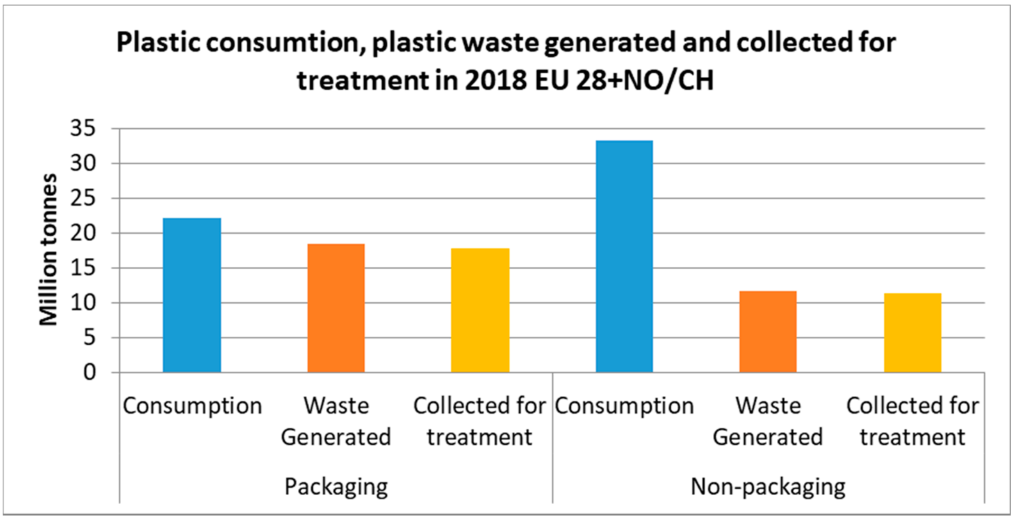


Figure 3. Plastics consumed and plastic waste generated and collected for treatment EU28, Norway and Switzerland.

In Europe, 97% of the waste generated for both packaging and non-packaging were collected for treatment in 2018. The fate of the remaining 3% is unknown and can be attributed to either leakage or improper disposal [12]. The presence and type of bioplastics in the European waste stream will highly depend on the market penetration in each application area. Figure 1 shows a trend of increasing quantity as well as the share of biodegradable plastics produced, which are used mainly in packaging [24]. Taking into account the high share of packaging in the waste stream, integration is, thus, particularly needed in the packaging waste management system for a holistic implementation of bioplastics. A waste management system includes the following elements: source separation, collection and transport, sorting, and, finally, reuse, recycling, energy recovery, treatment, and disposal (Figure 4). Source separation is commonly carried out in order to separate recyclables from non-recyclable waste for recycling. After consumption, the source-separated waste will need to be collected and transported to waste management facilities. After collection, sorting may be carried out to separate different collected materials that have commingled. In the case of plastics, further sorting based on polymer types is needed for recycling. Lastly, waste can either be sent to be reused, recycled, treated energetically, or disposed of.

The collection rate of plastic waste in Europe is high (approximately 97%) compared with the estimates for the world (approximately 70%) [12]. However, collection differs from region to region and highly depends on the plastic application area. Due to the widespread extended producer responsibility systems (EPR) for packaging in Europe [37,38], the separate collection of packaging for recycling is often in place. In addition, EPRs shift the burden of packaging waste collection to producers. Packaging can be either collected door-to-door or via drop-off systems at collection points [39]. Nevertheless, a portion of plastic packaging waste can be expected not to be source-separated and, instead, collected with mixed household waste [40–42]. Another major form of a separate collection method is the deposit–return system, which is common for PET beverage bottles and boasts higher take-back rates for the packaging involved, compared with countries without a DRS system [43]. In a DRS system, consumers pay a deposit when purchasing products included in the system, and the deposit is refunded with the return of the packaging at collection points [44]. Unlike plastic packaging waste, which often has targeted collection systems for recycling, other non-packaging household plastic waste is often disposed with mixed household waste or bulky waste. Sometimes they are delivered to civic amenity centres [39].

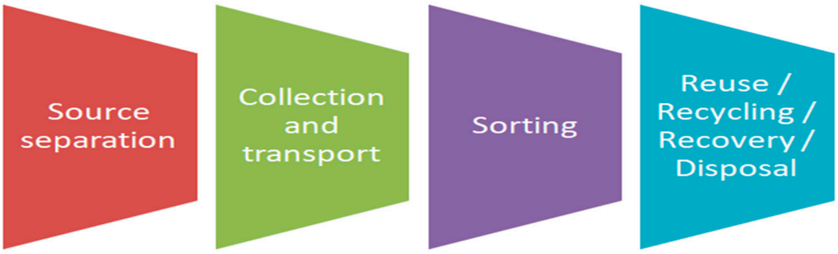


Figure 4. Elements in a waste management system.

After collection, sorting systems are employed to sort plastic packaging from commingled collected waste for recycling [45–47]. In automated systems, two-dimensional plastic films are sorted out by wind-sifting or air classifiers. Three-dimensional packaging made of PET, PE, PP, and PS are sorted out via NIR-based sorting systems and sent to recycling plants. However, a portion of the targeted plastic packaging are not separated into the correct fractions but instead fall into either the mixed plastics fraction or the sorting residue fraction. The reasons for this include complex multipolymeric packaging designs, surface dirt, deformation, and limitations of the sorting system [48]. These account for a loss of recycle output from the higher quality single polymer fractions, as is the case for Germany and the Netherlands [48]. Unlike regranulate from fractions of a single polymer type, the regranulate from the mixed plastic fraction has a limited application area.

Thus, the plastic waste is one of the most complex mixture of materials from a recycling perspective. Therefore, the recycling effort includes various methods, such as chemical recycling (pyrolysis, gasification, and depolymerisation), mechanical recycling, biotechnological processes, as well as integrated upgrading options, such as direct, ex situ catalytic pyrolysis (Figure 5) [49,50].

