Special Issue Article

WM&R

Waste Management & Research
1–12

DOI: 10.1177/0734242X241231408
journals.sagepub.com/home/wmr
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Consumers confused 'Where to dispose biodegradable plastics?': A study of three waste streams

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Abstract

Biodegradable plastics, either fossil- or biobased, are often promoted due to their biodegradability and acclaimed environmental friendliness. However, as demonstrated by previous literature, considerable confusion exists about the appropriate source separation and waste management of these plastics. Present study investigated this confusion based on manual sorting analyses of waste sampled from packaging waste (*P*), biowaste (*B*) and residual waste (*R*) in an urban area of Austria. The results were evaluated relative to near-infrared sensor-based sorting trials conducted in a German urban area. Although existing literature has focused on waste composition analyses (mostly in stand-alone studies) of the three waste streams, the present study focused on identifying the specific types of biodegradable plastic items found in each of these streams. Supermarket carrier bags ($P=90$, $B=14$, $R=33$) and dustbin bags ($P=2$, $B=46$, $R=6$) were found in all three waste streams in the Austrian urban area. Similarly, in the German urban area dustbin bags ($P=1$, $B=106$, $R=3$) were the common items. The results indicate that certain bioplastic items were present in more than one bin; thus, hinting that consumers are not necessarily aware of how-to source-separate the biodegradable plastics. This suggests that neither consumers nor current waste management systems are fully 'adapted' to bioplastics, and the management of these plastics' waste is currently not optimal.

Keywords

Bioplastics waste management, biodegradable plastics, consumer confusion, EU legislation, waste sorting analyses, waste collection and sorting, waste sorting guidelines

Received 28th April 2023, accepted 19th January 2024 by Associate Editor Anke Bockreis.

Introduction

Biodegradable plastics are often promoted over conventional plastics due to their biodegradability and could either be bio- or fossil-based (European Bioplastics, 2018; Meeks et al., 2015). Some of the most prominent biodegradable plastics currently available in the market are thermoplastic starch, polylactic acid (PLA), polyhydroxybutyrate, polybutylene adipate terephthalate and polybutylene succinate (Endres and Siebert-Raths, 2011). Their main applications include food packaging, takeaway containers, biowaste bin-liners and single-use plates/cutlery (Eubeler et al., 2010; Fredi and Dorigato, 2021). According to European Bioplastics e.V. (2022), biodegradable plastics contributed about 64% of total bioplastic production, which is expected to grow substantially in the future (European Bioplastics e.V., 2022). Biodegradability combined with a renewable origin enables plastics to be perceived as environmentally friendly (Moshood et al., 2022a). However, this perception does not necessarily ensure appropriate waste management. Considerable challenges associated with the waste management of biodegradable plastics have been discussed in the literature (Feghali et al., 2020; Rujnić-Sokele and Pilipović, 2017); for instance, contamination of conventional plastic recyclates or unacceptance by organic treatment facilities (Åkesson et al., 2021; Calabrò and Grosso, 2018). With consumers potentially preferring biodegradable plastics over other plastic types owing to their perceived environmental friendliness (Dilkes-Hoffman et al., 2019; Gill et al., 2020; Herbes et al., 2018; Moshood et al., 2022b), it is important to understand the fate of these plastics in the waste management phase.

Despite their perceived environmental properties, there appears to be considerable confusion surrounding the correct disposal of biodegradable plastics, both from consumers and the

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waste management sector (Meeks et al., 2015; ÖWAV, 2021; Soroudi and Jakubowicz, 2013). Consumers may falsely assume that all bioplastics are biodegradable (Blesin et al., 2017; Niaounakis, 2019), which may increase the perception of 'environmental friendliness' beyond what is warranted by the plastics themselves, thereby essentially leading to greenwashing (Arikan and Ozsoy, 2015; Atiwesh et al., 2021; Nazareth et al., 2019). Confusion from consumers is particularly associated with 'where to throw' the plastics (Dilkes-Hoffman et al., 2019; Lynch et al., 2017), leading to demands for clear information and appropriate sorting guidelines (Fletcher et al., 2021). This confusion concerning the choice of the waste bin is bound to be reflected in bioplastic waste disposal practices. Although most of the studies in the literature addressing consumer behaviour regarding bioplastics have been based on surveys and qualitative interviews, very little experimental data exist about the actual presence of bioplastic in household waste flows.

In most European countries, a separate collection of biowaste, packaging waste and residual waste is practiced. Since some bioplastics are both biogenic and plastic (European Bioplastics, 2018), the question of in which bin they should be disposed of is tricky. The present article addressed the indecisiveness regarding the correct disposal pathway for bioplastics as 'consumer confusion'. In this context, certain clarifications must be made: Firstly, there is neither a uniform expert opinion nor a uniform waste legislation regarding this issue (Briassoulis et al., 2019). In addition, the answer to the question of 'where to throw' is influenced by material properties (e.g. biodegradability, theoretical recyclability) and waste treatment infrastructures (practical recyclability) along with legal issues, namely, who pays for bioplastic waste treatment, as manufacturers pay for plastic packaging waste treatment, whereas biowaste treatment is paid by the communities (Bundes-Abfallwirtschaftsplan, 2023). This suggests that any decision based only on material properties is insufficiently justified. Secondly, factors such as different types of bioplastics (biobased non-biodegradable and fossil-based biodegradable), differences between biodegradability and compostability and their different behaviour under lab- and industrial composting conditions create further confusion (European Environment Agency, 2020; Rujnić-Sokele and Pilipović, 2017). In other words, the disposal route for the different bioplastic products often depends on the type of bioplastic and their application. Thus, to improve the management of these plastics, it is important to have better information about the actual sorting and fate of these plastics in collected waste.

