

Article

Effect of Bio-Based Products on Waste Management

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Received: 21 February 2020; Accepted: 27 February 2020; Published: 9 March 2020



Abstract: This article focuses on the end-of-life management of bio-based products by recycling, which reduces landfilling. Bio-plastics are very important materials, due to their widespread use in various fields. The advantage of these products is that they primarily use renewable materials. At its end-of-life, a bio-based product is disposed of and becomes post-consumer waste. Correctly designing waste management systems for bio-based products is important for both the environment and utilization of these wastes as resources in a circular economy. Bioplastics are suitable for reuse, mechanical recycling, organic recycling, and energy recovery. The volume of bio-based waste produced today can be recycled alongside conventional wastes. Furthermore, using biodegradable and compostable bio-based products strengthens industrial composting (organic recycling) as a waste management option. If bio-based products can no longer be reused or recycled, it is possible to use them to produce bio-energy. For future effective management of bio-based waste, it should be determined how these products are currently being managed. Methods for valorizing bio-based products should be developed. Technologies could be introduced in conjunction with existing composting and anaerobic digestion infrastructure as parts of biorefineries. One option worth considering would be separating bio-based products from plastic waste, to maintain the effectiveness of chemical recycling of plastic waste. Composting bio-based products with biowaste is another option for organic recycling. For this option to be viable, the conditions which allow safe compost to be produced need to be determined and compost should lose its waste status in order to promote bio-based organic recycling.

Keywords: polymers; bioplastic; recycling; biodegradable waste; compostable waste; waste collection

1. Bio-Based products

Biopolymers are one of the fastest growing segments within the global plastics market, in wake of plastic pollution increasing around the world. So far, in more than 60 countries, bans and levies have been introduced to limit single-use plastic waste. This plastic refers to disposable plastics, that are commonly used for plastic packaging and include items intended to be used only once. Considering the broad range of actions to limit single-use plastics, a 10-step roadmap for governments has been drawn, in which one of the main points is to change the use of plastic into biodegradable materials. The limitation of the use of single-use plastics may cause an increase in interest of using alternative materials, such as bio-based products [1].

Biopolymers (or bioplastics) are plastics that can be produced from renewable materials, including sugar, corn, soy, hemp, and captured methane from waste. Biopolymers do not have to be made entirely out of renewable materials, as many produced today are blends of conventional and renewable feedstocks [2]. Furthermore, some biopolymers such as Bio-PET have an identical polymeric structure as their conventional counterpart and can be recycled along with fossil-based plastics of the same resin. With such a variety of feedstocks and manufacturing processes, not all biopolymers are biodegradable

or compostable [3,4]. Plastics can be classified into four categories considering their biodegradability and raw materials (Table 1) [5].

Table 1. Plastics classification [5].

	Bio-based Plastics (Renewable Resources)	Oil-based Plastics (Fossil Resources)
Biodegradable plastics	poly(lactic acid) (PLA) polyhydroxyalkanoate (PHA) polysaccharide derivatives (low degree of substitution) poly(amino acid)	poly(ϵ -caprolactone) (PCL) poly(butylene succinate/adipate) (PBS/A) poly(butylene adipate-co-terephthalate) (PBA/T)
Non-biodegradable plastics	polysaccharide derivatives (high degree of substitution) polyol-polyurethane bio-polyethylene (bio-PE) bio-poly(ethylene terephthalate) (bio-PET)	polyethylene (PE) polypropylene (PP) polystyrene (PS) poly(ethylene terephthalate) (PET)

Polyethylene (PE), polypropylene (PP), and poly(ethylene terephthalate) (PET), are typical oil-based non-biodegradable plastics [6]. Bio-based plastics are considered to be biodegradable. However, polysaccharide derivatives with a high degree of substitution (DS), for example, cellulose acetate, which is used in films and filters, are not biodegraded in the environment. Though, cellulose is a natural polysaccharide and completely degraded by cellulase. Bio-PE is synthesized from bio-ethanol, which is produced by the fermentation of glucose. Recently, Bio-PET has also been produced from biomass by using bio-based ethylene glycol. The biomass content in Bio-PET is approximately 30%. Bio-PET is of course not biodegradable. Thus, bio-based plastics are not necessarily also biodegradable [5].

