

Article

Impact of Bio-Based Plastics on Current Recycling of Plastics

Luc Alaerts * , Michael Augustinus  and Karel Van Acker 

Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44, 3001 Leuven, Belgium; michael.augustinus@student.kuleuven.be (M.A.); karel.vanacker@kuleuven.be (K.V.A.)

* Correspondence: luc.alaerts@kuleuven.be

Received: 11 April 2018; Accepted: 4 May 2018; Published: 9 May 2018



Abstract: Bio-based plastics are increasingly appearing in a range of consumption products, and after use they often end up in technical recycling chains. Bio-based plastics are different from fossil-based ones and could disturb the current recycling of plastics and hence inhibit the closure of plastic cycles, which is undesirable given the current focus on a transition towards a circular economy. In this paper, this risk has been assessed via three elaborated case studies using data and information retrieved through an extended literature search. No overall risks were revealed for bio-based plastics as a group; rather, every bio-based plastic is to be considered as a potential separate source of contamination in current recycling practices. For PLA (polylactic acid), a severe incompatibility with PET (polyethylene terephthalate) recycling is known; hence, future risks are assessed by measuring amounts of PLA ending up in PET waste streams. For PHA (polyhydroxy alkanate) there is no risk currently, but it will be crucial to monitor future application development. For PEF (polyethylene furanoate), a particular approach for contamination-related issues has been included in the upcoming market introduction. With respect to developing policy, it is important that any introduction of novel plastics is well guided from a system perspective and with a particular eye on incompatibilities with current and upcoming practices in the recycling of plastics.

Keywords: bio-based plastics; recycling; circular economy; policy measures; market uptake; PLA (polylactic acid); PHA (polyhydroxy alkanate); PEF (polyethylene terephthalate)

1. Introduction

Bio-based plastics appear already in a broad array of consumption goods. Production of bio-based plastics currently comprises ca. 1% of total plastics production and this share is expected to rise [1]. The Nova Institute has estimated this growth of overall production of bio-based plastics will increase by ca. 50% in 2021 (Figure 1) [2]. Hence the share of bio-based plastics would then increase towards ca. 1.5%, the exact figure depending on the growth of fossil-based plastics. The development and growth of bio-based plastics fit into the search for alternatives to crude oil as a feedstock of organic compounds. Crude oil is a finite feedstock, and today most of the products made from it end up as carbon dioxide in the atmosphere, contributing to global warming. While the production of bio-based compounds is not at all sustainable by definition, the primary raw material source has the potential to be renewable if sufficient care is taken in the development of harvesting and production processes.

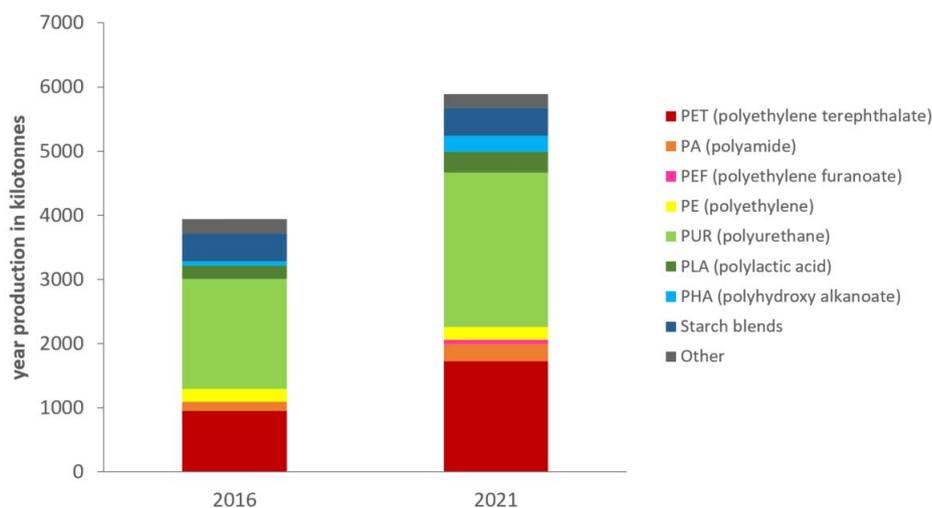


Figure 1. Global production capacities of bio-based plastics in 2016 and estimations for 2021 (data from [2]).

There are many types of bio-based plastics, and further subdivisions can be made; for instance, they differ based on their degree of biodegradability, or on their molecular similarity with existing fossil-based plastics. For example, plastics like bio-based PET (polyethylene terephthalate) or bio-based PE (polyethylene) are essentially identical to their fossil-based counterparts PET or PE, and are called ‘drop-in’ bio-based plastics for this reason. The only difference is in the production processes of the building blocks of these plastics, as the primary raw materials are different. There are also bio-based plastics with building blocks of a particular basis that are much more easily derived from plant-based feedstocks and from which no fossil-based counterparts have been developed, for reasons of molecular chemistry. Examples of such plastics are PLA (polylactic acid), PHA (polyhydroxy alkananoate) and PEF (polyethylene furanoate), which really amount to being new materials with new properties. As such, they offer the opportunity to compete with fossil-based plastics based on performance and not simply on price alone. An example is the application of PEF for the packaging of carbonated beverages [3]. It is for this reason that further growth of their market share is generally expected: Figure 1 shows the highest relative increases for bio-based PET and PHA, and in 2021 PEF is expected to be a newcomer to the market.

When bio-based plastics will be increasingly used for common applications like bottles, trays, packaging etc. they will also end up in waste streams and as such enter the established recycling processes for fossil-based plastics. As explained in the previous paragraph, a number of bio-based plastics have to be considered as new materials. Hence there may be risks that in some cases, from a certain minimum occurrence, they might prove to be incompatible with these processes, leading to a decreased quality of the recycled plastic stream in which the bio-based plastics have ended up [4]. If this is the case, this would hamper the closure of material cycles in plastics recycling, which is particularly relevant given the current policy focus on the circular economy and on the recycling of plastics, as reflected in the recent launch of a strategy for plastics in the circular economy by the European Commission [5].