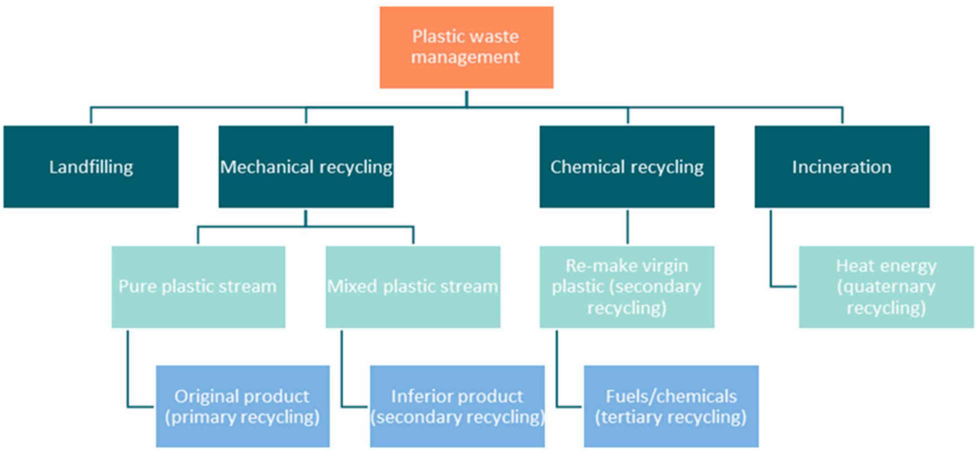


Figure 5. Plastic waste management options.

Currently, most of plastic waste is incinerated or placed in landfills since collection and sorting is costly and produces contaminated and mixed plastic waste streams. However, this raises another huge problem, i.e., the distribution of CO_2 emissions resulting from plastic waste streams [49], as seen in Figure 6.

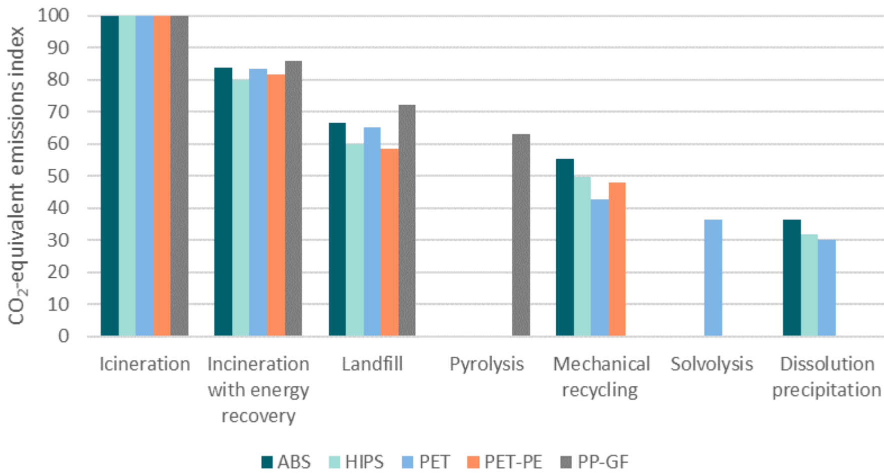


Figure 6. CO_2-equivalent emissions of different end-of-life treatment technologies applied to various plastic waste streams, expressed in relative emissions indexed to incineration (100%).

The advantages of incineration are a reduction of waste volumes by 90%, adaptation to large deposits of waste, energy recovery, and the recovery of metals for recycling. However, the disadvantages of incinerators include the formation of polluting waste (ashes), a low profitability of the equipment for small units, and high investment costs. In addition, operating costs are rising sharply, social opposition is growing, and a significant amount of greenhouse gases is released.

- Case Study: plastic waste treatment rates in Sweden

Approximately 1.7 million tons of plastic waste is generated in Sweden, and only 8% of the total generated amount of plastic waste is estimated to be recycled Figure 7. This consists primarily of PET beverage bottles within the deposit refund system, plastic packaging, and plastics in WEEE that are currently recycled. A minor share of the total amount of generated plastic waste is sent to landfills [51].

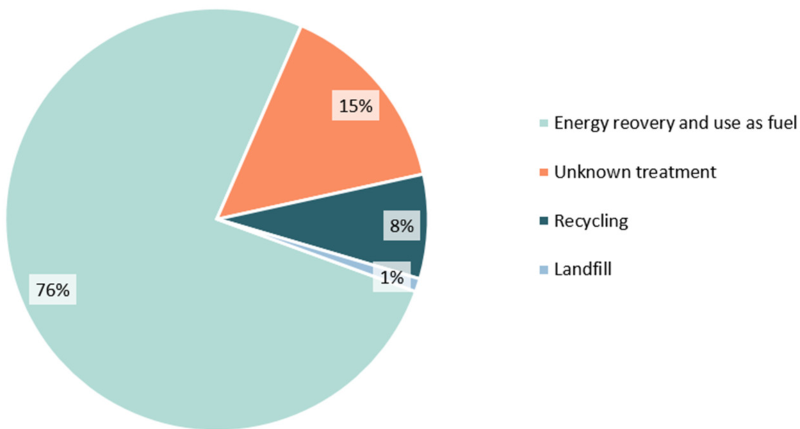


Figure 7. Post-consumer plastic waste treatment rates in Sweden in 2016.

However, more than 75% is sent to energy recovery (Figure 7). It is important to point out that plastic waste for energy recovery is found in mixed waste fractions from households and businesses, which have not been separately sorted for recycling, and from sorting operations. Thus, better techniques for collection and sorting of plastic waste, which facilitate chemical and/or mechanical recycling, need to be developed, as these recycling techniques have less CO_2 emissions in comparison with incineration [52].

4.2. The Main Factors Influencing Effective Plastic Waste Management

Effective plastic waste management requires good performance in each step of the waste management process. This includes high participation rates in the collection, correct source separation behaviour, good sorting efficiencies in the case of commingled collection, and having effective treatment or recycling processes in place.

- Collection and source separation

High collection rates for recycling will reduce the risk of mismanaged waste, which leads to environmental plastic pollution [53]. For example, deposit–return systems for PET beverage bottles have shown to be able to achieve high take-back rates. For commingled collection, the system design affects the collection rate. In the UK, a survey reported that collection schemes that accept more material types have higher participation rates [53]. Another study found that a combination of door-to-door collection and drop-off systems achieved higher collection rates and lower contamination rates compared with drop-off systems alone [54].