Although the term “biopolymer” can be used to refer to naturally occurring long-chain molecules, such as cellulose, polysaccharides, proteins, and DNA, the definition of the term has been extended to include bio-based materials made or derived from these natural polymers. Some bio-based materials differ from synthetic polymers, in that they can be decomposed by bacteria, fungi, or other organisms into natural metabolic products [7].

In this, they are similar to naturally produced biopolymers, like polysaccharides (e.g., starch, cellulose, lignin, and chitin), proteins (e.g., gelatine, casein, wheat gluten, silk and wool), and lipids (e.g., plant oils and animal fats), which are all biodegradable. Other examples of economically useful, biodegradable natural products are natural rubber and certain polyesters produced by microorganisms or plants (e.g., polyhydroxyalkanoates (PHA) and poly-3-hydroxybutyrate (PHB)) or synthesized from bio-derived monomers (e.g., polylactic acid (PLA)).

The applications of PLA include clear and opaque rigid plastics for packaging, disposable goods, durable goods, and bottles, as well as films and fibers for a variety of purposes [8,9]. PLA can be blended with petroleum-based polymers or fibers, either synthetic or natural, to improve the heat resistance or durability of the plastic [10]. PLA-based plastics can be biodegradable and compostable, features that offer a wider variety of options for disposal [11]. PHA is being used in more niche applications in medicine to agriculture. PHA be combined with other materials to form composites with improved properties. PHA is biodegradable and can be used to create compostable plastics [12]. Another biopolymer is thermoplastic starch (TPS). It is created using the starch polymers from renewable sources, primarily corn, which is then processed and combined with additives and formed into shape. TPS is incorporated into composites with synthetic polymers.

Other plant-based materials in the polymer industry are bio-based 1,3-propanediol (PDO) and bio-based polyethylene terephthalate (B-PET). Current applications of polymers made with PDO include carpeting, apparel, and films. B-PET is combined bio-based ethylene and other petroleum-based feedstocks and used in clear plastic bottles. The ethylene portion is produced from corn fermentation

similar to the corn ethanol process, and synthesized in the same process as PET. This results in a product identical to traditional PET that is recyclable but not biodegradable [4].

Bio-based polymers may be biodegradable (e.g., PLA, PHAs, polysaccharides (starch and cellulose)) or durable (e.g., bio-polyethylene terephthalate (bio-PET), bio-Polyethylene (bio-PE), bio-polyurethane (bio-PUR), bio-polypropylene (bio-PP), bio-polyamide (bio-PA) etc.), depending on their chemical structure. There are three major commercialized bio-based polymers: bio-based polyethylene terephthalate (beverage bottles); polylactic acid (single-use cups, single-use cutlery, packaging films), and starch plastics (clips, mulch films, and carrier bags).

Biodegradable polymers are converted to carbon dioxide, mineral salts, and water due to the action of microorganisms and enzymes under aerobic and specific environmental conditions. This process may take place in both the natural environment and in composting facilities. The terms of "biodegradable" and "compostable" can be confusing. "Biodegradable" polymer means that it can be biologically degraded, but without time limits (process is very slow and can take up to years). However, "compostable" means that polymers are biodegraded within a composting time frame and the mineralization process starts within the period required for biodegradation of biowaste (e.g., green waste, organic kitchen waste). Only in the case of compostable polymers, no substances with an unknown impact on the environment will be introduced into the environment. From the point of view of waste management, the time of biodegradation affects the right treatment when it becomes waste [13].

The European market for biodegradable bio-based products is dominated by compostable plastic bags, which are primarily used for shopping or biowaste collection. In 2015, these bags comprised about two-thirds of the total market of approximately 100,000 t of biodegradable plastic products sold. By 2020, the market for compostable and biodegradable plastic products could grow to beyond 300,000 tones, provided that the legal framework is adjusted to favor their production and sales [14].

Bio-based products are considered to have the advantage of being environmentally friendly, but they also have some disadvantages, such as high production costs and poor mechanical properties. It is possible, however, to reduce production costs by utilizing low-cost renewable resources, such as agricultural wastes, for producing these products [15].

The main applications of bio-based and biodegradable plastics are currently in (food) packaging, food service ware, (shopping) bags, fibers/nonwovens, and agricultural applications. Bio-based drop-in plastics such as Bio-PE and Bio-PET are identical to their fossil-hydrocarbon-based counterparts and can be used in exactly the same applications.

