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BIOPLASTIC CONTENT IN BIOWASTE: A GROWING PROBLEM IN COMPOSTING EFFICIENCY AND QUALITY

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ABSTRACT. The increase in fossil fuel–based plastic use and its subsequential refuse production and dispersion in the environment cause long-lasting waste that can pile up quickly. Compostable bio-based plastics, polymeric compounds that are functionally similar to fossil fuel–based plastics, seem to be more environmentally sustainable and particularly useful and recommended in food packaging. Even with the lower impacts of bioplastics, there is still a need for effective end-of-life management strategies to promote more efficient treatment of bioplastic waste. For biodegradable bioplastics, this endeavour could involve composting. Bioplastics would be processed like any other organic waste, prompting a closer study of how efficient this process is in degrading them, or if their presence can persist in high-quality compost or even in cultivated food. This paper focuses on organic waste treatment and compost production to assess the efficiency of bioplastic degrada-tion, aiming to explore the bioplastic content in compost in reference with a wide com-posting plants overview. An analysis of waste flow data from selected Italian composting plants highlighted a bioplastic reduction rate near 80%, with a small variance for different kinds of bioplastics, stressing the importance of investing in collection.

Keywords: bioplastic; biowaste; compost; treatment efficiency; waste management.

INTRODUCTION

Plastics are widely used manufacturing materials, with applications in a variety of industries. They are conventionally produced from petroleum, creating pollutants and greenhouse gases (Sorensen *et al.*, 2022). Petroleum-based plastics are not biodegradable, persisting in the environment as waste. To overcome some of these issues, there has been a

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growing interest in bioplastics, polymeric compounds that are both functionally similar to synthetic plastics and largely environmentally sustainable (Nanda *et al.*, 2022). There is not yet a universally recognised definition or terminology for bioplastics or bio-based plastic, but some of the most widely accepted options, like the European Union's (EU's), European Bioplastics (EB, 2024), state that a material is defined as such if it is either biobased, biodegradable, or both. Following the same EU definitions, 'biobased' means that the material or product is at least partly derived from biomass, while 'biodegradation' refers to the end of life (EOL) process where microorganisms convert materials into water (H_2O), carbon dioxide (CO_2), and compost. Given that this last property depends only on chemical structure, not all biobased plastics are biodegradable, while some fossil-based plastics can be.

There are some concerns associated with bioplastics, especially regarding the repurposing of land that has been used to fulfil food requirements. Indeed, a recent statistical study revealed that almost a quarter of the agricultural land producing grains is used to produce biofuels and bioplastics (Atiwesh *et al.*, 2021). The ability of bioplastics to decompose still needs to be evaluated more comprehensively, as low- or non-degrading bioplastics only break down at high temperatures or in industrial sites. Furthermore, when degrading, the process produces methane, albeit at much lower quantities than traditional plastic degradation in a landfill (Atiwesh *et al.*, 2021). Hence, the EOL management of these materials is still a topic of interest.

Bioplastics are suitable for a broad range of EOL treatments, including reuse, as is the case for rigid plates or most bags, mechanical recycling, anaerobic digestion, energy recovery, and, of course, composting (Abraham *et al.*, 2021). In particular, drop-in bioplastics – biobased-plastics such as bio-polyethylene terephthalate (PET) or bio-polyethylene (PE), which are chemically identical to their conventional counterparts – can easily be recycled via the existing infrastructure with no changes to technology or machinery, or even join conventional energy recovery streams (Fredi *et al.*, 2021; Kumar *et al.*, 2023; WWF, 2024).

Despite the relevant amount of bioplastic products that are produced as single-use goods, meaning that reuse is often not applicable, just like with any other waste stream, the European waste management hierarchy, EU Directive 2008 (EUR, 2024), should be followed. Biodegradation should still be seen as the very last life cycle step, after many steps of reuse and recycling, just like landfilling for their traditional counterparts (Abe *et al.*, 2022).