- Sorting of commingled fractions

Effective sorting of commingled collected waste is important, as polymeric separation is essential for mechanical recycling. In the case of packaging, design is important to ensure correct sorting of each item into their respective polymeric streams by NIR-based sorting systems. Black plastics, surface dirt, and multipolymeric packaging contribute to sorting errors [48]. In addition, the risk and reward of introducing non-standard polymer types to the commingled stream need to be assessed. For example, PLA contamination in the PET stream poses a risk to the quality of PET recycling [55]. For chemically distinct biodegradable plastics (i.e., PLA), the implementation of a separate sorting stream depends on the economics for the sorting plant [56].

- Effective waste treatment systems

In the case of biodegradable plastics, it is evident that integration efforts or separate waste management systems are needed for successful recycling or treatment. Despite the available standards for certification (i.e., for industrial compostability), they are still not universally accepted in organic waste treatment facilities. In Germany, the composting industry states the lack of benefit to the plant, and in Sweden, where anaerobic digestion is the most common organic waste treatment method, the feasibility of treating certified compostable plastics in anaerobic conditions is not guaranteed.

4.3. Bio-Based Plastics Waste Management

Like conventional plastic waste management, the management of bio-based and biodegradable plastics depends on the application area and the polymeric composition of these plastics. However, waste statistics for bio-based and biodegradable plastics are currently limited. In the Netherlands, selected small-scale waste-sorting studies from 2010 to 2012 indicated a low fraction of bio-based or biodegradable plastics in waste streams. For example, 0.3% of polylactic acid (PLA) and polyurethanes (bio-PUR) were found in municipal solid waste in 2012 and 0.12% of starch films in sorted mixed plastic waste (DKR-350) in 2010 [57]. An Italian study from 2016 to 2019 reported approximately 1.4% of compostable plastics, mostly waste bags, found in bio-waste sent to organic recycling plants [58].

Bio-based plastic that are chemically similar to conventional plastics, such as Bio-PET and Bio-PE, can be recycled together with PET and PE from fossil sources [55]. Thus, packaging products from Bio-PET or Bio-PE can be collected, sorted, and treated through the PET and PE packaging waste management route, assuming that consumers dispose of them in the recyclables bin.

The current management of chemically different plastics, such as PLA or PBS, which are bio-based and biodegradable plastics, differs from region to region and presents more challenges. Biodegradable plastics certified as industrially compostable could be disposed with separately collected bio-waste and treated in industrial composting plants. In Italy, a survey showed general acceptance of compostable plastic complying with EN 13432, certified by the Italian Consortium of Composters (CIC) [59]. In Germany, the waste management industry discourages the disposal of biodegradable and compostable plastic waste with biowaste, quoting concerns about compost quality. However, the bio-based and biodegradable bags for biowaste collection may be used if the local biowaste treatment plant operator agrees. The German Environmental Agency urges consumers to dispose of packaging made from biodegradable plastics with other packaging in the recyclables bin [60]. However, since there are no dedicated sorting streams for biodegradable plastics, this fraction is not recycled but ends up with other sorting residues, which are sent for thermal recovery [61].

Below is a review of the acts pertaining to plastics, plastic waste, waste management, marking, and bio-based plastics, starting with the main pillars of the legislative framework shaping EU policy on plastics and plastic waste.

5. Policies, Legal Actions, and Regulations

In the light of the climate crisis, there were numerous legislative acts adopted around the world. Some of them were new, responding to the newly arisen issues or situations requiring a solution; others were crafted as amendments to the previously adopted acts, as those covered the main principles but needed some alterations and updates to meet the demand of the current environment concerned society and policy makers. The United Nations agrees that financial incentives need to be introduced to change consumption habits, production, and consumption with higher attention to research and development of alternative materials that are more sustainable and environmentally friendly [62]. Governments around the world have scaled up the attention to the global plastic problem management by issuing and adopting numerous legislative acts. The main pillar of the legislative framework for EU policy on plastics and plastic waste management is the Basel Convention [63], the most comprehensive global environmental treaty on hazardous and other wastes, with a focus on plastic waste prevention and minimization. Sustainable Development Goals (SDGs) also refer to the plastic problem in the Agenda 2030 for Sustainable Development [64], where SDG 12 aims to ensure sustainable consumption and production patterns. The Circular Economy Action Plan introduced in 2015 [65] covers the whole cycle from production and consumption to waste management with one of the focus areas on plastics, aiming to accelerate transitioning to circular plastics economy. The New Circular Economy Action Plan [66] is included in the European Green Deal package [67], focusing on sectors that use most resources with high potential for the circularity (including packaging and plastics). Directive (EU) 2019/904 on the reduction of the impact of certain plastic products [68] regulates single-use plastic products, giving a priority to non-toxic and re-usable products and systems. EU rules on single-use plastic products have specific targets to increase the separate collection of plastic bottles to 90% by 2029 and incorporate 30% of recycled plastic in PET beverage bottles by 2030 [69]. The latest General Report on the activities of the EU is expected to cut littering of the top-10 single-use plastic items and reduce it by more than 50% [70]. However, the bio-based plastics are not included in the latest General Report. The EU is still developing a regulatory framework, which would address the sustainability challenges. The EU notes that the clear policy framework is needed on the use of bio-based, biodegradable, and compostable plastics [71]. The EU recognizes that their full life-cycle environmental impact should be clear, including land-use change, impacts on biodiversity and climate, and littering. It is also noted that biodegradability should be properly verified; only then can the role of such materials in the circular economy benefit the environment [71].

Due to the lack of legislative framework for bio-based plastics, there is a need for legal regulation, harmonizing definitions, terminology, and methodologies on identification of bio-based plastics, and their clear and ultimate distinction from other materials, leading to tailor-made treatment (e.g., production, marking, use, collection, recycling, monitoring, and reporting) both by Member States, regional and national authorities, producers, sorting, and recycling entities, as well as the end consumers. Legislation should outline the latest tendencies in materials, replacing conventional plastic in order to promote innovative solutions both on materials and their collection/sorting/waste management systems.