The following should be considered wasted bio-based products: biowaste bags, shopping bags, flexible packaging, rigid packaging, disposable tableware, coated paper/board, equipment for agriculture, aquaculture and forestry, consumer goods, fiber-based products, technical equipment, and the polymers used for producing these products. The use of bioplastics for packaging is growing by 20–25% per year, indicating that bio-based materials are increasingly viewed as a viable alternative for fossil-based materials [16], even more so when bio-based materials are biodegradable [17].

At its end-of-life, a bio-based product is disposed of and becomes post-consumer (PC) waste. During collection, a distinction is made between post-consumer and post-industrial bio-based waste (PI). Post-consumer waste is produced by the consumer and is often collected together with other municipal solid residual waste (MSRW). Post-industrial bio-based waste is produced by companies, and includes off-spec products and cutting waste. Typically, plastic waste consists of mixed bio-based waste of unknown composition, and it can be contaminated by organic fractions (such as food remains or paper) or non-polymer inorganic fractions, which makes it a more complex stream to recycle than post-industrial (PI) waste.

In treating PC and PI wastes, mechanical-biological treatment plants (MBT) play an important role. MBT plants are designed to prepare residual municipal waste for landfilling by stabilizing the organic substances that they contain. This is accomplished by aerobic or anaerobic stabilization after mechanically separating the biodegradable fraction from the residual waste. The material fractions,

such as paper, plastics, metals, and glass, are separated from residual waste by manual and automatic separation. In MBT plants, valorization of the selectively collected material and biowaste takes place by manual, automated separation followed by composting or anaerobic digestion [18,19]. Thus, any statements about the end-of-life of bio-based products are only valid if they take into consideration the availability of appropriate waste management infrastructures and facilities. Importantly, bio-based wastes are often commingled with organic wastes like food scraps, wet paper, yard trimmings, soil, and liquids. This makes it difficult and impractical to recycle the organic wastes, the bio-based wastes, or both fractions without expensive cleaning, separation, and sanitizing procedures. To clarify the challenges involved in recycling these fractions, this paper discusses management of bio-based wastes with a focus on recycling the organics and the bio-based materials.

2. Collection

Post-consumer waste collection is one of the most visible activities in a waste management system and thus highly valued by the public. Around the world, various waste collection systems are used. Although Dahlén and Lagerkvist [20] classify these systems as either drop-off point and property-close collection systems, Mbande [21] has pointed out that waste collection systems for households differ throughout the world. In drop-off collection systems, residents need to deliver recyclables to drop-off centers [22]. Property-close collection systems can be categorized into curbside collection systems and door-to-door collection systems. Finally, a buy-back collection system is a waste collection system based on waste recovery and recycling centers. From the point of view of Gallardo et al. [23] and Gallardo et al. [24], the best system combines aspects of two categories, in that mixed waste, organic material, and multiproduct waste are collected door-to-door, whereas glass is delivered to drop-off points. Thus, strictly classifying waste collection systems can be a challenge. Although currently existing collection systems separate household waste into categories such as glass, paper, metal, plastic, and biowaste (kitchen and garden waste), they do not separate bio-based products from the others because this new type of material constitutes 0.5% or less of total lightweight packaging waste collected from households.

If the bio-based waste is considered a fraction of the biowaste, some available technologies can be employed to utilize this waste, provided certain conditions are met [25]. Bio-based wastes can be collected with other plastics, residual waste, or organic waste. Assuming the sorting instructions for bio-based wastes are followed, they then will be selectively collected. After selective collection, this waste can be recycled if adapted sorting equipment is available, along with a sufficient quantity of good quality homogenous material, an existing sustainable recycling infrastructure and an outlet for the recycled material. If bio-based wastes are treated as a fraction of the residual waste, they can be incinerated with energy recovery, separated from household waste for combustion along with other residual waste with high calorific value, or separated for use as a reducing agent in blast furnaces. If bio-based wastes are considered a fraction of plastic waste, they can be used as a feedstock for recycling of materials. This requires separate collection of these wastes, sorting, cleaning, and mechanical recycling.

Regarding municipal solid waste, mixed plastic from municipal solid waste, and particularly household waste (HHW), these are highly heterogeneous waste streams, as they include a variety of different immiscible polymers, product types, and designs [26,27]. The method by which plastic waste is collected has little influence on the final quality of the recyclate, rather, the sorting and reprocessing steps have the major influence on the final quality. Although the mechanical properties of the recyclate clearly differ from those of virgin polymers, these properties can be improved by changes to the sorting and reprocessing steps [28].