Although considerable studies discussed the waste characterization of individual waste streams, such as (Chazirakis et al., 2023; Gala et al., 2020; Lase et al., 2022; Tomić et al., 2022), relatively few mentioned biodegradable plastic in the waste streams. For instance, a 2020 study found 0.14% (−0.06%, +0.32%) bioplastic packaging share in lightweight packaging (FHAnalytik, personal communication, April 25, 2023). Beigl et al. (2020) obtained a share of 0.62%wt. bioplastics in biowaste in the Neunkirchen district (2017–2020). In addition, another study of biowaste bins in Vienna (2019) found approximately 0.23% of bioplastics in biowaste and provided a share of biodegradable bags and dustbin bags (FHAnalytik, personal communication, April 25, 2023). Lastly, 0.19% biodegradable packaging was found in residual waste in Vienna in 2019 (FHAnalytik, personal communication, April 25, 2023). Moreover, simple identification of biodegradable plastics is of little use, because, unlike conventional plastics, a variety of biodegradable plastics exist with different properties and applications on the market (Fredi and Dorigato, 2021). No studies in the literature have characterized individual biodegradable plastic items and evaluated their presence in waste streams and potential confusion around source separation.

The present article aims to fill in this gap and address the confusion around the disposal of biodegradable plastics in the context of a waste sorting analysis. The main research question was to identify what kind of biodegradable plastic items are present in three waste streams – (i) packaging waste, (ii) biowaste and (iii) residual waste. This question was addressed by conducting sampling and manual sorting analyses in an urban area in Austria and sorting trials using a near-infrared machine in an urban area in Germany. Identifying whether this potential confusion is for all kinds of bioplastic items or is limited to only certain types will help in taking necessary actions to facilitate the proper disposal of these items. In addition, comparing the results with the existing sorting guidelines will help to identify prospective improvements needed.

Methodology

Two case studies are discussed in this article. The first study was conducted in an urban area of Austria, and the second case study was conducted in an urban area of Germany. The urban areas for the two countries were selected based on the waste availability with the two project partners (the sorting facility in Austria and TOMRA sorting GmbH in Germany). In addition, in the case of the Austrian study, the sampling methods were chosen based on the waste stream. The following sections discuss the chosen methodology in detail.

Study of three waste streams in Austria

Manual sorting analyses. The main idea of this study was to identify what type of biodegradable plastic items were disposed of in these three streams by the consumers, who can only use the visual identification (VI) method for source separation. The samples were manually sorted using the VI method (Figure 1(a)), where labels for compostability (e.g. Seedlings logo, TÜV Austria labels, DIN CERTO) and polymer identification number 7 (PLA) were used (Din Certco – TÜV Rheinland, 2022; TÜV AUSTRIA Belgium, 2022a). Thus, all waste items displaying the above labels/number were sorted out. The sorted samples were divided into seven categories: supermarket carrier bags, dustbin bags, nets from wood fibre, single-use rigid containers (PLA),