In this paper, a review of the risks associated with the increased occurrence of bio-based plastics made from novel building blocks in existing recycling processes will be provided. The results of this analysis will, on the one hand, allow detection of knowledge gaps in this area. On the other hand, this analysis will serve policy developments in the field of the circular economy and, in particular, plastics recycling. In this way, the paper provides an outlook as to if and how policy makers should be prepared for the increased occurrence of bio-based plastics.

2. Materials and Methods

The premise for setting up the analysis is that the preferred end-of-life scenario for bio-based plastic is to collect it as plastic waste and send it for recycling. Hence, for those bio-based plastics that claim to be biodegradable, the possibilities for collection together with organic waste for composting or digestion purposes are not included. From the perspective of keeping material cycling in the economy, mixing these two types of plastics is less desirable. Also, it is logical to organise plastic recycling per product category to the extent that this is feasible.

In order to undertake the risk analysis, we started by outlining the currently applied recycling processes. In the first place, we have considered the recycling of PET and HDPE (high-density polyethylene) bottles. These two plastics display, for the moment, the best outlook in terms of the production of high-quality recyclates: selective collection is in place in many countries, efficient mechanical recycling processes have been developed, and there are examples of the high-grade application of recyclates [6–8]. Next, we expand on the recycling of mixed household packaging waste, given the increased overall focus on plastics recycling as explained above.

In a next step, the impact of small amounts of bio-based plastics made from new building blocks was assessed. As we felt that this group of plastics is too heterogeneous in nature, we have chosen a case-by-case approach by considering subsequently the impact of three examples of such plastics, PLA, PHA and PEF, in order to develop a more general perspective on the risks. As preparation for these exercises, we first considered the impact of polyvinyl chloride (PVC) in PET recycling. PVC is known as an unwanted contaminant even in very low concentrations [8], and gathering the available information on the case of PVC in PET recycling was considered instructive as a preparation for assessing the impact of the selected bio-based plastics. Given the very small amounts of these plastics appearing on the market, setting up separate collection is not viable and hence they will act as contaminants whose impact on recycling processes and products has to be analysed [9]. The analysis starts by considering the physical, chemical and other, more practical, properties (for instance related to the particular application or appearance) of such contamination. Then, these are compared with the properties of PET and HDPE bottles or household packaging waste constituting the main flows. Eventually, this results in the identification of the possible pathways that particular bio-based plastics can follow and the possible impact that may arise from their presence in certain amounts.

The data at the base of this analysis was retrieved from research papers, policy documents, publications from sector organizations and websites. A deliberate and clear choice was made at the beginning of the research not to limit the consulted sources to peer-reviewed academic literature only. We realised that a significant part of this analysis pertains to unit operations interacting in a system, which is an area under focus by many other actors besides academic researchers. In fact, the reality that much of the work (including more conceptual aspects) in circular economy research is driven by non-academic actors has been reported before [10]. In that way, one of the aims of this paper is also to stimulate and define areas for further knowledge building.

3. Results

3.1. Current Recycling Processes

3.1.1. Polyethylene Terephthalate (PET) and High-Density Polyethylene (HDPE) Bottles

In this section, we focus on the currently operational series of unit operations to recover PET and HDPE from bottles for recycling. For many years PET and HDPE bottles have been routinely separated and collected in many European countries. A high-level representation of the recycling system is shown in Figure 2.

The overview in Figure 2 starts from bottles as they have been isolated from household waste—depending on how the selective collection of household waste has been organised, they may be collected separately or combined with other waste streams like metal cans and/or tetra packs. Further

separation of PET and HDPE bottles takes place in sorting centres, either manually or using optical recognition with near-infrared (NIR) spectroscopy, estimated to be in use at 60% of the sorting centres in 2006 [6]. In such equipment, the positive detection of polymer types takes place, and subsequent separation from the flow is done using air pulses. In a next step, a series of unit operations converts the bottles into small, cleaned fragments. These unit operations comprise for instance of washing to remove (residues of) labels, glue, paper etc., removal of caps, fragmenting, and further purification steps like, for instance, metal separation and flotation. The latter technique takes advantage of the density differences of HDPE and PET compared to water: HDPE flakes float while PET flakes sink to the bottom (see Table 1). This allows PET flakes to be obtained without HDPE and vice versa; also, other impurities can be removed if the density difference is suitable. The separate plastic fragment streams are then fed to the respective mechanical recycling processes. Here, the flakes are dried, molten and eventually pellets of rPET (recycled PET) and rHDPE (recycled HDPE) are extruded. During mechanical recycling, the chemical polymer structure itself is essentially maintained, although some degradation will always occur to a certain extent. For this reason, a direct full recycling into the same level of application is not possible. Therefore, it is not possible to obtain bottles solely from rPET with the same quality as bottles from virgin PET, and hence in practice downcycling is taking place, for instance in the production of bottles with a certain fraction of recycled content, the production of bottles for lower grade applications, e.g., soap bottles from beverage bottles, or the production of applications other than bottles, e.g., rPET textile and fillings or rHDPE storage boxes, tubings and cable trays [7].

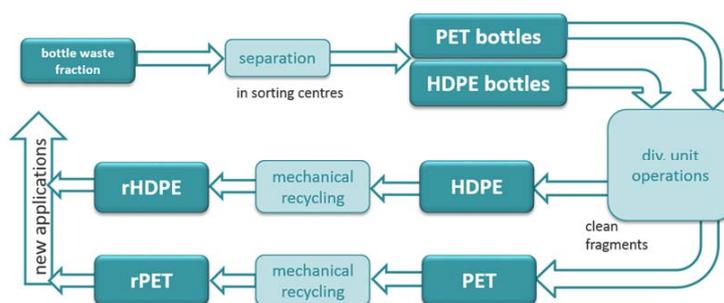


Figure 2. High-level overview of the unit operations from bottle collection to recyclates of polyethylene terephthalate (PET) and high-density polyethylene (HDPE).

Table 1. Densities and melting points of a number of plastics.

Plastic Type	ρ (kg/m ³)	T _m (°C)
Polyethylene terephthalate (PET)	1350–1390	255
High-density polyethylene (HDPE)	930–970	125
Polyvinyl chloride (PVC)	1100–1450	210
Polylactic acid (PLA)	1200–1450	155–165
Poly-3-hydroxybutyrate (PHB)	1300	180
Polyethylene furanoate (PEF)	1400–1550	225

The ranges are based on the results of a general search on the internet, completed by data retrieved in the references consulted for this paper.