Compostable bioplastics that are recovered along with organic waste go through the same EOL processes, which are comprised of aerobic composting and anaerobic digestion. The former is the process where microorganisms convert organic waste into CO_2, H_2O, heat, minerals, biomass, and humus that is useful for plant growth, regulated in the European Union by the EU Council Directive on Landfill of Waste (EUR 1999/31/EC, 2024). This directive describes the various phases of the process. First, active composting lasts a minimum of 21 days, with temperatures in the industrial-scale composting heaps ranging from 50 to 70°C. In addition to guaranteeing hygienisation, these high temperatures also create a favourable environment for bioplastic degradation (EUR 2019/1009, 2024; Manea *et al.*, 2024). Second, a curing phase involves a slow and steady decline in the rate of decomposition (Trautman and Olinciv, 2019). Industrial composting plants are large-scale professional facilities that deal with significant amounts of organic waste. Their structure helps assure optimal processing conditions, fast compostable bioplastic degradation, good emission control, and good compost quality (Anjaly *et al.*, 2023). Anaerobic digestion is a similar process that occurs in closed reactors, converting organic waste into three main substances: methane-rich biogas, biosolids (the microorganisms that grow on the organic matter), and liquor (the dissolved organic matter). These last two can be used as fertilisers. (Centemero *et al.*, 2022)

Bioplastic degradation is more difficult in anaerobic conditions compared with aerobic conditions for several reasons, especially regarding how microorganisms break down organic materials and the environmental conditions required for these processes.

Anaerobic conditions limit the efficiency of microbial metabolism, restrict the types of microorganisms available, and can create unfavourable environmental conditions that slow down the degradation of bioplastics. In the absence of oxygen, anaerobic microorganisms rely on less efficient pathways (e.g., fermentation or methanogenesis). The processes also generate less energy, leading to slower microbial growth and lower degradation rates (Bátori *et al.*, 2018). Bioplastics such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) are degraded through hydrolysis and microbial action.

Under aerobic conditions, microorganisms can quickly metabolise the breakdown products (e.g., lactic acid in the case of PLA), whereas under anaerobic conditions, there are fewer microorganisms capable of utilising these by-products, and they act more slowly (Ali *et al.*, 2023).

Furthermore, anaerobic digestion is sensitive to fluctuations in pH and temperature, making it harder to maintain the optimal conditions needed for microbial activity. Finally, enzyme production is often slower and less effective, limiting the rate at which the bioplastic can be broken down into compounds that microorganisms can utilise (Vázquez-Fernández *et al.*, 2022).

A solution is to follow this process with composting, creating a new type of plant. This integrated plant shows higher process efficiency, maximising either energy or material recovering and showing lower emissions, both for greenhouse gasses and odour pollution (Hamedani *et al.*, 2020; Moretto *et al.*, 2019).

Although composting is not the first choice for bioplastic EOL treatment, it still serves an important purpose for the recovery of nutrients from low-grade bioplastic waste (Lebreton and Andrady, 2019). Life cycle analyses have revealed different findings: in one study, the authors found that Mater-Bi bags have a significantly lower environmental impact than paper bags and would have a similar impact to incinerated PE (Bastioli *et al.*, 2001). In another study, Dolci *et al.* (2021) reported that paper bags are a better alternative when bioplastic bags are excluded from anaerobic digestion. Thus, it is extremely important to investigate whether they can actually be composted to generate a more complete picture of the EOL options that should be considered. Based on these findings, bioplastic is still the most widespread material for organic waste collection, so there will likely always be a bioplastic fraction entering the biodegradation streams (Acharjee et al., 2023).

This study focused on process efficiency regarding bioplastic reduction, with the aim of clarifying national flows to facilitate policy and compost quality schemes based on a novel statistical analysis method to aid in future control sampling.

This method only monitors the total bioplastic presence in waste so that it can be employed more easily. It considers two categories: flexible bioplastics, which encompasses most packaging materials from bags to internal or external films (*Figure 1*); and rigid bioplastic, mostly composed of single-use goods such as cups, plates, coffee pods, and PLA trays and cutlery (*Figure 2*). Moreover, there is no distinction on the specific types of bioplastic, but only biodegradable materials are considered.