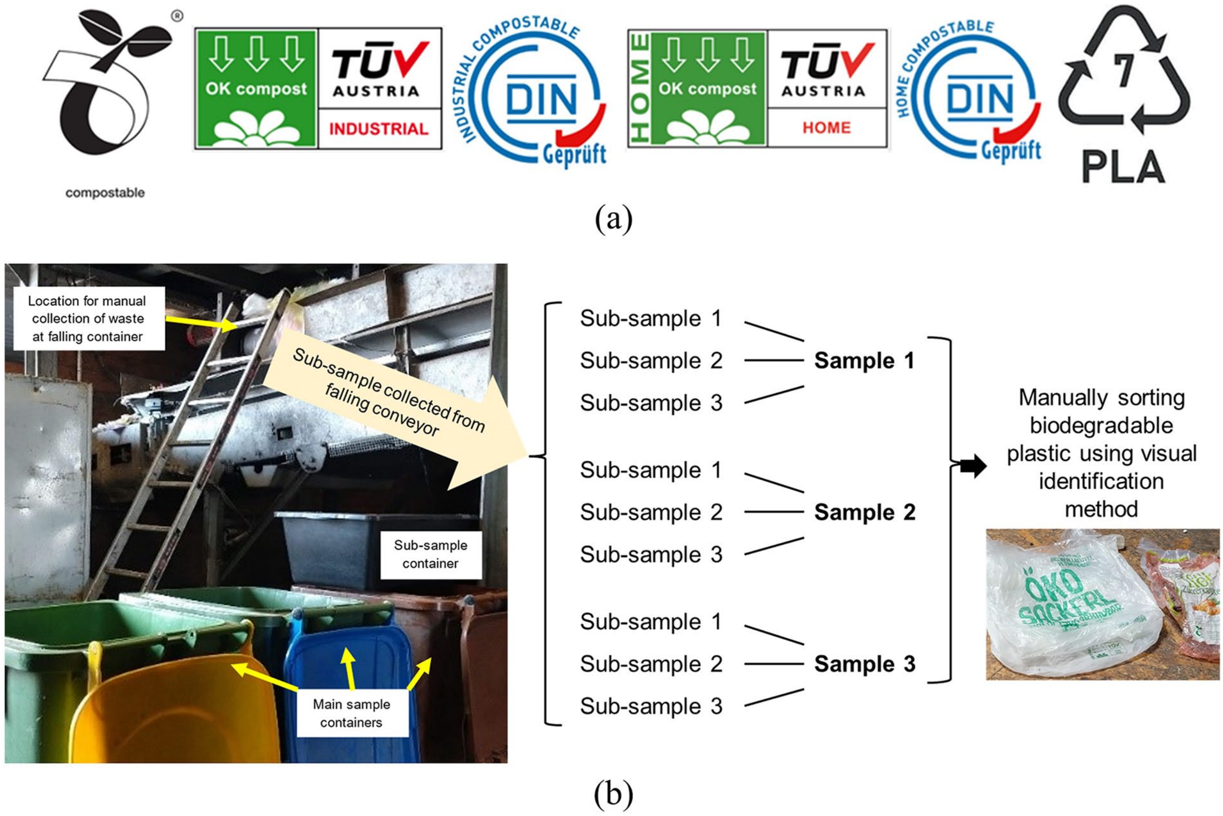

Figure 1. (a) Available compostability labels and resin identification number 7 (with PLA mentioned underneath 7) were used as the VI method for manual sorting. (b) Sampling process of packaging waste in a plastic-waste sorting plant in Austria.
Source: (a) European-bioplastics.org, tuv-at.be, dincertco.de, showsbee.com; (b) by Author.
PLA: polylactic acid; VI: visual identification.

compostable packaging with labels, and label-less claims. The label-less claims were greenwashing examples, which falsely claimed to be biodegradable without any compostability labels to support them.

Sampling of packaging waste. Sampling was conducted at a plastic-waste sorting plant in an Austrian urban area. The mixed plastic waste arriving at this plant first passes through a wind-sifter, magnetic separator and near infrared (NIR) sorting units, where metals, polyethylene terephthalate, polyethylene, polypropylene and polystyrene are extracted, and the rest (reject fraction) is packed into bales and sent for thermal recovery. This reject fraction was chosen for sampling, as biodegradable plastics mostly landed in this fraction (Lorber et al., 2015). For the present study, it was assumed that in the studied plant 100% of biodegradable plastic from the input lands in the reject fraction. Also, the possible contamination of biodegradable plastics in the conventional plastic recycling streams of the concerned sorting plant was considered negligible; thus, assuming that 100% of biodegradable plastic from the input lands in reject fraction.

Samples were collected manually from part of the material transported from a falling conveyor belt (Figure 1(b)), right before the material reached the bale-press unit. The black container (Figure 1(b)) filled with the waste formed one sub-sample. Three such sub-samples were collected in a bin (one of the brown, blue or yellow bins in Figure 1(b)), which formed one sample, and three such samples were collected at a time. This action was repeated three times a day (for two working shifts); thus, nine samples (minimum 5 kg each) were collected per day. As a result, in the 3-day sampling process, 27 samples were collected.

Sampling of biowaste. Sampling was conducted at an industrial compost plant in an urban area in Austria. Biowaste arrived at the compost plant in trucks and was laid in windrows on the ground for its composting. Samples were collected from this input fraction. Biowaste from a truck was emptied on the ground, which was then mixed using a wheel loader and spread into a linear heap. This heap was divided into three sections (Figure 2), and 10 sub-samples were taken from each section of this heap at random locations and depths, forming one sample, which was collected in a bin. Thus, three samples (minimum 2 kg each) were taken from a truckload of biowaste. In a day, samples from three trucks were collected; so, 9 samples per day. So, for 3 days 27 samples were collected.

Sampling of residual waste. Sampling was conducted in a residual waste treatment plant (splitting plant) in an urban area in Austria. The residual waste arriving in a truck was emptied in an indoor unloading area, from where it was transferred to the splitting plant with the help of a wheel loader. Samples were collected randomly from the input fraction arriving at the

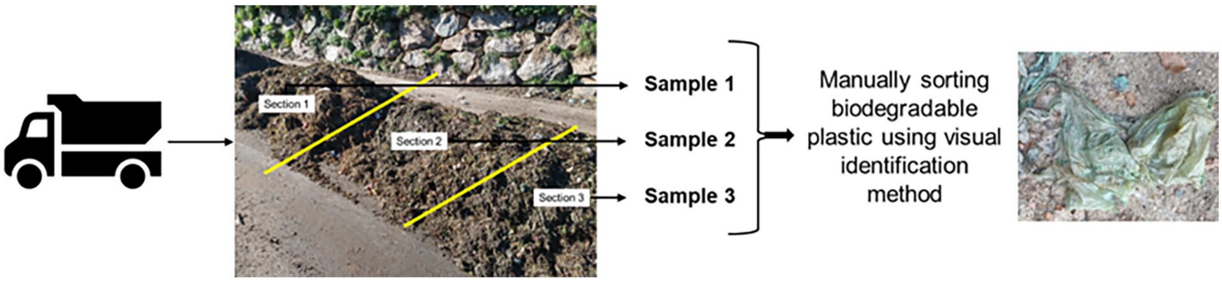

Figure 2. Sampling of biowaste in an industrial compost plant in Austria.
Source: By Author.