Regarding the ambiguity in marking/labelling bio-based plastics and products, there is a lack of a comprehensive and legally binding bio-based plastics (among others) identification system (marking), which leads to their wrongful treatment and, hence, often leads them to landfill waste. Therefore, introducing a standardized obligatory marking/labelling of bio-based plastics would help to clearly distinguish them from other materials, drive consumer's choice of the packaging when relevant, and allow both consumer and sorting/recycling/waste management entities contribute to plastic waste minimisation by proper management of the used bio-based plastics. Marking/labelling should clearly separate bio-based plastics from other materials (as these can be visually look alike) and emphasize the less harmful impact on environment.

Regarding loopholes in bio-based plastics waste management, currently, there are no legal provisions providing for the separate collection of bio-based plastics, leading to their disposal either with hazardous waste, conventional plastics, or municipal waste. There is a need for standardizing waste collection systems and creating harmonized waste collection infrastructure, which would lead to effective sorting of bio-based plastic waste. Local and regional authorities must play a key role in implementation, administration, and monitoring of such systems. In order to promote bio-based plastics and products thereof, certain financial incentives could be introduced.

6. Barriers and Motivators for Bio-Based and Biodegradable Plastics Market Growth and Effective Waste Management

Directions towards circular economy in EU set forth in the EU Action Plan for Circular Economy and EU Strategy for Plastics clearly indicate the need for conventional plastic use and plastic waste reduction and welcome environmentally friendly alternatives. There is a growing interest in the development of comprehensive bio-economy strategies in many countries, with scope for targeted bioplastics initiatives with them. Key messages can be summarised as follows [72]:

- Bio-based and biodegradable plastics are important elements of bio-economy due to their potential to mitigate environmental impacts across the whole value chain, contributing to sustainability aspects through additional development of social and economic values.
- Similarly, the development of the bio-based and biodegradable products can be seen within the logical context of bio-economy strategy, considering the life cycle approach from biomass growth to the end-of life options;
- More joint efforts are needed to overcome existing barriers on regulatory, social, and economic level for more rapid growth of bio-based and biodegradable materials.

However, complexity of the alternative materials cause ambiguity in their recycling, and waste management makes the achievement of the set goals rather sophisticated [73]. There are four main factors that can impact bio-based and biodegradable plastics market [21,74]:

- Macroeconomic factors, such as crude oil prices, building on GDP, and feedstock costs;
- regulatory factors, such as taxes, subsidies, and bans;
- technological factors, such as scale effect, learning rates, and production costs;
- social factors, such as awareness, customer's attitude, and switching intention.

The main barriers and motivators for bio-based and biodegradable plastics market are presented in Table 1.

Table 1. Barriers and motivators for bio-based and biodegradable plastics market.

Factor	Barriers	Motivators
Economic	• Potential competition with food feedstock • Increase in feedstock production costs • Higher manufacturing cost in comparison with fossil-based plastics	• Reducing dependence on oil cost • Higher investments to bio-based economy
Regulatory	• No provisions for separate collection of bio-based plastics • Lack of legislative framework for bio-based plastics	• Implementation of taxes for fossil-based goods • Subsidies for bioplastic manufacturers • Bans/prohibition of fossil-based goods • Development of supportive policy framework for the circular and bio-based economy
Technological	• Lack of bio-based plastics identification system • Low level of bioplastics production volume • Low level of separate collection of bioplastics	• Increase in the volume of bioplastics production • Additional waste management options • Effective sorting for bio-based plastic waste
Social	• Low customer awareness about bio-based and biodegradable products	• Increase in customer awareness about bio-based and biodegradable products • Changes in mentality and behaviour of society

Regarding economic factors, the main barriers for bio-based and biodegradable plastics are connected with the food feedstock and its production costs. If the price for primary production of bioplastic components increases, it will raise production costs of bioplastics and impact the market price. The biorefinery concept has potential to reduce bio-based material production costs, ensuring alternative feedstocks, or obtaining more valuable organic materials [34,75].

In the regulatory framework, there is a need for legal regulation, harmonizing definitions, terminology, and methodologies on identification of bio-based plastics, and their clear and ultimate distinction from other materials, hence, leading to tailor made treatment (e.g., production, marking, use, collection, recycling, monitoring, and reporting) both by Member States, regional and national authorities, producers, sorting and recycling entities, as well as the end consumers. Legislation should outline the latest tendencies in materials replacing conventional plastic, in order to promote innovative solutions, both for materials and their collection/sorting/waste management systems.

The main technological barrier is the lack of a comprehensive and legally binding bio-based plastics (among others) identification system (marking) which leads to their wrongful treatment and, hence, often leads them to landfill waste. Therefore, there standardized obligatory marking/labelling of bio-based plastics should be introduced, which would help to clearly distinguish them from other materials, drive consumer's choice of the packaging when relevant, and allow both consumer and sorting/recycling/waste management entities to contribute to plastic waste minimization by proper management of the used bio-based plastics. Additionally, there is a need for standardising waste collection systems and creating harmonized waste collection infrastructure, which would lead to effective sorting for bio-based plastic waste. Local and regional authorities must play a key role in implementation, administration, and monitoring of such systems.

Furthermore, there is ambiguity not only with producers or entities responsible for waste management but also with consumers who might be unaware of the variety of alternative plastics on the market, and may have a lack of knowledge on materials markings and are often confused regarding sorting of waste. Therefore, raising the awareness among customers of bio-based and biodegradable plastics will definitely have a positive impact on bioplastic market.

7. Conclusions and Discussion

To effectively manage bio-based and biodegradable plastic waste streams following influencing factors, such as effective collection and sorting separation, further appropriate treatment options must be considered. However, currently there are still economical, regulatory, technological, and social barriers, which hinder bio-based and biodegradable plastic waste management. One of the challenging factors is connected to the food-feedstock-related problems, which were highlighted similarly in other research papers [30,76]. To mitigate the impact on the food feedstock, the focus can be shifted from growing biomass and land use to the application of organic waste (agricultural and forestry) for bioplastics production. Another point of concern highlighted in current studies is low collection rates for the bioplastics, which were similarly reported by other authors [77–79]. This can be explained by consumer behaviour and their awarness of the law surrounding bio-based and biodegradable plastics properties and their treatment options [51,80].

In the research [81] of Fredy and Dorigato, recycling options for bio-based and biodegradable plastics were investigated. They divided recyling options for bioplastics into four main routes: mechanical recycling, chemical recycling, enzymatic recycling, and biodegradation, including composting and anaerobic digestion. The most promising options for biodegradable polymers, such as PLA and PHAs, were found in mechanical and chemical recycling, which coincides with the work of other authors [3,82,83].