Figure 1 – Examples of flexible bioplastic from one of the sampled plants

Figure 2 – Examples of rigid bioplastic from one of the sampled plants

MATERIALS AND METHODS

This study considered the efficiency of Italian composting plants in biodegrading bioplastic. In Italy, organic waste comprises domestic/food waste, biodegradable green waste, and industrial/mud waste; it can undergo aerobic, anaerobic, or integrated treatment. Regarding bioplastic assessment, humid (domestic) waste can be considered as the main vector of transport, as the presence of bioplastics in green (garden and plant) waste and muds should be irrelevant. The 2021 Italian Institute for Environmental Protection and Research (ISPRA) data for the total waste treated were used, as the sampling campaign was undertaken in the same year. In 2021, across 356 plants, a total of 5,010,595 t of humid waste was treated, producing 1,174,993 t of refuse (*Table 1*). *Figure 3* shows the distribution of the types of plants in Italy in 2021.

Before carrying out the sampling campaign, a minimum relevant value for the number of plants to sample as well as the number of samples to collect was defined based on the International Accreditation Forum (IAF MD, 2018) Mandatory Document for the Audit and Certification of a Management System

Operated by a Multi-Site Organization. Depending on whether the computation refers to a first or control campaign, the minimum number of sites to sample is as follows:

First sampling: the sample size needs to be equal to the square root of the total site number, rounded up to the nearest integer (*Equation 1*).

$$n = \sqrt{T_i} \tag{1}$$

In this formula, n is the minimum relevant number of plants and T_i the total number of plants in the region considered.

Control campaign: the sample size needs to be equal to the square root of the total site number multiplied by 0.6, rounded up to the nearest integer (*Equation 2*).

$$n = 0.6\sqrt{T_i} \tag{2}$$

In this formula, n is the minimum relevant number of plants and T_i the total number of plants in the region considered.

These formulas should only be applied to a homogeneous set of samples; homogeneity can be achieved by selecting plants of a similar size and geographic location. Thus, for the 2021 sampling campaign, Italy was divided into 10 smaller regions. For each region, a minimum relevant number of plants was calculated; these numbers were added together to obtain a national minimum relevant number of plants that considers the regional density of plants (see *Figure 3*).

UNI/PdR 79:2020 (2024) (test method for verifying the disintegration of manufactured objects in industrial composting plant) was used to identify which plants could be considered relevant. This method defines how to identify the minimum characteristics of a composting plant in terms of operations, process management, requirements (i.e., quality management systems), and process representativeness. For this study, the focus was on plants where waste is subjected to a composting process of more than 12 weeks for a minimum flow of 10000 t/year, because analysing plants under this size is not relevant. Thus, all plants with a flow of more than 10000 t/year were grouped together, without differentiating between the treatment technologies or turning methods.

The same statistical considerations are valid to define the minimum relevant number of samples to collect. This was also calculated by considering plants with a processing time of more than 12 weeks and a capacity of more than 10000 t/year, but also waste aeration (forced or convective) and sanitation (following D.M. 5/2/98 allegato 1, sub-allegato 1, cap. 16). Specifically, this study focused on plants that have been in production for over 3 years, and, if the plant has more than one output flow, clear separation and traceability.

Based on the ISPRA and regional guidelines, a representative analysis requires a sample for every 200 m^3 of material. Assuming an average density of 0.4 t/m^3, samples should be taken for every 80 t of inflow material.

Following the previously stated guidelines on statistics relevance, the number of samples is as follows.

For a first campaign, rounded up to the nearest integer (*Equation 3*):

$$N = \sqrt{(\frac{yearly\ capacity}{80})} \tag{3}$$

where N is the minimum relevant sample size.

For a control campaign, rounded up to the nearest integer (*Equation 4*):

$$N = 0.6\sqrt{\left(\frac{yearly\ capacity}{80}\right)} \qquad (4)$$

where N is the minimum relevant sample size. It is also important to note the variability of input flows over time and the need to repeat the sampling campaign multiple times during a year to deal with this heterogeneity.