Figure 3. Sampling of residual waste in a splitting plant in Austria.
Source: By Author, wheel loader icon made by Pixel perfect from www.flaticon.com.

facility. A wheel loader was used to mix the waste from the emptied truckload of waste. Then, a portion of the waste was taken by the wheel loader and emptied into a container, forming a sample, which was then delivered to the sorting area and emptied using a forklift. Afterwards, the heap was spread and divided into four quadrants (Figure 3). A random quadrant was selected, weighed and then used for sorting out biodegradable plastics. Three such samples (minimum 10 kg each) were collected at a time; thus, three times a day, nine samples were collected. So, for 3 days, 27 samples were collected.

Statistical evaluation. The share of manually sorted bioplastics was calculated based on weight. Descriptive statistical parameters (mean, standard deviation and coefficient of variation) were calculated for this dataset. For this study, a 95% confidence level was selected (European Commission, 2004). Additionally, assuming normality, confidence intervals for the resulting bioplastic share were provided. Lastly, bioplastic share results from the three waste streams were analysed with the help of the Kruskal–Wallis test to identify significant differences among the three waste streams.

Study of three waste streams in Germany

Setting up classifier. The sorting trials were to be conducted with a NIR AutoSort machine at the technical centre of TOMRA Sorting GmbH. A classifier was created on this machine with the aid of an onsite application engineer using the reference database created using two sets of data: group 1 and group 2.

Group 1: Known standard material. Virgin samples of biodegradable plastics were obtained from the Polymer Science department in Montanuniversitaet Leoben, which were used to create a reference database using a Fourier transform infrared (FTIR) spectroscopy machine. Additionally, a Mater-Bi carrier bag sample (privately collected) was used. Table 1(a) below shows the list of group 1 materials.

Group 2: Unknown material. For this set, privately collected biodegradable plastic samples from the Austrian market were used. Group 2 materials were identified using the FTIR reference database created in the previous step. Thus, a comprehensive database consisting of virgin and market-available biodegradable plastics was created. Table 1(b) shows the list of group 2 materials.

This database was used for training the TOMRA AutoSort NIR machine at the test centre, while also validating the results from FTIR identification. The wood-fibre nets were also taught in the classifier. Additionally, the database was optimized using manually sorted biodegradable plastics (similar samples based on brand and type) from the Austrian sampling analysis (previous section), to include the possible influence of surface contamination. In the end, all these materials were combined under a common bioplastics NIR recipe for conducting the sorting trials.

Table 1. (a) List of group 1 reference material used for setting up the classifier; (b) list of group 2 reference material used for setting up the classifier.

(a).

Sr. no.	Material	Description
1	PBAT	Jinhui Zhalon Ecoworld 1908 PBAT
2	PBS	Mitsubishi Bio FZ91 PM PBS
3	PHB	Lab-made
4	PHBH	Kaneka X331N
5	PLA	PLA INGEO 4032D PLA
6	PLA	Naturplast NPSF 141
7	PLA	Grade 2 PLA
8	PLA	PLA INGEO 2003 PLA 73290
9	PLA blend	BioFed Mvera B5029 (22)
10	PLA composite	PLA Composite BioFlex F1804
11	PLA/PBAT blend	BioFlex F2110
12	PLA/PBAT blend	Ecovio F23B1
13	PLA/PBS blend	Lab-made, 70% INGEO (PLA 73290) and 30% Mitsubishi F271 PM PBS
14	TPS	Bioplast 300
15	Mater-Bi bag	Licenza NOVAMONT n.021 plastic bag

PHBH: polyhydroxybutyrate-hexanoate; PBAT: polybutylene adipate terephthalate; PBS: polybutylene succinate; PHB: polyhydroxybutyrate; PLA: polylactic acid; TPS: thermoplastic starch.

(b).

Sr. no.	Application	Description	Material by FTIR
1	SB	SB_Item-1 – from supermarket 1	TPS
2	SB	SB_Item-2 – from non-supermarket shop 1	Mater-Bi
3	SB	SB_Item-3 – from supermarket 3	Mater-Bi
4	SB	SB_Item-4 – from non-supermarket shop 2	TPS
5	SB	SB_Item-5 – from non-supermarket shop 3	TPS
6	SB	SB_Item-6 – from non-supermarket shop 4	TPS
7	DB	DB_Item 1 – 35L bag, company 1	TPS
8	DB	DB_Item 2 – 20L bag of company 1	TPS
9	DB	DB_Item 3 – 10 L bag, company 2	TPS
10	FP	FP_Item 1 – 500 g carrot packaging, company 1	Bio-PBS
11	FB	FP_Item 2 – wood-fibre net, company 2	Identified as Rayon Fibre (taught as wood-fibre to classifier)
12	FB	FP_Item 2 – wood-fibre net company 3	Identified as Rayon Fibre (taught as wood-fibre to classifier)
13	FB	FP_Item 2 – cookie packaging company 4	TPS
14	SUR item	SUR_Item 1 – compostable cup	PLA

PLA: polylactic acid; PBS: polybutylene succinate; SB: supermarket carrier bags; DB: dustbin bags; FB: food packaging; SUR: single-use rigid; TPS: thermoplastic starch; FTIR: Fourier transform infrared; Mater-Bi: Novamont brand name for a TPS, polybutylene adipate terephthalate and polycaprolactane blend.