3.1.2. Mixed Plastic Waste

This kind of waste comprises all plastic household packaging like foils, cans, jars, margarine containers, yoghurt pots, flower pots etc. A focus on separate collection for this fraction has appeared recently, either together with or without bottles (in the former case, such separation can take place in sorting centres). This fraction is intrinsically much more heterogeneous in nature, due to the following [11,12]:

- Objects made from different polymer types can have very similar appearances.
- A same polymer type can be used in very different ways given the application, e.g., with different additives, crystallization degrees, intrinsic viscosities etc. Compared to bottles, there is much less uniformity per plastic type among the encountered applications.
- The occurrence of all kinds of add-ons like labels, inks, impurities, combinations etc.
- Different behavior in sorting unit operations depending on the final application; consider, for instance, the different aerodynamics of foils vs. yoghurt containers vs. clamshells that become apparent in wind shifting.
- Different objects may clump in the case of bale packing that is too dense.

Such mixed plastic streams are evidently much more challenging with respect to recycling. At present, there is only marginal production of recyclates of any particular plastic type from streams in operation today. In fact, there are quite a few applications of recyclates in objects occurring in these kinds of streams (e.g., PET-thermoforms containing up to 50% rPET from bottles) [13]. Some examples exist of composite products derived from mixed plastics, like garden tables or traffic infrastructure [14].

3.1.3. Impact of Polyvinyl Chloride (PVC) on Recycled PET (rPET)

The negative impact of PVC (polyvinyl chloride) in PET bottle recycling has been known for many years in the field. As both PVC and PET have a density higher than water, PVC impurities that are not taken out in the first unit operations automatically end up in the PET fraction obtained after flotation and are sent for mechanical recycling. Even with PVC contaminations as low as 0.005% (coming down to e.g., one bottle of PVC in 20,000 PET bottles) the obtained rPET is not applicable for most applications any more. The melt temperature of PVC is much lower than that of PET (see Table 1). This means that at the temperatures applied in the mechanical recycling of PET in a molten state, PVC contamination is at temperatures much higher than their melting point for a prolonged time. In such conditions it is typical that degradation starts to occur, leading to chain scissions and/or the release of functional groups. In the case of PVC, hydrochloric acid is released, chemically breaking the polymer chains. The decomposed PVC assumes a yellow to brown discoloration and the occurrence of black spots in the obtained rPET. It is clear that the resulting rPET is unacceptable and has inferior material properties [8,15,16].

Due to the above, a number of modifications to the chain of unit operations has been implemented already to protect the quality of rPET from the negative influence of PVC. At first, the occurrence of PVC in bottle applications decreased considerably over the years, e.g., PVC is currently not used for food and beverage packaging. The only possible occurrence may still be in all kinds of add-ons to bottles, like sleeves, labels etc. In fact, the PET recycling sector actively discourages any introduction of PVC-containing add-ons to PET bottles [8]. PVC can be detected by NIR, so sorting installations equipped with this technology are able to reject PVC objects, PVC bottles or PET and HDPE bottles with sleeves, labels or other add-ons made from PVC. The European Pet Bottle Platform (EPBP) website mentions a separation accuracy level of 85–96%.

In summary, the issue of PVC in PET recycling is known and has been taken up by the field. The occurrence of PVC in the current bottle fraction is already very low. Together with the application of NIR separation technology, this should ensure that today PVC does not hamper the mechanical recycling of PET and HDPE bottles. Let us consider now how the analogy with newly introduced bio-based polymers works.

3.2. Impact of Polylactic Acid (PLA) on Plastics Recycling

PLA or polylactic acid claims to be a fully bio-based plastic and also to be biodegradable. The building block of PLA is lactic acid, obtained by fermentation of plant-derived sugars. PLA is applied in transparent bottles, containers, packaging and foils. Given the high permeability of PLA to water, it is an interesting material for the packaging of food products like lettuce or bread. Its application

in bottles is rather modest for the same reason [6]. With respect to bottle applications, starting from Figure 2 and considering properties and existing knowledge of PLA we can come to a rough analysis of the behaviour of a PLA bottle in the current recycling chain. At first, visual discrimination based on appearance between a bottle made from PET and from PLA is not possible: both materials are transparent and very similar. So, both at the level of consumers and of manual sorting, separation is not possible unless an extra element is introduced e.g., via labelling [6]. Next, at the level of sorting centres, if NIR technology is available for the positive detection of PET bottles, then at least the majority of PLA bottles would become separated. The EPBP estimates an efficiency of 86–95% for this. Other sources report numbers up to 99.6% (see Table 2). Also, PLA is denser than water so in the flotation tank any PLA fragments will eventually follow the PET stream towards mechanical recycling [17]. Hence, the impact of PLA on rPET quality will especially have to be assessed.

Table 2. Separation efficiencies of PLA bottles from PET bottles by near-infrared (NIR) spectroscopy.

Separation Efficiency (%)	Reference
86–95	[8]
96	[18]
97	[19]
90–98	[20]
99.6	[21]

3.2.1. Occurrence of PLA in Plastic Waste

Starting from available numbers on the current and expected occurrence of PLA, we have calculated the level of PLA estimated to occur in the bottle and the mixed plastics fractions from household waste. This approach allows sufficient accuracy to provide an order-of-magnitude estimation of PLA occurrence. The raw numbers at the basis of these calculations are available in Appendix A, Table A1. The next paragraph describes the most important steps and numbers in the calculations.

We started from general numbers describing the European market. In first instance we have assessed the total amounts of PET, as PLA contaminations are especially relevant with respect to this fraction (see above). Next we subdivided bottles and mixed plastics. For PET, we started from reported production data for the year 2015 and estimated production data for the year 2021, and assumed that 71% is applied in bottles and 10% in objects ending up in the mixed plastics fraction, based on a number of sources. For PLA, we started from reported production data for the year 2016 and estimated production data for the year 2021. We found a proportion of 60% of PLA applied for bottles and other packaging [22]; for bottles only, we did not find any proportion and estimated a range of 5–35% of total PLA production used for bottles. Taken these proportions together (and assuming as such that all plastics are retrieved via the existing collection systems), estimations of PLA concentrations in waste fractions have been obtained as shown in Table 3.