Given that the sampling guidelines consider large-sized plants, it is suggested to sample every 3 to 4 months. This variability is not very relevant for the refuse analysis, as it is the cumulative amount for the year.

Table 1 – Biodegradation flows in Italy for 2021 (source: ISPRA, 2024)

ISPRA 2021	Composting	Integrated	Anaerobic	Total
Humid waste (t)	1,864,997	2,824,222	321,376	5,010,595
Refuse (t)	481,718	654,835	38,440	1,174,993
Number of plants	293	42	21	356

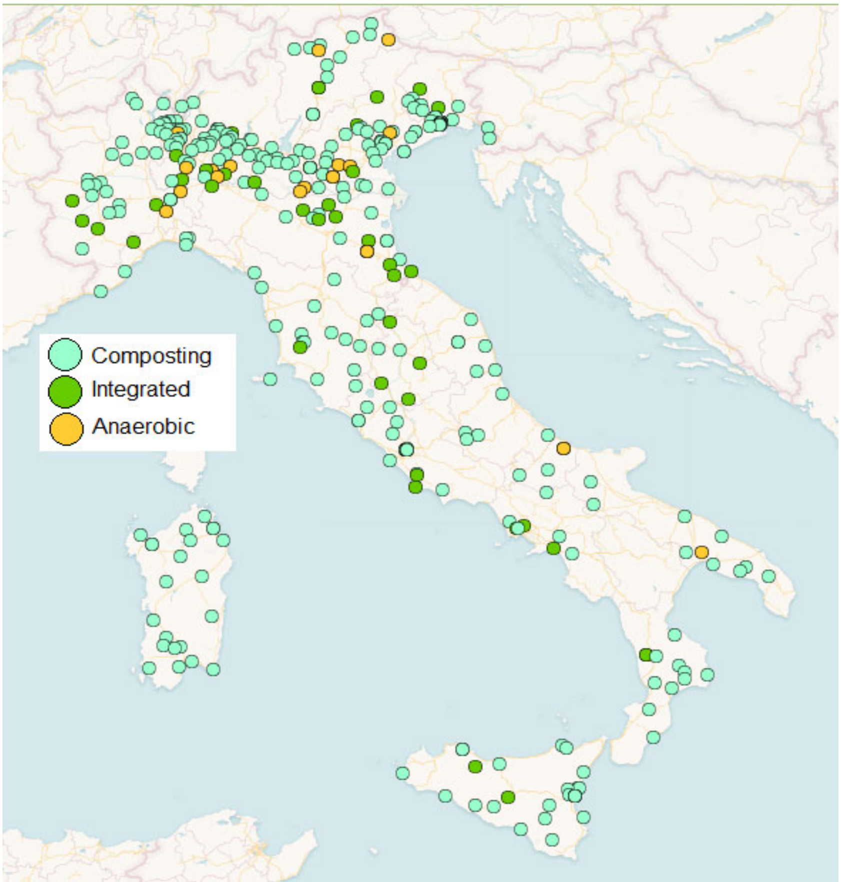

Figure 3 – Distribution of all plants that treated organic waste in Italy in 2021 (source: ISPRA, 2024)

For this sampling method, each sample should be around 3–4 t, the size of a truck load, and quartered, a sub-sampling procedure where each sample is spread evenly and separated into four equal parts. Then, this procedure is repeated on one of these four parts. After all the collection vessels (such as trash bags) are opened and emptied, they are saved for a separate vessel analysis.

Each product category is separated and weighed. During the 2021 sampling campaign, two sets of categories were used, specifically one for the vessels and one for the waste itself. After testing the incoming waste, the procedure was repeated on the refuse from the composting plants. The exact results of this analysis will not be shared in this study because they represent proprietary data, but the method used and statistical analysis are still relevant and implementable for any other sampling campaign.