Sorting trials. Waste from three waste streams was arranged by TOMRA from an urban area in Germany. The previously set classifier was used for sorting all the biodegradable plastics irrespective of their type. The sorting programmes were set with the aim of high recovery of all bioplastics regardless of losses.

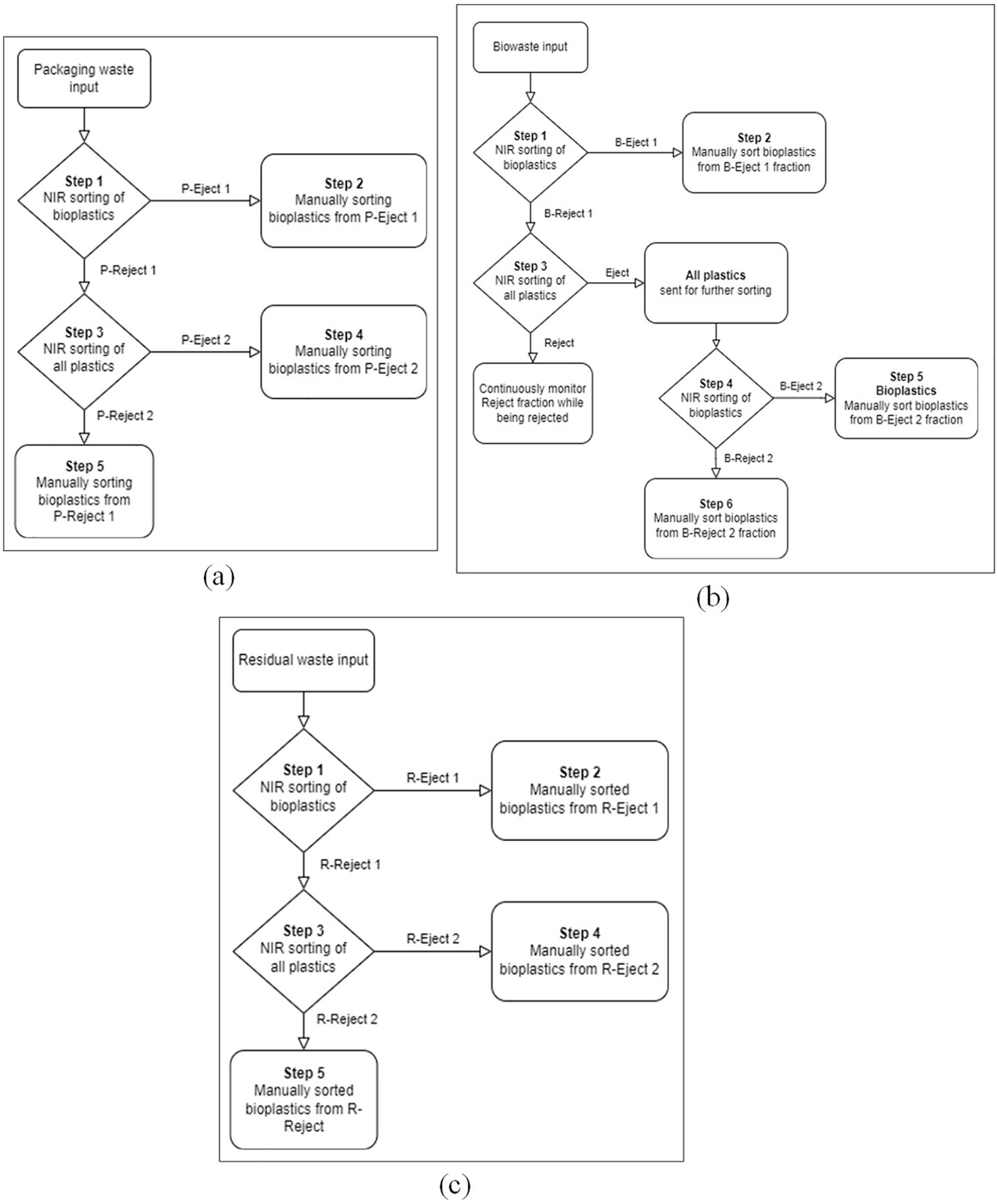

Figure 4. (a) Steps for sorting trial for packaging waste; (b) steps for sorting trial for biowaste; (c) steps for sorting trial for residual waste.

Packaging waste. The reject fraction arranged from the sorting plant was used for the analyses, after extracting metals and valuable recyclables as well as polyvinyl chloride. Figure 4(a) illustrates the steps followed during the sorting trials. The input fraction used for the trial was delivered in two large bulk bags; therefore, the steps for sorting trials were repeated twice (Supplemental Figure S1).

Biowaste. The overflow and reject fractions of the biowaste treatment plant were mixed and used for the sorting trials. The steps followed to conduct the sorting trial for biowaste are illustrated in Figure 4(b) and the resulting mass balance is described in Supplemental Figure S2.

Residual waste. The higher calorific fraction from the residual waste treatment plant was used for the analyses. Figure 4(c) illustrates the steps followed during the sorting trials. The input material was delivered in two large bulk bags; therefore, the steps for sorting trials were repeated twice (Supplemental Figure S3).