Degradation of biodegradable plastics in different environmental media, such as marine, soil, and fresh water, depends on the chemical composition of the polymer and charcteristics of the media. However, degradation rates of bioplastics in different environments were very low: PLA blends took 4–5 years to degrade in soil and, in comparison, up to 12 years to completely degrade in aquatic media [73]. This leads to the understanding that bio-based and biodegradable plastics have to be separately collected and treated mostly under controlled, regulated conditions.

The effective plastic waste management strategy relates to good performance in each step of the waste management process; therefore, the identified barriers to the post-consumer management of bio-based and biodegradable plastics must be based on an effective strategy for the management of plastic waste. Thus, it is necessary to combine legal and other measures—efforts to improve the production process of the product, to create products with a longer life cycle, and to encourage the population to purchase and use ecological, environmentally friendly, and long-lasting products. The experience of the European Union member states shows that economic benefits, dissemination and adaptation of good practices, consumer habits, and other social changes have a significant impact on waste reduction.

Author Contributions: Conceptualization, Ž.S., L.D. and J.B.; methodology, L.D., Z.K.C., K.K. and V.V.; formal analysis, Z.K.C., L.D., Ž.S., J.B., W.L.F. and V.V.; resources, J.B., L.D., Z.K.C., K.K. and V.V.; writing—original draft preparation, L.D., Z.K.C. and V.V.; writing—review and editing, L.D., Ž.S., Z.K.C., K.K., V.V., W.L.F. and J.B.; visualization, Z.K.C. and L.D.; supervision, L.D., J.B. and Ž.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Horizon 2020 Framework Programme of the European Union—Grant Agreement N° 860407.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: This paper has been prepared as part of the "100 papers to accelerate the implementation of the UN Sustainable Development Goals" initiative.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ryberg, M.W.; Laurent, A.; Hauschild, M. Mapping of Global Plastics Value Chain and Plastics Losses to the Environment. 2018. Available online: https://wedocs.unep.org/handle/20.500.11822/26745 (accessed on 15 June 2022).
2. Plastics—The Facts 2019. An Analysis of European Plastics Production, Demand and Waste Data. 2019. Available online: https://plasticseurope.org/wp-content/uploads/2021/10/2019-Plastics-the-facts.pdf (accessed on 15 June 2022).
3. Bianco, A.; Passanant, M. Atmospheric Micro and Nanoplastics: An Enormous Microscopic Problem. *Sustainability* **2020**, *12*, 7327. [CrossRef]
4. European Academies' Science Advisory Council (EASAC). Policy Report 39, Packaging Plastics in the Circular Economy. 2020. Available online: https://easac.eu/publications/details/packaging-plastics-in-the-circular-economy/ (accessed on 15 June 2022).
5. International Energy Agency (IEA). The Future of Petrochemicals—Towards More Sustainable Plastics and Fertilisers. 2018. Available online: https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The_Future_of_Petrochemicals.pdf (accessed on 15 June 2022).
6. Zheng, J.; Suh, S. Strategies to reduce the global carbon footprint of plastics. *Nat. Clim. Chang.* **2019**, *9*, 374–378. [CrossRef]
7. Cabernard, L.; Pfister, S.; Oberschelp, C.; Hellweg, S. Growing environmental footprint of plastics driven by coal combustion. *Nat. Sustain.* **2021**, *5*, 139–148. [CrossRef]
8. Yusuf, A.A.; Ampah, J.D.; Soudagar, M.E.M.; Veza, I.; Kingsley, U.; Afrane, S.; Jin, C.; Liu, H.; Elfasakhany, A.; Buyondo, K.A. Effects of hybrid nanoparticle additives in n-butanol/waste plastic oil/diesel blends on combustion, particulate and gaseous emissions from diesel engine evaluated with entropy-weighted PROMETHEE II and TOPSIS: Environmental and health risks of plastic waste. *Energy Convers. Manag.* **2022**, *264*, 1–20. [CrossRef]
9. Tekman, M.B.; Walther, B.A.; Peter, C.; Gutow, L.; Bergmann, M. *Impacts of Plastic Pollution in the Oceans on Marine Species, Biodiversity and Ecosystems*; Worldwide Fund for Nature: Gland, Switzerland, 2022.
10. Jiang, B.; E Kauffman, A.; Li, L.; McFee, W.; Cai, B.; Weinstein, J.; Lead, J.R.; Chatterjee, S.; I Scott, G.; Xiao, S. Health impacts of environmental contamination of micro- and nanoplastics: A review. *Environ. Health Prev. Med.* **2020**, *25*, 29. [CrossRef]
11. Jambeck, J.R.; Andrady, A.; Geyer, R.; Narayan, R.; Perryman, M.; Siegler, T.; Wilcox, C.; Lavender Law, K. Plastic waste inputs from land into the ocean. *Science* **2015**, *347*, 768–771. [CrossRef]
12. Alessi, E.; Di Carlo, G. Out of the Plastic Trap Saving the Mediterranean from Plastic. Worldwide Fund for Nature Report. 2018. Available online: https://www.wwf.org.uk/sites/default/files/2018-06/WWF_Plastics_MED_WEB.pdf (accessed on 15 June 2022).
13. Lindner, C.; Beylage, H. Global Plastics Flow 2018. Converstio Market & Strategy GmbH. 2020. Available online: https://www.carboliq.com/pdf/19_conversio_global_plastics_flow_2018_summary.pdf (accessed on 15 June 2022).
14. Kamalakkannan, S.; Abeynayaka, A.; Kulatunga, A.K.; Singh, R.K.; Tatsuno, M.; Gamaralalage, P.J.D. Life Cycle Assessment of Selected Single-Use Plastic Products towards Evidence-Based Policy Recommendations in Sri Lanka. *Sustainability* **2022**, *14*, 14170. [CrossRef]
15. Nova-Institute GmbH. The Global Bio-Based Polymer Market 2019—A Revised View. 2020. Available online: https://www.bioplasticsmagazine.com/en/news/meldungen/20200127-The-global-bio-based-polymer-market-in-2019-A-revised-view.php (accessed on 15 June 2022).
16. Zhang, F.; Zhao, Y.; Wang, D.; Yan, M.; Zhang, J.; Zhang, P.; Ding, T.; Chen, L.; Chen, C. Current technologies for plastic waste treatment: A review. *J. Clean. Prod.* **2021**, *282*, 124523. [CrossRef]
17. Alassali, A.; Picuno, C.; Chong, Z.K.; Guo, J.; Maletz, R.; Kuchta, K. Towards Higher Quality of Recycled Plastics: Limitations from the Material's Perspective. *Sustainability* **2021**, *13*, 13266. [CrossRef]
18. Thiounn, T.; Smith, R.C. Advances and approaches for chemical recycling of plastic waste. *J. Polym. Sci.* **2020**, *58*, 1347–1364. [CrossRef]
19. Lamberti, F.M.; Román-Ramírez, L.A.; Wood, J. Recycling of Bioplastics: Routes and Benefits. *J. Polym. Environ.* **2020**, *28*, 2551–2571. [CrossRef]
20. Filho, W.L.; Barbir, J.; Abubakar, I.R.; Paço, A.; Stasiskiene, Z.; Hornbogen, M.; Fendt, M.T.C.; Voronova, V.; Klõga, M. Consumer attitudes and concerns with bioplastics use: An international study. *PLoS ONE* **2022**, *17*, e0266918. [CrossRef] [PubMed]
21. Popa, C.L.; Dontu, S.I.; Savastru, D.; Carstea, E.M. Role of Citizen Scientists in Environmental Plastic Litter Research—A Systematic Review. *Sustainability* **2022**, *14*, 13265. [CrossRef]
22. Horvat, D.; Wydra, S.; Lerch, C.M. Modelling and Simulating the Dynamics of the European Demand for Bio-Based Plastics. *Int. J. Simul. Model.* **2018**, *17*, 419–430. [CrossRef] [PubMed]
23. Wang, C.; Tang, J.; Yu, H.; Wang, Y.; Li, H.; Xu, S.; Li, G.; Zhou, Q. Microplastic Pollution in the Soil Environment: Characteristics, Influencing Factors, and Risks. *Sustainability* **2022**, *14*, 13405. [CrossRef]
24. European Bioplastics. Bioplastics Facts and Figures. 2021. Available online: https://docs.european-bioplastics.org/publications/EUBP_Facts_and_figures.pdf (accessed on 15 June 2022).
25. European Bioplastics. Available online: https://www.european-bioplastics.org/global-bioplastics-production-will-more-than-triple-within-the-next-five-years/ (accessed on 11 November 2022).
26. European Bioplastics. Frequently Asked Questions on Bioplastics. 2022. Available online: https://docs.european-bioplastics.org/publications/EUBP_FAQ_on_bioplastics.pdf (accessed on 15 June 2022).