RESULTS

The ISPRA (2021) data showed that in total, Italy's 356 composting plants processed 8,307,426 t of waste, of which 5,010,595 t, or around 60%, was humid waste. The 2021 sampling campaign covered around 35% of the organic waste treated nationally. The category analysis revealed that on average 93.11% (± 1%) of the waste treated was compostable organic material, of which 3.22% (± 1%) was bioplastics, while around 7% was non-compostable material (NCM), of which half was plastic and non-compostable bioplastic.

Based on the ISPRA (2021) data, the national total refuse produced was 1,174,993 t; again, around 35% was considered in the sampling campaign. Not all the refuse was analysed, as a part was identified as liquids, metals, and inert materials and separated before the sampling: liquids result from the biodegradation process, while metals and inert materials should not contain relevant amounts of bioplastics. The remaining refuse contained 35.90% (± 1%) of other NCM. Of the compostable material, 64% (± 1%), just 2.39% (± 1%) was bioplastic.

Because these averages have statistical relevance to the national situation, they can also be applied to the total national flows to obtain a clearer picture of the composting efficiency. The percentages obtained from the refuse analysis were adapted so that they would be relevant for the totality of refuse and not just for the relevant fraction, given that the sampling disregarded liquid, metallic, and inert waste.

This adaptation was done by proportionally relating the percentages from the relevant fraction to the total weight and using this new percentage to compute the total national amounts, which can be seen in *Figure 4*, it was also assumed that green waste would only be converted into compost and not end up in refuse.

To focus on bioplastic reduction, the amount involved in the total flow was calculated for the flexible and rigid categories (*Figure 5*). There was a significant reduction in the bioplastic content, around 78%, especially regarding the rigid fraction, where the reduction rate can be assumed to be near total. Meanwhile, almost 36% of the refuse comprised NCM, including approximately 25% of plastic and non-biodegradable bioplastic. Of note, a part of the flexible bioplastic, which is the most resilient with a reduction rate of around 66%, did not come from the waste itself, but rather from the necessary collection vessels. Only four samples were subjected to vessel analysis, as most of the waste had been delivered loose. Of all analysed vessels, 63.49% were made of bioplastic, 36.39% of conventional non-biodegradable plastic, and the remainder were paper. The most used kind of bioplastic vessel was a shopper; it has an as-is weight of around 40 g and thus contributed a significant part of the treated flexible bioplastic.

The findings from this sampling campaign are corroborated by the rise (seen in *Figure 6*) in plants adhering to the Italian Composting Consortium's (CIC) quality label. This scheme intends to guarantee consistency in the compost produced trough frequent product sampling. The presence of extraneous objects such as unreduced bioplastics could render plants ineligible for the label.

DISCUSSION

The data were assumed to be statistically relevant because the sampling was based on an initial planned strategy. Nevertheless, as part of this method we also propose a simple analysis to confirm the relevance of the acquired data. First, each region's computed minimum representative number of plants is compared with the number of sites actually tested in the area, to see which areas were the most under-represented.