Results

Study of three waste streams in Austria

Results of manual sorting. From 27 samples of packaging waste, a total weight of 224.8 kg was amassed. Out of this, about 0.463 kg ($0.21 \pm 0.05\%$) of biodegradable plastics were sorted out using VI. As shown in Table 2, 101 items were sorted out, of

Table 2. Biodegradable plastic items in the manually sorted samples from packaging waste (*P*), biowaste (*B*) and residual waste (*R*) in an Austrian urban area.

Biodegradable plastic items		Number of items in three waste streams			Sorting instructions	
		P	*B*	*R*	National legislation	Sorting guidelines
Supermarket carrier bags		90	14	33		
Dustbin bags		2	46	6		
Wood-fibre nets		7	0	0		
PLA single-use containers		0	0	4	*P*[1]	*P*[2]
Compostable packaging		1	0	0		
Label-less claim		1	2	10		
Total		101	62	53	-	-

Data source: 1 – Bundesministerium für Nachhaltigkeit und Tourismus, 2019; 2 – Holding Graz (2023a, 2023b).
Supermarket carrier bags are provided in supermarkets and are promoted to be reused as dustbin bags; dustbin bags are biowaste collection aids; wood-fibre nets are used for lemons and onion; single-use rigid containers are takeaway containers and cups made of PLA; compostable packaging is for vegetables with compostability labels available in supermarkets; label-less claims (greenwashing) are items displaying 100% biodegradable without any compostability label.
PLA: polylactic acid.

Table 3. Biodegradable plastic items in the manually sorted samples from packaging waste (*P*), biowaste (*B*) and residual waste (*R*) in a German urban area.

Items	Number of items			Sorting instruction	
	P	*B*	*R*	National legislation	Sorting guidelines
Supermarket carrier bags	10	0	2	*P*[1]	
Dustbin bags	1	106	3	*B*[2]	
Wood-fibre nets	7	0	2		*P*[3]
PLA single-use containers	2	0	0	*P*[1]	
Compostable packaging	1	0	0		
Label-less claim	1	0	0		
Total	22	106	7	-	-

Data source: 1 – Umweltbundesamt (2020); 2 – Biowaste Ordinance (2013); 3 – Abfallwirtschaftsbetriebe Köln GmbH, 2023a (2023b).
Supermarket carrier bags are provided in supermarkets and are promoted to be reused as dustbin bags; dustbin bags are biowaste collection aids; wood-fibre nets are used for lemons and onion; single-use rigid containers are takeaway containers and cups made of PLA; compostable packaging is for vegetables with compostability labels available in supermarkets; label-less claims (greenwashing) are items displaying 100% biodegradable without any compostability label.
PLA: polylactic acid.

which supermarket bags were found in the majority, followed by wood-fibre nets. Additionally, a few dustbin bags, compostable packaging and one label-less claim were found.

In the case of biowaste, 27 samples amounted to a total weight of 215.3 kg. Manual sorting of biodegradable plastics resulted in an average of 1.35 ± 0.42% (3.094 kg). In comparison to the other two waste streams, it was challenging to identify bioplastics because of the surface contamination and their smaller size. Of the total 62 sorted items, dustbin bags were in majority, followed by supermarket bags (Table 2). No other bioplastic items were found.

In residual waste, the 27 samples resulted in a total weight of 660.3 kg, from which about 0.14 ± 0.10% (0.826 kg) of biodegradable plastics were manually sorted out. Table 2 shows that of the total 53 items, supermarket bags were in majority, followed by dustbin bags. For the first time, one PLA single-use container was found. Additionally, 10 label-less claims were found.

With the help of a Kruskal–Wallis test, it was confirmed that there is a significant difference between bioplastic share data from the three waste streams. Additionally, the coefficient of variation was calculated for bioplastic share from each waste stream and resulted in values of 63.43, 78.12 and 166.07% for packaging, bio- and residual waste, respectively. However, this higher value of the coefficient of variation hardly affects the conclusions, as the present article is more concerned about similar kinds of bioplastics found in the three waste streams, instead of the percentage share of bioplastic in each waste stream; thus, the results were deemed applicable for the derived interpretation.

Study of three waste streams in Germany

Results from the sorting trials. It was found that about 0.067 kg of bioplastics were found in the packaging waste fraction (110.46) kg, amounting to 0.061%. Supplemental Figure S1 shows the mass balance of the biodegradable plastics during the sorting trials. It was observed that more quantity of biodegradable plastics was found in P-Eject 2 and P-Reject 2 fractions, than in the previous step (P-Eject 1 and P-Reject 1). In addition, most of the bioplastic items were supermarket carrier bags, wood-fibre nets and one item of PLA single-use rigid container (Table 3). Table 2 shows the images of the bioplastic items.

It was found that about 3.01 kg of bioplastics were present in the entire biowaste fraction (971.71 kg), amounting to 0.31%. Supplemental Figure S2 shows the mass balance of the biodegradable plastics during the sorting trials. It could be seen that most of the bioplastics (about 71.6%) were sorted out in the P-Eject 1 fraction, and about 24.1% and 4.2% were recovered from the P-Eject 2 and P-Reject 2 fractions, respectively. Here, only biodegradable dustbin bags were found (Table 3).