To introduce bio-based products on the market, the mentality and behavior of society will need to change. Meeks et al. [29] identified and studied where consumers are most likely to come into contact with compostable biopolymers, current disposal methods for these bio-based products, and the motivation behind compostable bio-based product use and disposal. Consumers are most

likely to encounter compostable biopolymers in a commercial food service setting. The decision to purchase compostable biopolymers was based on a variety of factors, such as their perceived sustainability, but was not directly tied to the ability to compost them. One of the clearest distinctions between those who were able to compost biopolymers and those who sent these products to a landfill was the type of sustainability goals that each organization had set. The consumers' knowledge on packaging disposal labels turns out to be limited and currently different label schemes exist in different countries [30], all involved actors (i.e., producers, retailers, and policymakers) should take action to develop communication tools that provide consumers with the knowledge needed to make an informed disposal choice. Collection and sorting largely determine the efficiency of waste management systems. This implies that consumers and their behavior are an important factor for waste processing efficiency. As disposal of bio-based waste can be confusing for consumers, pictograms have been introduced to indicate the preferred disposal route. There are so many labels that they may merely confuse, rather than inform, consumers. European standards are currently being developed to provide guidance on how to communicate information about bio-based products to consumers (EN 16935:2017. Bio-based products–B2C reporting and communication–Requirements for claims) and in business to business relations (EN 16848:2016 Bio-based products–Requirements for business to business communication of characteristics using a Data Sheet) [31].

3. Separation and Mechanical and Chemical Recycling

Recycling is an industrial process that treats materials and products so that they can be used again. In recycling, new raw materials are obtained via mechanical means (typically leading to re-granulated products) or chemical means (typically leading to monomer building blocks). The overwhelming part of the bio-based waste volume produced today can easily be recycled alongside their conventional counterparts in separate recycling streams, assuming that these streams are present (e.g., bio-based PE from the PE-stream or bio-based PET from the PET-stream). This way, bio-based waste can contribute to meeting higher recycling quotas. Recycling of plastic waste and bio-based waste that is classified as mechanical recycling involves the recovery of waste through mechanical processes (separating, grinding, washing, drying, re-granulating, and compounding) to produce recyclates that can be converted into new products. Unlike mechanical recycling, organic and chemical recycling aim to reuse plastics and bio-based waste as sources of carbon and biogenic substances for the synthesis of new materials. Valorization of bio-based waste from post-consumer wastes is more complex than valorization of bio-based wastes from industrial sources because it involves separating bio-based waste from plastic waste. For example, PLA is an attractive material for the packaging of food products like lettuce or bread because of its high permeability to water, and it is also used in bottles to a modest extent. When it comes to separating PLA from PET, however, visual discrimination based on appearance is not possible because both materials are transparent and very similar. Thus, if consumers are to separate bio-based PLA from PET, extra labeling is necessary.

- Moreover, although PLA is potentially recyclable, no separate recycling stream for PLA yet exists. It is crucial to sort out bio-based plastics from PET to avoid affecting the recycling of PET (yield and quality) and also to recover single streams of materials like PLA in order to recycle them. PLA requires a much lower transition temperature than PET, which means that, at the drying temperature for PET, PLA flakes melt and clump. Furthermore, 2% and 5% PLA concentrations in the PET stream cause agglomeration and sticking to dryer walls. As little as 0.1% PLA results in significant opacification of recycled PET, and in concentrations higher than 0.3%, PLA causes yellowing of PET [32]. When recycling other materials, the share of PLA that is mixed in with those materials also needs to be limited. For example, up to 3 weight percent of PLA in post-consumer recyclates and up to 10 percent of PLA in PS (polyolefin) re-granulates do not disturb or negatively affect the quality of the recycled material. Higher proportions of PLA in post-consumer waste would encourage the establishment of separate PLA recycling streams, as they would become economically feasible [33] (<https://www.european-bioplastics.org/pla-in-the-waste-stream/>).

However, methods for separating PLA from other plastics are still not efficient. The best available method is NIR (near-infrared spectroscopy). The use of static processes for separating and/or pre-concentrating plastics for recycling is limited in terms of the capacity and size of material that it can treat commercially. For this reason, Gent et al. [34] reviewed methods for improving the separation of plastics that involve cylindro-conical and cylindrical cyclone-type media separators.