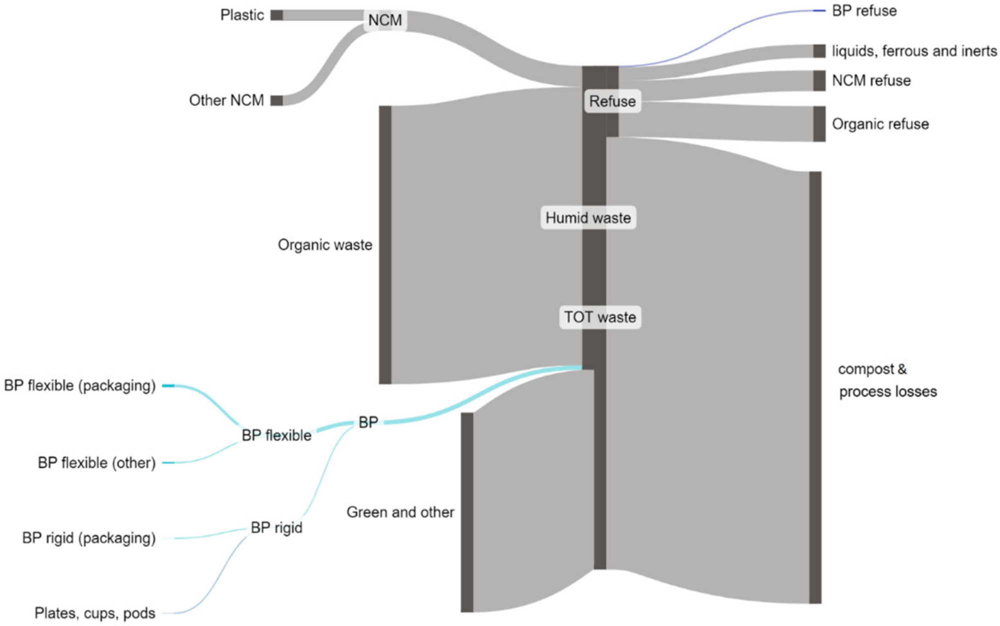

Figure 4 – Simplified visualisation of the mass balance of waste treated in Italian composting plants in 2021, based on the results of the sampling campaign

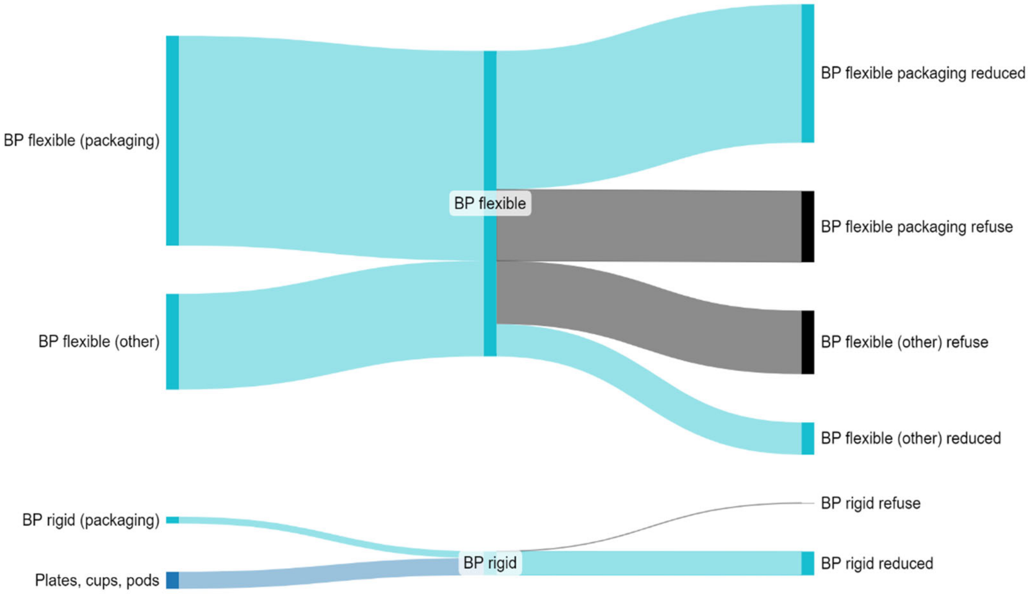

Figure 5 – Mass balance of bioplastic treated in Italian composting plants in 2021, based on the results of the sampling campaign