In the entire residual waste fraction (561.33 kg), about 0.0725 kg of bioplastics were found, which amounted to 0.013%. Supplemental Figure S3 shows the mass balance of the sorting trials. A considerable number of biodegradable plastics were found in P-Eject 2 and P-Reject 2 fractions. In addition, the bioplastic items found were dustbin bags, wood-fibre nets and supermarket carrier bags (Table 3).

Discussion of results

The main purpose of the study was to identify which kind of biodegradable plastics are found in the three waste streams in an Austrian urban area, for which sampling and manual-sorting analyses were conducted. These results were evaluated relatively by the data obtained from sorting trials of waste from three streams conducted in an urban area in Germany. The study was focused only on biodegradable plastics, and hence, did not consider the presence of other plastic types in the waste.

From the manual-sorting analyses in an Austrian urban area, it was found that about 0.21, 1.35 and 0.14% of biodegradable plastics were sorted out from packaging-, bio- and residual waste streams, respectively. These findings were in line with the results of a sampling study conducted by FHAnalytik (personal communication, April 25, 2023) in 2020, which found a 0.14% share of bioplastic packaging in lightweight packaging. Moreover, a bioplastic share of 0.62 and 0.23% was found in biowaste in studies conducted by (Beigl et al., 2020) and FHAnalytik (personal communication, April 25, 2023), respectively. The share of biodegradable plastics found in the current study is slightly more than that found in the two studies; however, it still could be considered comparable, as the difference is not outrageously high. Lastly, 0.19% of bioplastic packaging was found in residual waste (FHAnalytik, personal communication, April 25, 2023). The 0.14% bioplastic share found in the present study is slightly below the one mentioned in the previous study.

The results show that for the chosen period of sampling waste in an Austrian urban area, a total of 101 items were found in packaging waste, 62 items in biowaste and 53 items in residual waste. Supermarket carrier bags were found in majority in packaging waste (90) and residual waste (33), whereas in biowaste, dustbin bags (46) were in the majority. Smaller quantities of supermarket carrier bags were also found in biowaste (14) and dustbin bags in packaging (2) and residual waste (6). Thus, supermarket carrier bags and dustbin bags were found in all three waste streams, although in varied quantities. This suggests that even with the presence of compostability labels, similar bioplastic items were found in the three waste streams.

Similar results were observed with the sorting trials conducted in an urban area of Germany, with a share of biodegradable plastics of 0.061, 0.31, and 0.013% in packaging-, bio- and residual waste, respectively. Here, the highest number of biodegradable plastic items were seen in biowaste (106) – all dustbin bags. Packaging waste had 22 items, with a majority of supermarket carrier bags (10) and wood-fibre nets (7), and 1 dustbin bag. Residual waste had only 7 items, with mostly dustbin bags (3), followed by supermarket carrier bags (2) and nets (2). As a result, even though in small quantities, it was seen that dustbin bags were present in all three waste streams, whereas supermarket carrier bag were present in packaging and residual waste. Thus, in all three waste streams, common biodegradable plastic items were found.

In other words, in both cases, specific biodegradable items were found in more than one waste stream. As this study focused on finding what kind of bioplastic items are found in the three waste streams, the obtained data sufficiently hints at the confusion surrounding their disposal based on the distribution of specific items in more than one bin. This confusion could be because either the consumers know in which bin they should be thrown but are unable to correctly identify biodegradable plastic (Blesin et al., 2017; Niaounakis, 2019); or they know how to identify biodegradable plastics but are unsure of in which bin should they throw these bioplastics (Dilkes-Hoffman et al., 2019; Patrício Silva, 2021). It can be safely assumed that the first type of confusion is mainly applicable to biodegradable plastic products without compostability labels; for example, PLA containers. The second type of confusion arises from consumers' unawareness about where to throw these plastics, assuming that they are aware of the compostability labels. Although both confusion types could be addressed with proper awareness creation, it is the second type that is heavily influenced by the sorting guidelines. The results from the present study point towards consumers' 'where-to-throw' dilemma (Lynch et al., 2017; Marchi et al., 2020), as in both the studies, supermarket carrier bags and/or dustbin bags were the common bioplastic items in all three streams. Unlike PLA containers, where there are no compostability labels, these items had clear labels. A possible way to handle this confusion would be to provide updated and clear sorting guidelines for correctly disposing of biodegradable plastics.

In Austria, all plastic packaging should be included in the yellow bin starting in 2023 (ARA, 2022), and as per the sorting guidelines, plastic bags should be included in the yellow bin and no bioplastics should be thrown in biowaste (Holding Graz, 2023a, 2023b). Similarly, in Germany, only certified compostable bags are allowed in biowaste, whereas other biodegradable packaging is to be disposed of in packaging waste (Umweltbundesamt, 2020). However, the sorting guidelines of the studied urban area directed that no plastic bags (including bioplastics) belong in the biowaste bin; instead, they instructed to throw all kinds of plastic bags in the recycling bin (Abfallwirtschaftsbetriebe Köln GmbH, 2023a). On the contrary, the results from the present analysis show that certain biodegradable plastic items were found in all three waste streams of the studied urban areas (Tables 2 and 3), which showed consumer confusion about some bioplastic items (supermarket carrier bags and dustbin bags).