27. Institute for Bioplastics and Biocomposites (IfBB). Biopolymers Facts and Statistics. 2021. Available online: https://www.ifbb-hannover.de/files/IfBB/downloads/faltblaetter_broschueren/f+s/Biopolymers-Facts-Statistics-einseitig-2021.pdf (accessed on 11 November 2022).
28. Manjunatha, M.; Seth, D.; Balaji, K.V.G.D.; Bharath, A. Engineering properties and environmental impact assessment of green concrete prepared with PVC waste powder: A step towards sustainable approach. *Case Stud. Constr. Mater.* **2022**, *17*, e01404. [CrossRef]
29. Carus, M.; Porc, O.; Chinthapalli, R. How Much Biomass Do Bio-Based Plastics Need? *Bioplastic Magazine*. 2020. Available online: https://renewable-carbon.eu/publications/product/how-much-biomass-do-bio-based-plastics-need-%E2%88%92-article-in-bioplastics-magazine/ (accessed on 15 June 2022).
30. Rujnić-Sokele, M.; Pilipović, A. Challenges and Opportunities of Biodegradable Plastics: A Mini Review. *Waste Manag. Res.* **2017**, *35*, 132–140. [CrossRef]
31. Garrido, R.; Cabeza, L.F.; Falguera, V. An Overview of Bioplastic Research on Its Relation to National Policies. *Sustainability* **2021**, *13*, 7848. [CrossRef]
32. Bioplastics Boom: Global Production Will Triple in Five Years as Asia Dominates, Finds EUBP. Available online: https://www.packaginginsights.com/news/bioplastics-boom-global-production-will-triple-in-five-years-as-asia-dominates-finds-eubp.html. (accessed on 21 November 2022).
33. Sidek, I.S.; Sarifah, F.S.D.; Siti Rozaimah, S.A.; Nornizar, A. Current Development on Bioplastics and Its Future Prospects: An Introductory Review. *Technol. Mag.* **2019**, *1*, 3–8. [CrossRef]
34. Morales, M.E.; Lhuillery, S.; Ghobakhloo, M. Circularity Effect in the Viability of Bio-Based Industrial Symbiosis: Tackling extraordinary events in value chains. *J. Clean. Prod.* **2022**, *348*, 131387. [CrossRef]
35. Döhler, N.; Wellenreuther, C.; Wolf, A. Market dynamics of biodegradable bio-based plastics: Projections and linkages to European policies. *EFB Bioeconomy J.* **2022**, *2*, 100028. [CrossRef]
36. Horvat, D.; Wydra, S. System Dynamics Modelling of the European Demand for Biobased Plastics. An Analysis Ofects and Framework Conditions on Price Competitiveness and Market Growth. In Proceedings of the XVII International Scientific Conference on Industrial Systems (IS'17), Novi Sad, Serbia, 4–6 October 2017.
37. Plastics—The Facts 2020. An Analysis of European Plastics Production, Demand and Waste Data. PlasticsEurope. 2020. Available online: https://plasticseurope.org/wp-content/uploads/2021/09/Plastics_the_facts-WEB-2020_versionJun21_final.pdf (accessed on 15 June 2022).
38. Leal Filho, W.; Saari, U.; Fedoruk, M.; Iital, A.; Harri, M.; Klöga, M.; Voronova, V. An overview of the problems posed by plastic products and the role of extended producer responsibility in Europe. *J. Clean. Prod.* **2019**, *214*, 550–558. [CrossRef]
39. Monier, V.; Hestin, M.; Cavé, J.; Laureysens, I.; Watkins, E.; Reisinger, H.; Porsch, L. Development of Guidance on Extended Producer Responsibility (EPR). Final Report. 2014. Available online: https://ec.europa.eu/environment/archives/waste/eu_guidance/pdf/Guidance%20on%20EPR%20-%20Final%20Report.pdf (accessed on 15 June 2022).
40. Seyring, N.; Dollhofer, M.; Weißenbacher, J.; Herczeg, M.; McKinnon, D.; Bakas, I. Assessment of Separate Collection Schemes in the 28 Capitals of the EU. Final Report. Copenhagen Resource Institute (CRI); BiPRO GmbH. 2015. Available online: https://publications.europa.eu/resource/cellar/2c93de42-a2fa-11e5-b528-01aa75ed71a1.0001.01/DOC_1 (accessed on 15 June 2022).
41. Picuno, C.; Alassali, A.; Chong, Z.K.; Kuchta, K. Flows of post-consumer plastic packaging in Germany: An MFA-aided case study. *Resour. Conserv. Recycl.* **2021**, *169*, 105515. [CrossRef]
42. Van Eygen, E.; Laner, D.; Fellner, J. Circular economy of plastic packaging: Current practice and perspectives in Austria. *Waste Manag.* **2018**, *72*, 55–64. [CrossRef]
43. Dahlbo, H.; Poliakova, V.; Mylläri, V.; Sahimaa, O.; Anderson, R. Recycling potential of post-consumer plastic packaging waste in Finland. *Waste Manag.* **2018**, *71*, 52–61. [CrossRef]
44. Calabrese, A.; Costa, R.; Levialdi Ghiron, N.; Menichini, T.; Miscoli, V.; Tiburzi, L. Operating modes and cost burdens for the European deposit-refund systems: A systematic approach for their analysis and design. *J. Clean. Prod.* **2021**, *288*, 125600. [CrossRef]
45. Zhou, G.; Gu, Y.; Wu, Y.; Gong, Y.; Mu, X.; Han, H.; Chang, T. A systematic review of the deposit-refund system for beverage packaging: Operating mode, key parameter and development trend. *J. Clean. Prod.* **2019**, *251*, 119660. [CrossRef]
46. Glerean, P. Differences in Sorting and Recycling in Europe. Delara Burkhardt; German Environment Agency. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/421/dokumente/presentation_3._glerean_pre.pdf (accessed on 15 June 2022).
47. Jansen, M.; van Thoden Velzen, U.; Pretz, T. Handbook for Sorting of Plastic Packaging Waste Concentrates. Wageningen UR Food & Biobased Research. 2015. Available online: https://research.wur.nl/en/publications/handbook-for-sorting-of-plastic-packaging-waste-concentrates-sepa (accessed on 15 June 2022).
48. Institute Cyclos-HTP. Verification and Examination of Recyclability. Requirements and Assessment Catalogue of the Institute Cyclos-HTP for EU-Wide Certification. Institute Cyclos-HTP. 2021. Available online: https://www.cyclos-htp.de/publications/r-a-catalogue/#:~{}:text=Recycling%20is%20an%20important%20element,instrument%20of%20applied%20product%20responsibility (accessed on 15 June 2022).