Questions remain about other bio-based plastics as well. For example, it still needs to be determined the number of times PHBV (poly(3-hydroxybutyrate-co-3-hydroxyvalerate), PLA, and PHBV/PLA blends can be recycled before they lose their desirable properties. According to Zembouai et al. [35], after 6 cycles of mechanical recycling, PLA was less affected than PHBV, which was significantly degraded. Thus, the mechanical properties of PLA and PHBV/PLA blends are less affected by six cycles of recycling than unblended PHBV, which exhibits a reduction in these properties. It should also be remembered that, in many applications, PHA will not be recycled because, for example, agricultural foils will biodegrade in the field, and medical waste in general does not end up in the selectively collected household waste streams destined for recycling.

The addition of starch or natural fibers to traditional polymers can complicate recycling processes [36,37]. It can be expected that bio-based plastics could disturb the current mechanical recycling of plastics and hence inhibit the closure of plastic cycles. In chemical recycling, the polymer chain molecules are broken down into smaller hydrocarbon molecules (e.g., monomers), which are then fed into the polymerization process. Regarding the energy balance as well as costs, these processes stand between pure re-melting and combustion [38]. Two main processes have been used for chemical recycling of PLA. The first one is hydrolysis of PLA at high temperatures to obtain lactic acid and the second one is thermal degradation of PLA to prepare L,L-lactide, which is a cyclic dimer and can be used for polymerization of new PLA [39]. The chemical recycling process that breaks down PLA into lactic acid is called hydrolysis, and requires the presence of water as well as high temperature. The obtained lactic acid has a high purity and can be polymerized to virgin PLA. This recycled PLA closes the loop and the process may be called a cradle-to-cradle process [40].

Chemical recycling of bioplastic blends has also been investigated because of the limitations of the mechanical recycling method, especially the required sorting, thermomechanical degradation of polymers, and sensitivity to material impurities. For example, PLA and PET cannot be easily or cheaply sorted by sight or by separation methods based on density, which are not efficient enough because of the similar densities of the polymers. Recycling of bio-based waste is environmentally beneficial. The life cycle assessment confirmed that mechanical recycling as well as feedstock recycling bio-based waste contributes to a reduction of environmental impacts due to the substitution of virgin material. Furthermore, recycling bio-based wastes shows environmental benefits in almost all investigated impact categories compared to the application for energy recovery.

4. Organic Recycling

Certified bio-based products are designed intentionally to be recovered by means of organic recycling. Furthermore, using compostable bio-based waste's bags, food packaging, and cutlery strengthens industrial composting (organic recycling) as a waste management option and helps to increase waste management efficiency. In order to be suitable for organic recycling, bio-based wastes need to meet the criteria of the European norm EN 13432 on industrial compostability.

Bio-based waste that is selectively collected with biowaste requires mechanical pretreatment before organic recycling. The purposes of mechanical treatment of organic waste are the following: separation of mis-sorted materials like bags for waste collection, separation of supermarket food packaging, reduction of particle sizes to <12 mm for better bioavailability, and mixing of different organic substrates for optimal dry matter content and C/N-ratio [41].

Research on the recycling of bio-based materials, especially bio-blends and bio-composites, is still at a preliminary stage and lacks a deep understanding of the different factors affecting the performance, economy, and sustainability of recycled bioplastics.

Composting is a process highly valued in municipal solid waste management owing to its robustness and the possibility of obtaining a valuable product with that can be used as a soil amendment. It is a widely used technology for transforming organic waste to compost, thus recycling mineral nutrients (nitrogen (N), phosphorus (P), and potassium (K)) that can be utilized for agricultural purposes [42]. A primary benefit of compost from selectively collected biowaste (MSW) is its high organic matter content and low bulk density. A survey of MSW compost reported that, on average, 20% of the total C in MSW compost was organic C, 8% carbonate C, and 71% residual C, which may have included organic C components. The majority of the humic substances found in MSW compost were identified as humic acids, with a humic acid to fulvic acid ratio of 3.55 [43]. Selectively collected biowaste compost had a high water holding capacity because of its organic matter content, which in turn improved the water holding capacity of the soil [44].