Table 3. Amounts of PET and PLA applied in bottles and in other packaging in Europe, and ratio of PLA vs. PET (data sources: see Appendix A, Table A1).

Application	PET (Mton)		PLA (kton)		PLA/PET Ratio (%)	
	2015	2021	2016	2021	2015/2016	2021
Bottles	3.3	3.9	2.9–20	4.2–30	0.09–0.6	0.1–0.8
Other packaging	0.47	0.55	14–32	21–46	3–7	4–8

The overall numbers in the table reflect the fact that production of both PET and PLA is expected to increase towards 2021, with the increase of PLA relatively higher than that of PET. This is reflected in the expected (slight) increase of the concentrations of PLA in PET. The ranges appearing in the table are the result of a chosen range for the total PLA production directed to bottle production. These ranges

are to be considered as a reflection of the order of magnitude in which to consider current and future potential contaminations by PLA.

3.2.2. Impact of PLA in Current Recycling of Bottles

The different behavior of PLA at higher temperatures has already been reported to cause a number of issues in the drying and processing steps of the mechanical recycling of PET [11,15,17,23,24]:

- The difference in melting temperatures between PLA and PET is ca. 100 °C (see Table 1). This means that at the temperatures applied in mechanical PET recycling, implying PET is in a molten state, PLA contamination is at temperatures much above its melting point for a prolonged time. In such conditions degradations start to occur, in a similar way as explained above for PVC. PLA degradation leads to a yellowing of the resulting product. Also, in the pretreatment of the feed to the mechanical recycling of PET, issues can occur during drying of the flakes, as the lower softening point of PLA causes the PLA fragments to become sticky, resulting in an agglomeration of flakes and fouling of the drying installation [17].
- PLA has a different glass-transition temperature, resulting in opaqueness or haziness when processing rPET into pellets, as PLA and PET will undergo phase separation as they are not miscible in the solid state [15,25,26].
- Also, upon further processing of contaminated rPET pellets, the pellets with PLA contamination could stick to surrounding PET pellets, resulting in the formation of clusters, hampering further operations [15].

The first of the above issues starts to occur from contamination of 2% and higher. The issues with respect to transparency and discoloration are evidently present already from contamination of 0.1% or even lower (see Table 4). There is some discussion in literature about where the safe threshold for having no quality impact at all is situated; a number of claims have been published, both by entities marketing PLA and by bodies defending the PET recycling industries. These claims need to be checked further with respect to the exact experimental conditions (lab scale vs. full-size process; to which extent is virgin PET added) and the exact application (e.g., PLA contamination up to 5 wt % does not affect a bottle-to-fibre application [20]). An overview of the available data on the impact of PLA contamination in PET is given in Table 4. However it is clear that PLA contamination should be kept under stringent control if rPET quality and the ability to process is to be protected, especially with respect to bottle applications.

Table 4. Reported threshold concentrations for PLA in PET and impact.

Concentration		Impact	Test Details	Ref.
%	ppm			
0.05	453	“No visual deviations in terms of colour and transparency”	Foil of 1.3 mm thickness obtained by extrusion tests with 70:30 ratio of rPET:PET	[23]
0.05	453	“Not any significant difference in colour and haze”	Plaque let-down study with plaques between 0.063 and 3 mm	[18]
<0.1	<1000	“Makes any rPET resin unsuitable”	“For most applications”—no further details obtained after request	[24]
0.1	1000	significant opacification of recycled PET	Plaque test	[17,20]
0.1	1000	PET recyclate unusable for many end-products	n.a.	[27]
0.3	3000	“Lowers the onset of crystallization and retards recondensation”	Injection molding	[25]
>0.3	>3000	PLA causes yellowing of PET	Plaque test	[17]
2	20,000	Besides lower quality resin, also agglomeration and sticking to dryer walls	n.a.	[17]
5	50,000	Besides lower quality resin, also agglomeration and sticking to dryer walls	n.a.	[17]

In our analysis of the market penetration of PLA, we estimated contamination of collected PET bottles by PLA to be 0.8% at the highest in 2021 (including the assumption that all PLA bottles are collected via the existing systems). With NIR separation technology, assuming a sorting efficiency of 90% (a conservative estimation, see Table 2), this assumed contamination level would come down to 0.08%, which is still quite close to the 0.1% threshold to be really sure for having smooth rPET quality. Then, it is clear that further removal of PLA may be very well required in the recycling chain in order to assure high-quality rPET. The following options can be considered if additional purification of the PET bottle stream is necessary:

- Adjustment of NIR sorting equipment for decreasing the number of sorting mistakes leading to positive selection of PLA bottles or PET bottles with PLA add-ons. This may, however, also lead to a larger stream of rejected bottles, decreasing the rPET yield and the eventual financial return of the recycling process [6].
- Installation of additional NIR sorting equipment into the fragment stream going to flotation: this would lead to a further decrease of 90% of the amount of PLA contamination and would also allow removal of all kinds of add-ons, as these are in that stage of the process also occurring as fragments.
- Perhaps the low softening temperature of PLA (see above) would allow running a separation process based on a hot conveyor belt or a rotating drum, as has been described already for the removal of PVC from PET [7,16,28].
- Other options are explicit labeling of PLA bottles, either for the purpose of communication at the consumer level (sorting message), or for instance using chemical markers, allowing smooth detection in automatic sorting [29].

Any of these options would lead to an increased cost for the overall recycling process, either because of the installation of new hardware or because of yield losses. In fact, this situation of PLA contamination in PET is very reminiscent to that of PVC in PET, as described above, with the PET recycling sector being concerned that even small market penetrations would seriously hinder the existing recycling infrastructure and actively discourage the use of PLA add-ons of any kind for PET bottles [8,24]. The difference with PVC is that PLA is becoming more popular for use, hence the trend is towards increasing amounts of PLA ending up in waste streams.

3.2.3. Impact of PLA in Current Recycling of Mixed Plastic Waste

For the moment, the applications already developed for mixed plastic waste (see above) have not yet revealed issues to the best of our knowledge—given the expected increase of PLA applications, the question is whether from a certain moment, for instance, the lower melting and degradation temperature of PLA could hamper the existing processes, or that the biodegradability could impact the quality of the products over time, for instance, when applied outdoors.