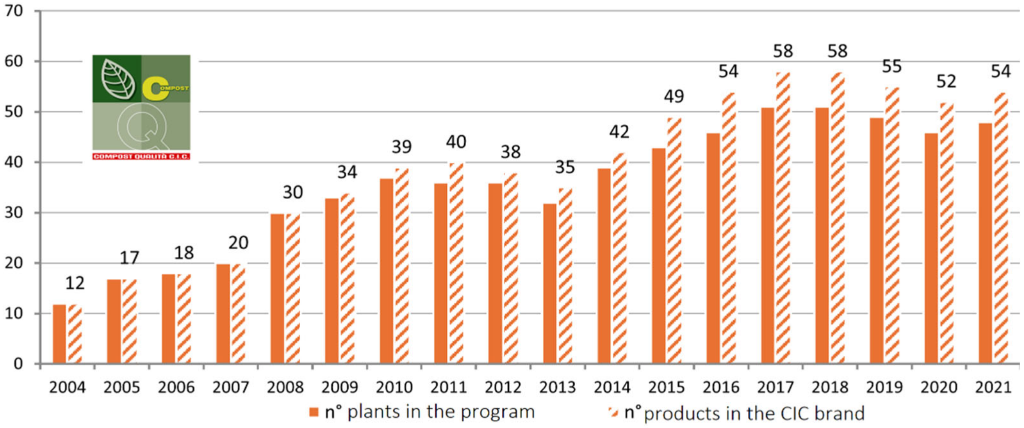

Figure 6 – Adherence to the Italian Composting Consortium's quality label (source: CIC Annual Report, 2022)

If discrepancies are found, then they should be justified. In the present study, there was a small discrepancy between the number of tested plants and the required minimum due to a change in the area subdivisions. Initially, only 5 macro-areas were planned, but this number was doubled to 10. This issues highlights the need to finalise the initial plan. Next, we propose an analysis to check that the proportional distribution was maintained close to the regional plant density, with a concentration in the regions where the waste flow is higher. This means that although the regional sampling plant distribution might not be exact, it still covers most of the national flows. This was true in the 2021 sampling campaign, as the three regions with the highest waste flow were even over-sampled. Finally, the number of samples is compared with the required minimum with the same process, while considering that for the refuse a re-sampling over 3 or 4 months might not be needed, as the seasonal variation is minor, and refuse can often be stored for longer times. Furthermore, there might be cases where the initial delivered NCM seems to increase in weight in the refuse analysis. This issue could be caused by inclusion of the sampling category in the previous categories as well as liquid refuse, which is a by-product of the composting process.

This final analysis aims to guarantee that the results are both reliable and relevant on a national scale. Because of sensitive data, most of the results could only be shown in a simplified visualisation (i.e. the mass balance of waste treated). *Figure 4* and *Figure 5* are only finalised to show the relative amount of all fractions, aiming to have a qualitative, big-picture view.

Even without specific data it is clear that there has been a noticeable, especially for single-use goods such as cutlery and coffee pods. The sampling methodology can also be adapted to several other *in situ* analyses.

CONCLUSIONS

Bioplastics also present production issues that have plagued traditional plastics, such as energy and water requirements and the use of hazardous chemicals/additives, albeit to a lesser extent. Nevertheless, bioplastics have the potential to reduce the use of fossil fuels and related environmental and health impacts, and to avoid non-degradable plastic waste (Piemonte, 2011). The method described in this study proved to be an effective monitoring strategy on the national level, and it can be deployed going forward. The 2021 sampling campaign data confirmed that bioplastics can decompose instead of persisting in the environment. For most consumable goods (the bulk of rigid bioplastics), this degradation is almost perfect, meaning that there are no fragments in the final compost, and its quality is in no way impacted by the processing of rigid bioplastic. Flexible bioplastics (mostly packaging and bags) present less efficient degradation, but still only a third persists. Any macroplastic contamination could simply be reprocessed in the same plant or left to further reduce in the finished product, because it is clear that bioplastic decomposition is fully viable. A legislative push to incentivise the switch to biodegradable bioplastic and clarification regarding what should be considered compostable organic waste would reduce landfill waste and lead to virtually complete recovery of the resources used to produce bioplastics.

The results revealed as a near perfect reduction in rigid bioplastic (e.g., cups, plates, and cutlery). This finding should encourage an increase in the production of food packaging products made of bioplastic, as they could also easily be conferred as organic waste along with any related food scraps. Another highlighted hotspot concerns the vessels used to collect waster (e.g., the film-like bags currently used in waste collection). Based on the findings, the system could also be redesigned, aiming to limit the thin flexible bioplastic fraction entering biodegradation. To tackle the issue of slower reduction of flexible bioplastics, additional studies should be done on the proprieties of different plastics and their reaction times in the industrial composting process, to guide future implementation of the most efficient option.

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