Some studies were conducted to improve the biodegradability of bio-based waste in a compost environment. For instance, increasing the content of soluble sugar in the biowaste through the addition of materials containing high protein content enhanced the biodegradability of bio-based waste. In order to increase the biodegradability of PBS poly(butylene succinate) bioplastic, biofuel byproducts were added to the composting mixture. It was observed that a mixture of PBS and meal-based filler biodegraded more quickly than pure bioplastic, which was attributed to the high concentration of soluble sugars in meal-based fillers [45]. The presence of corn in PLA/corn bioplastic may enhance its biodegradation in compost because corn is a highly biodegradable material. Thus, microorganisms could degrade the material and the PLA fraction more efficiently [46]. PLA pots in with poultry feather fibers (PFF) had a higher rate of deterioration than PLA pots alone. This might be related to the substances used in molding and extruding the PLA pot, which could inhibit biodegradation [47].

In a large-scale study from March 2001, in Kassel, Germany, biodegradable packaging was introduced into the local retail trade. The compost feedstock was monitored to ensure a relatively low proportion of one plastic to 99 parts organic waste on a weight basis. The compost produced showed no differences in terms of quality parameters compared with conventional compost comprising solely green and kitchen waste and had the same positive effects on soil and plant characteristics [48].

The home composting is an option in managing biowaste at local levels. It must be noted that it is difficult to regulate home composting, and anaerobic composting conditions occurring in poorly managed systems will result in the generation of methane. Temperature conditions do not reflect composting process principles which require them, by definition, to go through a thermophilic phase (55–65 °C) that can last from a few days to a couple of months depending on the composting volume. The thermophilic phase of composting is of importance to ensure the destruction of thermo sensitive pathogens, fly larvae, and weed seeds. Home composting using compost bins or heaps is more variable and less optimized than industrial composting and the temperature achieved is rarely more than a few degrees Celsius above ambient temperature [49]. There is some debate about the degree to which biodegradable bio-based waste that is certified with the Seedling logo can be composted in industrial composting installations.

The general opinion is that when the characteristics of bio-based products are in line with the EN 13432 standard, they can be composted by industrial composters, but should not be composted in home installations.

Due to its organic- and nutrient-rich composition, selectively collected biowaste can be utilized as a useful resource for production of biofuel through various fermentation processes. Valorization of biowaste has attracted increasing interest, with biogas, hydrogen, ethanol, and biodiesel as final products. Anaerobic digestion is becoming increasingly popular as a means of processing biowaste for energy and fertilizer recovery. Besides heat and power production, new applications of biogas have emerged in recent years. Conversion of biogas to biomethane is already a strategic target. Biomethane can be produced via the biogas production, which includes the anaerobic digestion of wet biowaste and a successive upgrading of obtained biogas, with good environmental performance. The existing plant assumed as reference treats 100 t/d of the organic waste, as obtained by separate collection. It includes a

wet digester, continuously operated under mesophilic regime at 37–39 °C, and a membrane separation unit that upgrades the obtained 583 m³ N/h of raw biogas to 302 m³ N/h of biomethane, ready to be injected into the natural gas grid [50]. The utilized wet biowaste in an anaerobic digester to produce biogas that is then upgraded to biomethane is recommended as a solution for organic recycling.

Regarding the current level of the presence of bio-based waste in the stream of the biowaste according Zhang et al. [51], it is not possible to quantify additional biomethane production as a result of bio-based waste addition in the semi-continuous digestion trial, even where a high degree of degradation of the bio-based waste was observed, as the relative proportion of gas production from the bioplastics is low in comparison to that from food waste. This is inevitable unless a much higher plastics loading is used than is likely to occur in a real mixed biowaste stream.

If bioplastics can no longer be reused or recycled, it is nevertheless possible to use them in the production of bio-energy.

5. Waste-to-Energy (WTE)

The processes in waste-to-energy (WTE) incineration would not be substantially affected by whether the input plastic is degradable or not, because 56% of all energy resulting from WTE incineration comes from biogenic organic municipal solid waste (MSW), and so combustion of MSW produces energy that is at least half-derived in a way that does not increase the amount of CO₂ in the biosphere. In other words, incineration of bio-based waste emits CO₂ which was recently captured and will be captured again when new bio-based products are produced, whereas incineration of fossil plastics emits CO₂ that had been sequestered for millions of years. Therefore, bio-based plastics may be a good alternative to fossil plastics which are incinerated at end-of-life, e.g., laminates or plastics with low volumes [31].