As explained above, there are currently no operational processes that extract PET from mixed plastic waste for production of rPET. If in the future such attempts would be undertaken (PET is one of the common polymers found in mixed plastics waste, occurring in different forms), it is clear that the same issues with respect to rPET quality would arise. Our estimations have revealed that contamination of PET by PLA could be as high as 8% by 2021, showing that a very large supplementary effort would be needed to get below the safe limit of 0.1%.

3.3. Impact of Polyhydroxy Alkanoate (PHA) on Plastics Recycling

PHA (polyhydroxy alkanoate) is a collective name for a group of polymers made of chemically similar building blocks. PHB (poly-3-hydroxybutyrate) is the most widespread member of the PHA family. PHA plastics are produced in a biological process induced by micro-organisms. The polymers obtained are biodegradable. While the different PHA types differ in properties depending on their chemical composition, a particular characteristic of PHA is its biocompatibility, making them

suitable for medical applications. PHA also has good barrier properties, of interest for food product packaging. For these reasons, applications of PHA are found, for instance, in single-use packaging films, bags, containers, paper coatings, agricultural foils, biodegradable carriers for long-term dosage of compounds like drugs or fertilizers, and medical applications like surgical pins, sutures, wound dressings, bone and blood-vessel replacements etc. [30].

3.3.1. Occurrence of PHA in Plastic Waste

Data on the occurrence of PHA were difficult to retrieve. Some overall numbers have been presented already in Figure 1: PHA shows an estimated fourfold increase between 2016 and 2021; in the latter year world production is estimated to be 0.25 Mton and European production 0.065 Mton. With respect to applications, the consulted data sources stress the wide range of applications for PHA, with most of the applications in soft packaging. However, we did not retrieve numbers allowing estimation of the amounts ending up in the bottle or mixed plastic fractions. Hence, it is assumed that current bottle applications are marginal, and that the end-of-life scenarios for many PHA applications are determined by the application itself, e.g., 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 [30].

3.3.2. Impact of PHA on Current Plastic Recycling

The few data that were retrieved on properties of PHB allow us to conclude that if it were to end up in the feed of rPET production (e.g., via the bottle fraction), similar issues as encountered for PLA with respect to the mechanical recycling of PET may occur. Due to its higher density compared to water, PHB may eventually end up in the feed to rPET production. Moreover, its melting temperature is 180 °C, much lower than that of PET. The current application of PHA for bottles is estimated to be negligible. Although a steep increase of applications is expected, the assumption is that the main developments are in the direction of more complex applications and not bottles [30].

With respect to mixed plastics, most probably some PHA applications are already ending up there. Given the state-of-the-art of knowledge with respect to the occurrence of the much more common PLA in this stream (see above), for the moment no further conclusions can be drawn on its impacts.

3.4. Impact of Polyethylene Furanoate (PEF) on Plastic Recycling

PEF (polyethylene furanoate) is produced by the building blocks ethylene glycol and furane dicarbonic acid. It is obtained from fructose sugar, which can be obtained from many plant feedstocks. The most particular feature of PEF is its enhanced barrier properties, for instance, for carbon dioxide and oxygen, making the material very interesting for soft drink bottles and food packaging [3]. Currently, PEF is not available on the market, but its entrance is very near given the announced startup of Synvina in Antwerp, being a joint venture of BASF and Avantium.

With respect to the future PEF bottles, starting from Figure 2 and considering the properties and existing knowledge of PEF, we can come to a rough analysis of their behaviour in the current recycling chain of bottles. Visual discrimination based on appearance between a bottle made from PET and from PEF is not possible: both materials are transparent and very similar. So both at the level of consumers and of manual sorting, separation is not possible unless an extra effort were to be introduced, e.g., via labelling. Next, at the level of sorting centres, if NIR technology is available for positive detection of PET bottles, it is probable that the majority of the PEF bottles would be separated [31]. Also, PEF is denser than water (see Table 1) so after flotation PEF fragments will follow the PET stream towards mechanical recycling. Hence, quality needs to be assessed, especially the impact of PEF on rPET.

3.4.1. Occurrence of PEF in Plastic Waste

The market entrance of PEF is imminent in coming years. For the year 2021, a yearly production in Europe of ca. 18 kton is expected by the Nova Institute [2]. It is difficult to estimate further production

growth beyond 2021. Besides the overall growth in plastics produced for packaging and the expected increase in the share of bio-based plastics, there is also a scenario that PEF might replace PET at an accelerated rate given the expected superior barrier properties of PEF [3], allowing beverage bottles to be made with much less material and/or increasing the shelf life of the products.

As PEF contamination is especially relevant with respect to the PET bottle fraction (see above), we have tried to estimate the relative amounts of PEF compared to the amount of PET used for bottles (see Table 5). In the calculations for PET, we have used the same assumptions as above for assessing the market penetration of PLA; for PEF, we have used the estimated production from the Nova Institute and further assumed that all PEF goes into bottles. It appears from these calculations that the occurrence of PEF in PET could be as high as 0.45% by 2021.

Table 5. Amounts of PET and PLA applied in bottles and in other packaging in Europe, and ratio of PLA vs. PET (data sources: see Appendix A, Table A1).

Application	PET (Mton)		PEF (kton)		PEF/PET Ratio (%)	
	2015	2021	2016	2021	2016	2021
Bottles	3.3	3.9	0	0.067	0	0.45

3.4.2. Expected Impact of PEF on Current Recycling of Bottles

The impact of PEF on the mechanical recycling of PET has been investigated: one source states that contamination of up to at least 2% has been demonstrated not to lead to any negative impact on rPET quality, e.g., negative impact on haze, colour and other properties [31]. Another source states that no negative effect on haze occurs up to 5% [32]. The absence of haze could suggest that PET and PEF are miscible in the solid state at least up to these amounts [24]. Compared with the estimations above in Table 5, it appears that at least until 2021 the amount of PEF available on the market will be far below these levels.