Greenwashing is also a major issue with biodegradable plastics (Orset et al., 2017). As seen, a considerable number of label-less claims items were found in the sampling analyses of three waste streams in Austria and 1 item in packaging waste in Germany. These were mostly bags claiming to be 100% biodegradable; however, they were polyethylene plastics. Some of these samples were part of the blacklist published by the compostability certification organization TÜV AUSTRIA Belgium (2022b), where they listed the items with wrong and misappropriated labels.

Nonetheless, the question remains where to throw these biodegradable plastics. The EU policy framework on biobased, biodegradable and compostable plastics, 2022 instructed that very lightweight biodegradable carrier bags (like supermarket carrier bags in the current study) should be thrown in biowaste (along with fruit stickers, tea bags and coffee pods), and the rest of biodegradable plastics should be thrown in plastic waste for material recovery. However, asking consumers to throw some biodegradable items in biowaste, and others in plastic waste, will further add to their confusion instead of reducing it. A rough extrapolation of the results from the two urban area studies suggests that the highest mass of bioplastic was estimated to land in biowaste (Supplemental Section S.III). However, dustbin bags were in the majority in biowaste for both the areas. Thus, only having bioplastic share does not provide enough information and needs to be supplemented with the type of product that lands in each waste stream. Additionally, the sorting guidelines of the two studied urban areas state that all plastic packaging should be directed to plastic waste (Tables 2 and 3). This raises the question of having biodegradable dustbin bags in the market when the sorting guidelines instruct to collect all plastic bags with packaging waste.

Thus, it could be inferred that assuming consumers are willing to correctly dispose of the bioplastics, the availability of correct (and uniform) sorting instructions is crucial to reduce this confusion. One possible way of doing this could be for manufacturers to include a note on their product stating: 'Biodegradability of this item does not imply a certain disposal route since this depends also on the existing waste treatment infrastructure and waste legislation. Please follow the waste sorting guidance in your region'. Additionally, having uniform sorting guidelines for a product throughout the country would also help in easing the confusion. Finally, for tackling greenwashing, updating the waste sorting guidelines with this information and providing accessible media with the blacklisted items could help in creating the necessary awareness amongst the consumers. Plus, shopkeepers need to be informed about greenwashing (especially in the case of carrier bags) because if they do not provide it, consumers will not be introduced to these items.

Conclusion

The present study examined the presence of biodegradable plastics in three waste streams – (i) packaging waste (P), (ii) biowaste (B) and (iii) residual waste (R). The main aim was to investigate the confusion around the disposal of biodegradable plastics in the context of a waste sorting analysis. For this, biodegradable plastics from these three waste streams were manually sorted out from the collected samples in an Austrian urban area, where 101, 62 and 53 items were found in packaging-, bio- and residual waste, respectively. Supermarket carrier bags ($P=90$, $B=14$, $R=33$) and dustbin bags ($P=2$, $B=46$, $R=6$) were found in all the waste streams. After finding that the three datasets were significantly different from each other using a statistical test, it was surmised that the findings suggest consumers' confusion about where to throw biodegradable plastic waste. These results were supported by NIR sensor-based sorting trials conducted with waste from a German urban area, where 22, 106 and 7 items were found in packaging-, bio- and residual waste, respectively. And dustbin bags ($P=1$, $B=106$, $R=3$) were found common in all three waste streams, while supermarket bags were found in the packaging (10) and residual waste (2). These results suggest consumers' confusion based on the distribution of specific items in more than one bin.

Unlike existing literature, which was more focused on consumer confusion about the disposal of biodegradable plastic expressed in the surveys and interviews, the current findings showed this confusion from a waste management perspective through manual sorting of sampled waste and sorting trials (manual and NIR-based). Additionally, the present study investigated different biodegradable items in the three waste streams while existing research mainly focused on the waste composition analyses of these three waste streams (often stand-alone studies). It was observed that the information on bioplastic share needs to be supplemented with the type of bioplastic product landing in the waste stream to improve its sorting.

As a further research possibility, it would be interesting to conduct another sampling analysis of the three waste streams after the release of the EU policy framework on biobased, biodegradable and compostable plastics, 2022, to understand whether this regulation has impacted the disposal of the biodegradable plastics. Lastly, a lifecycle assessment comparing the possible disposal methods for different bioplastic products could also assist in addressing this confusion.

Acknowledgements

The authors are grateful to the supervisor at Saubermacher Dienstleistungs AG and the staff at the waste-sorting, composting and splitting plants in Austria for their assistance during the waste sampling analyses. The authors are thankful to colleagues at the Chair of Waste Processing Technology and Waste Management (AVAW) in Montanuniversität Leoben for their physical support during the manual sorting of biodegradable plastics from biowaste and residual waste streams. Additionally, the authors would like to express their gratitude to supervisor, Ms Lisa Höflechner and the staff at the technical centre for TOMRA Sorting GmbH in Germany for their support in arranging the waste and conducting waste sorting trials. Finally, the authors would like to express a hearty gratitude to FHAnalytik, the company for chemical-technical analytics GmbH Chemical Laboratory, Engineering Office *(FHA – Gesellschaft für chemisch-technische Analytik GmbH Chemisches Laboratorium, Ingenieurbüro)* for providing certain data required for comparison in the 'Discussion of results' section of this article.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The project C-PlaNeT has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant agreement no. 859885.

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Supplemental material

Supplemental material for this article is available online.

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