Another way to produce the energy from waste is solid recovered fuel (SRF) prepared from non-hazardous waste. SRF is utilized for energy recovery in incineration/co-incineration plants and must meet European requirements [EN 15359 Solid Recovered Fuels—Specifications and Classes]. This distinguishes SRF from refuse derived fuel (RDF), as RDF is not manufactured in compliance with CEN standards. SRF/RDF production from municipal solid waste provides an alternative to fossil fuels. SRF/RDF is used industrially in gasification and combustion processes as fuel/co-fuel for the production of electricity and heat [52]. Bio-based waste can be one of the feedstocks for SRF production, although limits on polluting and toxic elements in SRF/RDF need to be kept in mind.

6. Biowaste for Fuels and Chemicals

Bio-based waste and biowaste can be used for fuel production, and this novel approach is gaining ground as a method of waste management. Methods for producing fuel from these wastes involve both biological and thermochemical conversions. Thermochemical methods of biowaste utilization involve gasification, pyrolysis, torrefaction, and hydrothermal carbonization [53]. Gasification is a new approach in biowaste management, in which dry or semi-dry feedstock is pyrolyzed in a gasifier to produce syngas, which is then cleaned, conditioned, and sent for methanation. According to Ardolino et al. [54], the syngas strategy shows better environmental performance and higher levels of carbon utilization than fossil fuel production for road transportation. However, its technology readiness level is still too low, and it appears to be economically viable only for plants with a capacity of 200 MW biomethane or more. On the other hand, syngas production seems to have more potential for improvement, including the possibility of producing not only biomethane, but also chemicals with higher added-value [55].

Biological methods include the production of fuels (e.g., ethanol, biogas, hydrogen, and butanol), biopesticides, oils from microalgae, and enzymes (such as amylases, carbohydrases, pectinases, and lipases). The use of biowaste for the production of H₂ is another alternative for the conversion of biowaste to a high-value fuel. The nature and composition of the biowaste used greatly affect the hydrogen yields, which was showed by Dong et al. [56] in studies using different sources of MSW

with varying composition. Generally, biowaste from kitchens is considered a very good substrate for hydrogen production. Jayalakshmi et al. [57] used kitchen wastes from a hostel, which mainly consisted of vegetable waste (66% and 27% respectively), followed by packing material (1.4%), egg shells (1.1%), and tea waste (1%).

MSW is a promising raw material for the production of ethanol. During ethanol fermentation, the carbohydrate fraction of MSW (e.g., glucose, fructose, starch, and cellulose) can be converted to ethanol, whereas the proteins and minerals present in MSW are necessary for the growth of the fermenting microorganism. There are many reports in the literature that used different sources of MSW [58].

7. Landfilling

In accordance with European legislation before landfilling, the residual municipal waste should be pre-treated for reducing of the calorific value of waste to below 6 MJ/kg and stabilize the organic fraction to respiration activity of the waste (AT4) below 10 mg O₂ /g d.m. This requires using mechanical and biological processes in the MBT plant. In another cause, the bio-based waste in landfills can be decayed and influence the rise of methane, production of higher strength leachate, and carbon sequestration. Since it seems most likely that bio-based waste will not decay readily in landfills, use of these wastes likely would lead to a small environmental benefit due to enhanced sequestration effects.

8. Conclusions

The increasing amount of bio-based products has created a number of issues for waste management. First, it needs to be determined how these products are currently being managed, as this information is currently lacking. Second, methods for valorizing bio-based products should be developed. One option would be separating bio-based products from plastic waste, either via separation after collection, or by consumers disposing of these products in separate bins. A second option is composting bio-based products that are collected together with biowaste. However, taking into account the differences in the biodegradable and compostable bio-based products market, the most important is defying the time needed for complete mineralization. Only compostable polymers are biodegraded within a composting time frame and the mineralization process starts within the period required for biodegradation of other compostable biowaste. Only in this case, no substances with an unknown impact on the environment will be introduced into the environment with compost. Therefore, the conditions which allow safe compost to be produced, need to be determined.

Author Contributions: Conceptualization, I.W.-B.; Writing-Original Draft Preparation and Writing-Review, I.W.-B., D.K., K.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by European Union's Horizon 2020 program (as a part of the findings of the project STAR-ProBio, Work Programme BB-01-2016: Sustainability schemes for the bio-based economy), grant number No. 727740.

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

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