In this context it is relevant to learn that Synvina has proactively approached the EPBP to assess the impact of PEF on the existing recycling chain of PET bottles, and has obtained a conditional ‘approval’ for market entrance from this entity. Based on dedicated studies, the EPBP concluded that until a market penetration of 2% is reached there will be no issues with PEF ending up in PET streams. For larger market penetrations, either additional tests or the development of a separate collection and recycling system for PEF bottles will need to be in place in order to further anticipate any negative impact on rPET quality [31].

3.4.3. Expected Impact of PEF in Current Recycling of Mixed Plastic Waste

Given the limited relative occurrence of PEF on the market in the near future, the absence of negative impacts on PET recycling processes and the main application of PEF expected to be in first instance in bottles, the amounts ending up in mixed plastic waste will most probably be sufficiently small to exclude any negative effects in coming years, both in processing mixed plastics as one single fraction as such and in any attempt to obtain pure plastic waste streams like PET from this fraction.

4. Discussion and Conclusions

The approach followed in the three cases above has shown that the introduction of bio-based plastics on the current operational range of recycling processes should be considered as the introduction of a number of types of novel plastics. In the first instance, every new introduction starts as a contamination, and with respect to further evolutions the following questions are most relevant:

- Which incompatibilities may occur? From which amounts do they become noticeable?
- How strong are the current recycling processes that have been developed?
- By which amounts is the development of dedicated collection and recycling rewarding?

One aspect of assessing the impact of a contamination comes down to the probability of a novel plastic ending up in the final products of current plastics recycling. This is a consequence of the properties of the contamination compared to the main flow of plastics, and the organisation and technologies of sorting and recycling that deal with this main flow in a certain manner. Starting with the estimated, measured or known market penetration, it is possible to assess the pathway of a contamination and to obtain probable concentrations in the recycling processes and at the recyclate level, and comparing these with the lowest levels on which negative impacts have been observed or demonstrated—this is the second aspect of the impact of a contamination. This can be measured with tests; here the definition of what is being tested is crucial, as an incompatibility may be less noticeable in one application compared to another one. For instance the impact for an rPET bottle destined for beverages is different compared to the impact for an opaque rPET bottle destined to contain soap.

The latter two of the above questions pertain to the current recycling of PET: processes for high-grade rPET destined for bottle production have been established and sector organizations have been founded in particular to protect these activities, e.g., by promoting the design for recycling. This has resulted in published compatibility lists, e.g., discouraging particular materials for sleeves and add-ons, with the ability to produce high-grade rPET as the reference. Hence any negative impacts of contaminations have a higher chance of being discovered right in this chain, so it is not a coincidence that PET recycling features so prominently in the analyses above. To a certain extent it is beneficial that compatibility with the established recycling processes is being strived for, because it may lead to smoother introductions of novel plastics and the detection of possible issues well in advance. For instance, the market entrance of PEF has been anticipated in this way. On the other hand there is the risk that the mere power exerted by the incumbent actors in recycling inhibits the introduction of novel plastics for too long a time, even if such introductions would be beneficial for other reasons.

In this paper, a review has been carried out for three concrete bio-based plastics. For PLA, the evidence is clear that its presence, even in small amounts, is detrimental to the quality of rPET: contamination in the feed to mechanical recycling should be maintained well below 0.1% in order to protect rPET quality. For the bottle fraction, our estimations for now and coming years till 2021 have shown that state-of-the-art separation (equipped with NIR technology) might lead to a contamination in the feed to mechanical recycling of PET currently and in the near future not too far below this 0.1% threshold. In order to further elaborate this analysis, a next step could be to obtain better reference values by checking the numbers of the estimation, e.g., by sample measurements of bottle waste streams (also considering sleeves and add-ons). These actions could then be repeated to keep track of evolutions in PLA concentrations over time. Also, the current occurrence of any quality issues related to PLA in PET in the field could be checked, e.g., by interviewing companies. The outcome of these actions should allow an assessment of when the set of currently applied unit operations for separation and recycling would not be able to lead to rPET of sufficient quality in the longer term. If this were to be done, then further options to consider are investments in extra unit operations and/or developing adequate labeling of PLA bottles. The value of the latter option will also be dependent on any further developments in the direction of bringing value to a separate PLA stream for recycling PLA. It appears that there are several possibilities for additional technologies for PLA separation, like an extra separation of flakes using NIR technology, or technologies that are already known for PVC removal.

With respect to PLA contamination of mixed plastics, our estimations have shown that contamination may be in the range of several percent. Although any issues were not revealed in the current study, perhaps due to the application development in this area that is only emerging, with further sorting and separation technology and application developments the estimated higher concentration of PLA in mixed plastics might very well give rise to issues (e.g., due to its lower heat stability compared to many fossil-based plastics). Hence here also sample measurements and interviews with companies using mixed plastics as an input to their production could be helpful to establish reference values and to monitor evolution. In this respect, any plans to implement, extend or

modify post-consumer plastics collection should be thoroughly evaluated with respect to the creation of possible contamination pathways of PLA into rPET.

For PHA, besides the different kinds of polymers considered, there is also a whole range of applications and only few data available, making analysis of the current situation difficult. Similar issues as encountered with PLA might occur, given the rather low heat stability of PHB. For the moment, no issues are known or expected as the main current applications of PHA do not seem to lead to end-of-life scenarios hampering the existing high-end mechanical recycling processes. There are no indications that this would change in the short term, but any trends in application of PHA are to be monitored given the expected steep increase in PHA production in coming years.

With respect to PEF, no issues are known with respect to the impact on mechanical recycling of common plastics. For the impact on rPET this has been effectively tested for contamination up to 2%. As PEF still has to be launched on the market, this allows us to conclude that in coming years no issues are to be expected. What could happen in the longer term is not clear; much is also dependent on to which extent a separate collection and recycling system for PEF would be operational and successful. Anyhow, this has gained the attention of both the (future) producer of PEF and the sector organization of PET recycling, hence it is very probable that any risk will be anticipated well. In fact the producer's approach to assess in advance compatibility with the existing recycling landscape is to be encouraged as it is a clear demonstration of the necessary system thinking in this field.

Summarizing the three case studies, for PLA the facts are known so future risks can be assessed by measuring amounts. For PHA, it will be crucial to monitor future application development, and for PEF, a particular approach for contamination-related issues has been an element of project management. Hence the study did not reveal bottlenecks or negative impacts generally valid for all bio-based plastics. One of the next questions could then be what would be the next bio-based candidate material to appear in post-consumer plastics waste.