49. Picuno, C.; van Eygen, E.; Brouwer, M.T.; Kuchta, K.; van Thoden Velzen, E.U. Factors Shaping the Recycling Systems for Plastic Packaging Waste—A Comparison between Austria, Germany and The Netherlands. *Sustainability* **2021**, *13*, 6772. [CrossRef]
50. Vollmer, I.; Jenks, M.J.F.; Roelands, M.C.P.; White, R.J.; Harmelen, T.; Wild, P.; Laan, G.P.; Meirer, F.; Keurentjes, J.T.F.; Weckhuysen, B.M. Beyond Mechanical Recycling: Giving New Life to Plastic Waste. *Angew. Chem. Int. Ed.* **2020**, *59*, 15402–15423. [CrossRef]
51. Dilkes-Hoffman, L.S.; Pratt, S.; Lant, P.A.; Laycock, B. 19—The Role of Biodegradable Plastic in Solving Plastic Solid Waste Accumulation. In *Plastics to Energy*; William Andrew Publishing: Norwich, NY, USA, 2019. [CrossRef]
52. Lange, J.-P. Managing Plastic Waste—Sorting, Recycling, Disposal, and Product Redesign. *ACS Sustain. Chem. Eng.* **2021**, *9*, 15722–15738. [CrossRef]
53. Ljungkvist Nordin, H.; Westöö, A.-K.; Boberg, N.; Fråne, A.; Guban, P.; Sörme, L.; Ahlm, M. Mapping of Plastic Flows in Sweden (Kartläggning av Plastflöden i Sverige). SMED-Rapport nr 1. 2019. Available online: https://www.naturvardsverket.se/globalassets/media/publikationer-pdf/8800/978-91-620-8854-5.pdf. (accessed on 15 June 2022).
54. Woodard, R.; Harder, M.K.; Bench, M. Participation in curbside recycling schemes and its variation with material types. *Waste Manag.* **2006**, *26*, 914–919. [CrossRef] [PubMed]
55. Martinho, G.; Gomes, A.; Santos, P.; Ramos, M.; Cardoso, J.; Silveira, A.; Pires, A. A case study of packaging waste collection systems in Portugal—Part I: Performance and operation analysis. *Waste Manag.* **2017**, *61*, 108–116. [CrossRef] [PubMed]
56. Niaounakis, M. Recycling of biopolymers—The patent perspective. *Eur. Polym. J.* **2019**, *114*, 464–475. [CrossRef]
57. Spierling, S.; Röttger, C.; Venkatachalam, V.; Mudersbach, M.; Herrmann, C.; Endres, H.-J. Bio-based Plastics—A Building Block for the Circular Economy? *Procedia CIRP* **2018**, *69*, 573–578. [CrossRef]
58. Van den Oever, M.; Molenveld, K.; Van der Zee, M.; Bos, H. Bio-Based and Biodegradable Plastics—Facts and Figures. Focus on Food Packaging in The Netherlands. Wageningen Food & Biobased Research. 2017. Available online: https://www.wur.nl/upload_mm/1/e/7/01452551-06c5-4dc3-b278-173da53356bb_170421%20Report%20Bio-based%20Plastic%20Facts.pdf (accessed on 15 June 2022).
59. Consorzio Italiano Compostatori. Paper and Bioplastics: Monitoring of Compost Friendly Materials. Carta e Bioplastiche: Il Monitoraggio dei Materiali Amici del Compost. Available online: http://www.compostabile.com/carta-e-bioplastiche-il-monitoraggio-dei-materiali-amici-del-compost/ (accessed on 15 June 2022).
60. Italian Composting and Biogas Association. Annual Report on Biowaste Recycling. Italian Composting and Biogas Association. 2017. Available online: https://www.compost.it/wp-content/uploads/2019/08/Rapporto-CIC-2017-Eng-v-2.6-web-version.pdf (accessed on 15 June 2022).
61. Umweltbundesamt. Bio-Based and Biodegradable Plastics. 2020. Available online: https://www.umweltbundesamt.de/biobasierte-biologisch-abbaubare-kunststoffe#haufig-gestellte-fragen-faq (accessed on 15 June 2022).
62. UNEP. Plastics: Single-Use Plastics: A Roadmap for Sustainability. 2018. Available online: https://www.unep.org/resources/report/single-use-plastics-roadmap-sustainability (accessed on 15 June 2022).
63. UNEP. Basel Convention on the Control of Transboundary Movement of Hazardous Wastes. 2011. Available online: https://wedocs.unep.org/20.500.11822/8385 (accessed on 15 June 2022).
64. United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development. 2015. Available online: https://sustainabledevelopment.un.org/post2015/transformingourworld/publication (accessed on 15 June 2022).
65. European Commission. Closing the Loop—An EU Action Plan for the Circular Economy. 2015. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614 (accessed on 15 June 2022).
66. European Commission. A New Circular Economy Action Plan. For a Cleaner and More Competitive Europe. 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0098 (accessed on 15 June 2022).
67. European Commission. Communication from the Commission. The European Green Deal. 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640 (accessed on 15 June 2022).
68. European Commission. Directive (EU) 2019/904 of the European Parliament and of the Council. On the Reduction of the Impact of Certain Plastic Products on the Environment. 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590979695787&uri=CELEX:32019L0904 (accessed on 15 June 2022).
69. European Commission. Single-Use Plastics. 2021. Available online: https://environment.ec.europa.eu/topics/plastics/single-use-plastics_en (accessed on 28 November 2022).
70. The EU in 2021. General Report on the Activities of the European Union. 2022. Available online: https://op.europa.eu/webpub/com/general-report-2021/en/ (accessed on 28 November 2022).
71. European Commission. Policy Framework on Biobased, Biodegradable and Compostable Plastics. 2021. Available online: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13138-Policy-framework-on-biobased-biodegradable-and-compostable-plastics_en (accessed on 28 November 2022).
72. OECD. *Policies for Bioplastics in the Context of a Bioeconomy*; OECD Science, Technology and Industry Policy Papers, No. 10; OECD Publishing: Paris, France, 2013. Available online: https://www.oecd-ilibrary.org/science-and-technology/policies-for-bioplastics-in-the-context-of-a-bioeconomy_5k3xpf9rrw6d-en (accessed on 28 November 2022).
73. European Commission. Regulation (EC) No 66/2010 of the European Parliament and of the Council on the EU Ecolabel. 2009. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02010R0066-20171114&qid=1590991576604&from=EN (accessed on 15 June 2022).