Overall, the challenge with respect to bio-based plastics is a matter of guiding well both their introduction together with developments in the recycling landscape, with a particular eye on their incompatibilities e.g., with process conditions or combinations with other plastics. The story in this paper is, therefore, fully written within the context of the current state of the art of applied recycling technologies and, in general, how post-consumer plastic collection and sorting have been organized. Hence, the findings are to be seen fully in the light of the current situation. With any future changes of the recycling landscape, the analysis has to be repeated. For instance, if there were to be initiatives in extended producer responsibility, maybe the waste streams obtained would become much more pure and some issues may simply disappear, if for example PLA bottles would then not end up with PET bottles any more.

With respect to developing policy advice, a number of suggestions for preparing next steps can be made. First, it is important that introduction of novel plastics is guided well, with a clear focus on the whole system; see as an example the way the introduction of PEF is being anticipated. Next, it is important that all plastic types occurring as contamination in current waste streams are considered in the context of any changes in the recycling landscape. On the other hand, with the supply of plastic types constantly changing and more abrupt changes to be expected in the (near) future, it has to be considered that from a certain moment the recycling landscape itself would need a reorganisation; such an operation requires a realignment of many actors and is, hence, complex, but it would avoid desirable developments in the production of plastics being blocked for an unnecessarily long time.

Finally, the current analysis did not aim to draw any conclusions about the mere desirability of bio-based plastics and/or future increases in these plastics. Such developments should, anyhow, not be steered too much by the concrete implications for the recycling landscape; as long as these plastics can be recycled well by themselves, the recycling landscape should be able to accommodate them over time, and here policy has the option to support or even guide this process by carefully managing the new entries temporarily as contaminants.

Author Contributions: L.A. conceived the approach for the study, arranged interactions with policy officers of the Flemish administration, and wrote the paper; M.A. performed the literature research; K.V.A. reviewed the paper and guided the overall process from phrasing the research questions to elaborating the policy advice.

Acknowledgments: The authors are very grateful for full financial support received from the Flemish administration via the Steunpunt Circulaire Economie (Policy Research Centre Circular Economy). This publication contains the opinions of the authors, not that of the Flemish administration. The Flemish administration will not carry any liability with respect to the use that can be made of the produced data or conclusions. The authors are also grateful to policy officers of the Waste Agency Flanders (OVAM) for extended discussions and comments.

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

Appendix A

Table A1. Data used to estimate penetration of PLA, PHA and PEF in post-consumer plastics.

Data	Value	Unit	Reference
World plastics production 2015	322	Mton	[33]
Yearly growth of world plastics production	8	Mton/y	[33]
World plastics production 2021	370	Mton	based on previous
World PET production 2015	27.8	Mton	[33]
World PET production 2021	32.2	Mton	based on previous
Share of PET in world plastics production	9	%	calculated 2015 data
Share of PET production in Europe	17	%	[33]
Share of PET used for bottles	71	%	[33]
Share of PET used for non-bottle packaging	10	%	[11]
World production of bioplastics 2016	4.16	Mton	[2]
World PLA production 2016	5.1	%	[2]
World production of bioplastics 2021	6.11	Mton	[2]
World PLA production 2021	5.3	%	[2]
European bioplastics production 2016	27.1	%	[2]
European bioplastics production 2021	26	%	[2]
Share of PLA used for bottles and other packaging	60	%	[22]
Share of PLA used for bottles	5–35	%	own estimation
World PHA production 2016	1.6	%	[2]
World PHA production 2021	4.1	%	[2]
World PEF production 2016	0	%	[2]
World PEF production 2021	1.1	%	[2]

References

1. Van den Oever, M.; Molenveld, K.; van der Zee, M.; Bos, H. *Bio-Based and Biodegradable Plastics—Facts and Figures*; Report no. 1722; Wageningen Food & Biobased Research: Wageningen, The Netherlands, 2017; Available online: <http://edepot.wur.nl/408350> (accessed on 6 April 2018).
2. Nova-Institute. European Bioplastics. 2016. Available online: <http://www.european-bioplastics.org/market/> (accessed on 31 August 2017).
3. Lauwers, B. Avantium Werkt aan de Drankverpakking van de toekomst—Dit is Bijzonder Disruptief. *Trends*, 9 February 2017.
4. Giljum, S.; Bruckner, M.; Gözet, B.; de Schutter, L. *Land under Pressure: Global Impacts of the EU Bioeconomy*; Friends of the Earth Europe: Brussels, Belgium, 2016; Available online: https://www.foeeurope.org/sites/default/files/resource_use/2016/land-under-pressure-report-global-impacts-eu-bioeconomy.pdf (accessed on 6 April 2018).
5. European Commission. A European Strategy for Plastics in a Circular Economy. Available online: <http://ec.europa.eu/environment/circular-economy/pdf/plastics-strategy.pdf> (accessed on 6 April 2018).
6. Bioplastics. OVAM, Projectgroep Bioplastics. 2015. Available online: <http://www.ovam.be/sites/default/files/atoms/files/Rapport%20Bioplastics.pdf> (accessed on 6 April 2018).
7. ASG Environmental Science Research & Development Institute. Available online: <http://www.petbottlewashingline.com> (accessed on 6 April 2018).
8. EPBP Website. Design Guidelines. Available online: <http://www.epbp.org/design-guidelines> (accessed on 6 April 2018).

9. Greene, K.L.; Tonjes, D.J. Degradable plastics and their potential for affecting solid waste systems. *WIT Trans. Ecol. Environ.* **2014**, *180*. [CrossRef]
10. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [CrossRef]
11. NAPCOR. Report on Postconsumer PET Container Recycling Activity. 2017. Available online: https://www.plasticsrecycling.org/images/pdf/resources/reports/NAPCOR-APR_2016RateReport_INAL.pdf (accessed on 6 April 2018).
12. Schedler, M.; Eagles, K. *Moving Forward on PET Thermoform Recycling*; Resource Recycling Inc.: Portland, OR, USA, 2011; pp. 26–28.
13. Petcore. The Recycling of Thermoforms: An Important Challenge for the PET Value Chain. 2016. Available online: <https://petcore-europe.prezly.com/the-recycling-of-thermoforms-an-important-challenge-for-the-pet-value-chain> (accessed on 6 April 2018).
14. Het ECO-OH! Recycling Proces. ECO-OH! 2017. Available online: <https://www.eco-oh.com/nl/eco-oh-groep> (accessed on 6 April 2018).
15. Dvorak, R.; Kosior, E.; Fletcher, J. WRAP Final Report—Improving Food Grade rPET Quality for Use in UK Packaging. 2013. Available online: <http://www.wrap.org.uk/sites/files/wrap/rPET%20Quality%20Report.pdf> (accessed on 6 April 2018).
16. Hurd, D. *Best Practices and Industry Standards in PET Plastic Recycling*; Washington State Department of Community, Trade and Economic Development: Washington, DC, USA, 2000. Available online: http://www.seas.columbia.edu/earth/RRC/documents/best_practise_pet_recycling.pdf (accessed on 6 April 2018).
17. Eco Entreprises Québec. Fact Sheet Impact of Packaging on Curbside Recycling Collection and Recycling System: PLA Bottle. 2012. Available online: <http://www.eeq.ca/wp-content/uploads/PLA-bottles.pdf> (accessed on 6 April 2018).
18. NatureWorks. Using NIR Sorting to Recycle PLA Bottles. 2009. Available online: https://www.natureworkslc.com/~media/The_Ingeo_Journey/EndofLife_Options/mech_recycling/20090708_NatureWorks_UsingNIRSortingtoRecyclePLABottles_pdf.pdf (accessed on 6 April 2018).
19. European Bioplastics: Fact Sheet Mechanical Recycling. 2015. Available online: http://docs.european-bioplastics.org/publications/bp/EUBP_BP_Mechanical_recycling.pdf (accessed on 6 April 2018).
20. COTREP. Fiche Technique 35. 2007. Available online: http://www.cotrep.fr/fileadmin/contribution/mediatheque/avis-generaux/francais/corps-de-l-emballage-et-additifs/Cotrep_AG35_bouteille_PLA.pdf (accessed on 6 April 2018).
21. Gertman, R.; Shireman, B.; Pfahl, D.; Disa, A. *The Bioplastics Sorting Project—Final Grant Report of Technical Findings*; California’s Department of Resources Recycling and Recovery: St. Sacramento, CA, USA, 2013. Available online: <http://www.calrecycle.ca.gov/publications/Documents/1464/20131464.pdf> (accessed on 6 April 2018).
22. Detzel, A.; Kauertz, B.; Derreza-Greeven, C. *Study of the Environmental Impacts of Packagings Made of Biodegradable Plastics*; Report no. 001643/E; Umwelt Bundesamt: Dessau-Roßlau, Germany, 2013; Available online: <http://www.uba.de/uba-info-medien/4446.html> (accessed on 6 April 2018).
23. STW Foodgate. Recyclage van PET- en PLA-flessen na NIR-Sortering. 2009. Available online: <http://www.pack4food.be/files/documents/nieuwsbrieven/Recyclage%20van%20PET-%20en%20PLA-flessen%20na%20NIR-sortering.pdf> (accessed on 6 April 2018).
24. Petcore. Petcore Position Statement. Polylactic Acid (PLA). Petcore Evaluation of Polylactic acid (PLA). 2008. Available online: <http://www.emballagedigest.fr/blog.php?2008/02/22/6818-petcore-evaluation-of-polylactic-acid-pla> (accessed on 6 April 2018).
25. Thoden van Velzen, E.U.; Brouwer, M.T.; Molenveld, K. *Technical Quality of rPET*; Report no. 1661; Food & Biobased Research: Wageningen, The Netherlands, 2016; Available online: <http://library.wur.nl/WebQuery/wurpubs/fulltext/392306> (accessed on 6 April 2018).
26. McLauchlin, A.R.; Ghita, O.R. Studies on the thermal and mechanical behavior of PLA-PET blends. *J. Appl. Polym. Sci.* **2016**, *133*. [CrossRef]
27. Hollstein, F.; Wohllebe, M.; Sixto, A.; Manjon, D. Identification of bio-plastics by NIR-SWIR-Hyperspectral-Imaging. In Proceedings of the 2nd Optical Characterization of Materials, Karlsruhe, Germany, 18–19 March 2015; Beyerer, J., León, F.P., Längle, T., Eds.; KIT Scientific Publishing: Karlsruhe, Germany, 2015.
28. Bedekovic, G.; Salopek, B.; Sobota, I. Electrostatic separation of PET/PVC mixture. *Tech. Gaz.* **2011**, *18*, 261–266.

29. Kosior, E.; Mitchell, J.; Davies, K.; Kay, M.; Ahmad, R.; Billiet, E.; Silver, J. Plastic packaging recycling using intelligent separation technologies for materials (PRISM). In Proceedings of the ANTEC Conference, Anaheim, CA, USA, 8–10 May 2017; pp. 500–506.
30. Bugnicourt, E.; Cinelli, P.; Lazzeri, A.; Alvarez, V. Polyhydroxyalkanoate (PHA): Review of synthesis, characteristics, processing and potential applications in packaging. *eXPRESS Polym. Lett.* **2014**, *8*, 791–808. [[CrossRef](#)]
31. European Pet Bottle Platform. European PET Bottle Platform Technical Opinion—Synvina—Poly(ethylene 2,5-furandicarboxylate) Resin. 2017. Available online: <http://www.epbp.org/download/319/interim-approval-synvina-polyethylene-25-furandicarboxylate-or-pef> (accessed on 6 April 2018).
32. De Jong, E.; Dam, M.A.; Sipos, L.; Gruter, G.-J.M. Furandicarboxylic Acid (FDCA), A Versatile Building Block for a Very Interesting Class of Polyesters. In *Biobased Monomers, Polymers, and Materials*; ACS Symposium Series; Smith, P.B., Gross, R.A., Eds.; American Chemical Society: Washington, DC, USA, 2012. [[CrossRef](#)]
33. Website Plastics Insight. Available online: <https://www.plasticsinsight.com/global-pet-resin-production-capacity/> (accessed on 6 April 2018).



© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).