74. *ISO 14024*; Environmental Labels and Declarations—Type I Environmental Labelling—Principles and Procedures. European Union: Brussels, Belgium, 2018. Available online: https://www.iso.org/standard/72458.html (accessed on 15 June 2022).
75. Senthilkumaran, A.; Babaei-Ghazvini, A.; Nickerson, M.T.; Acharya, B. Comparison of Protein Content, Availability, and Different Properties of Plant Protein Sources with Their Application in Packaging. *Polymers* **2022**, *14*, 1065. [CrossRef]
76. Mülhaupt, R. Green Polymer Chemistry and Bio-based Plastics: Dreams and Reality. *Macromol. Chem. Phys.* **2013**, *214*, 159–174. [CrossRef]
77. Cucina, M.; de Nisi, P.; Tambone, F.; Adani, G. The role of waste management in reducing bioplastics' leakage into the environment: A review. *Bioresour. Technol.* **2021**, *337*, 125459. [CrossRef] [PubMed]
78. Taufik, D.; Reinders, M.J.; Molenveld, K.; Onwezen, M.C. The paradox between the environmental appeal of bio-based plastic packaging for consumers and their disposal behavior. *Sci. Total Environ.* **2019**, *705*, 135820. [CrossRef]
79. Magnier, L.; Crié, D. Communicating packaging eco-friendliness: An exploration of consumers' perceptions of eco-designed packaging. *Int. J. Retail. Distrib. Manag.* **2015**, *43*, 350–366. [CrossRef]
80. Sijtsema, S.J.; Onwezen, M.C.; Reinders, M.J.; Dagevos, H.; Partanen, A.; Meeusen, M. Consumer perception of bio-based products—An exploratory study in 5 European countries. *NJAS -Wagening. J. Life Sci.* **2016**, *77*, 61–69. [CrossRef]
81. Fredi, G.; Dorigato, A. A Recycling of bioplastic waste: A review. *Adv. Ind. Eng. Polym. Res.* **2021**, *4*, 159–177. [CrossRef]
82. Piemonte, V.; Sabatini, S.; Gironi, F. Chemical recycling of PLA: A great opportunity towards the sustainable development? *J. Polym. Environ.* **2013**, *21*, 640–647. [CrossRef]
83. Rivas, L.F.; Casarin, S.A.; Nepomuceno, N.C.; Alencar, M.I.; Agnelli, J.A.M.; De Medeiros, E.S.; Neto, A.D.O.W.; Oliveira, M.; De Medeiros, A.M.; E Santos, A.S.F. Reprocessability of PHB in extrusion: ATR-FTIR, tensile tests and thermal studies. *Polímeros* **2017**, *27*, 122–128. [CrossRef]