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Disintegration of commercial biodegradable plastic products under simulated industrial composting conditions

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Biodegradable plastics are often promoted as sustainable alternatives to conventional plastics. Nevertheless, significant knowledge gaps exist regarding their degradation under relevant conditions, particularly when compounded into commercial products. To this end, the present research investigates the disintegration of ten commercially available biodegradable plastic products under simulated industrial composting conditions. The tested products included polymer compositions of either polylactic acid (PLA), polybutylene adipate terephthalate (PBAT)/starch, or polyhydroxyalkanoate (PHA), covering both flexible and rigid plastics. These products comprised three waste bags, one waste bag drawstring, one food bag (flexible plastics), two flower pots, one food container, one plate, and one lid (rigid plastics). Among the tested products, nine were marketed as compostable. Of these, six were certified under the European standard EN 13432 for compostable packaging, two held TÜV Austria's "OK compost home" certification, and one was labeled as compostable but lacked certification. Additionally, one product was labeled as 100% biodegradable but lacked certification, and the environment in which the product could biodegrade was not specified. Disintegration was determined according to ISO 20200 in laboratory scale tests conducted at 58 °C with 55% moisture content over 90 days. Results showed disintegration degrees ranging from 75 to 100%, with five products achieving complete disintegration. Two products, however, reached only 75% disintegration. Following the disintegration test, compost particles smaller than 2 mm were examined for microplastics (MPs) via light microscopy. MPs were detected in compost undersieves for two of the ten biodegradable plastic products, while no MPs were detected for the conventional plastics. Notably, the visual inspection was performed without pretreating the compost matrix due to the observed degradation of biodegradable plastics when using chemicals for oxidative digestion. Considering the limitations of visual MP observation without pretreatment, future research should prioritize the development of methods for extracting biodegradable MPs from complex matrices like compost. Enhanced extraction methods are essential for understanding compost's potential role as a source of MPs in the environment.

Keywords Bioplastic, Disintegration, ISO 20200, Degradability, Compostability, Microplastic

Abbreviations

Bio-MP	Microplastic from biodegradable plastics
C	Carbon
CO_2	Carbon dioxide
DSC	Differential scanning calorimetry
FTIR	Fourier-transform infrared

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H_2O	Water
H_2O_2	Hydrogen peroxide
He	Helium
H_f	Enthalpy of fusion
KOH	Potassium hydroxide
LDPE	Low-density polyethylene
MP	Microplastic
N	Nitrogen
OH	Hydroxy group
PBAT	Polybutylene adipate terephthalate
PBS	Polybutylene succinate
PC	Polycarbonate
PCL	Polycaprolactone
PE	Polyethylene
PET	Polyethylene terephthalate
PETG	Polyethylene terephthalate glycol
PHA	Polyhydroxyalkanoate
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
TCD	Thermal conductivity detector
Tg	Glass transition temperature
Tm	Melting point
VS	Volatile solids

Since the 1950s, conventional plastics (fossil-based and non-biodegradable) have gained worldwide popularity for their durability, lightweightness, cost-effectiveness, and versatility. Currently, global plastic production stands at an annual volume of approximately 400 million metric tonnes and is expected to triple by 2060 due to economic and population growth[1–3]. On a global scale, insufficient waste management leads to continuous emissions of plastics into the environment. Here, due to their persistence, pervasiveness, and chemical complexity, plastics contribute to multifaceted environmental challenges and pose a risk to natural habitats[4–6].

In recent years, bioplastics (bio-based and/or biodegradable) have gained attention as a potential solution to the environmental concerns associated with conventional plastics. Particularly, biodegradable plastics (including compostable plastics) emerge as a promising solution where recycling and reutilization are hampered by contamination from food residues or soil[7]. In 2022, the global bioplastic production capacity reached 1.8 million tonnes and is expected to increase fourfold by 2028, with an increasing share of biodegradable plastics (from 48 to 62%)[8]. Polylactic acid (PLA), starch blends, and polyhydroxyalkanoates (PHAs) are the three biodegradable plastic types with the highest expected production capacities in 2027[9]. The "*EU policy framework on biobased, biodegradable and compostable plastics*" emphasizes that industrially compostable plastics can help improve the collection of biowaste while decreasing the contamination of compost with non-biodegradable plastics[10]. European Bioplastics also shares this opinion, arguing that compostable plastics reduce the contamination of organic waste streams with conventional plastics, thereby decreasing the presence of microplastics (MPs) in the soil[11]. Moreover, they advocate for the convenience and hygiene enhancements in biowaste sorting facilitated by compostable bags, alongside the increased biowaste volume from food packaging, given its convenience for disposal alongside food waste[11]. However, the role of bioplastics as an alternative to conventional plastics is heavily debated in other forums such as during negotiations for a UN global treaty to reduce plastic pollution[12]. While bioplastics are perceived by certain stakeholders to "*contribute significantly to a more sustainable society*"[13], others emphasize that "*caution is required to ensure these materials do not become regrettable substitutions*"[14].

Concerns have been raised about the degree of degradation of biodegradable plastics and their potential to generate MPs[15–17], as well as the environmental and human health effects of associated chemicals[18]. Degradation is a broad term referring to the breakdown of materials under environmental conditions. The term covers two distinct processes: disintegration, which is the physical fragmentation of plastics into smaller pieces, and biodegradation, where microbial activity breaks down materials into simpler compounds such as carbon dioxide (CO_2), water (H_2O), and biomass[19,20]. Existing literature on degradation studies of biodegradable plastics reveals certain limitations. Most studies have focused on pure polymers and/or experimental products (i.e., items produced specifically for the purpose of a given study) rather than commercial products[15]. However, commercial products have been shown to contain more chemical substances (i.e., additives) than pure polymers[18], emphasizing the need for testing of commercial products. Additionally, most degradation tests on biodegradable plastics do not adhere to standardized test methods[15]. The lack of uniformity in testing procedures and test conditions hinders the comparability of test results, making it challenging to evaluate and contrast the degradation behaviors of different types of biodegradable plastics[15,21]. Also, prior research on biodegradable plastics has primarily focused on PLA and starch-based bioplastics, with limited attention on PHAs, polybutylene adipate terephthalate (PBAT), and polybutylene succinate (PBS)[15]. Finally, research on MP production due to bioplastic degradation is lacking[15,16]. The lack of research on MP formation from plastic degradation is due to (1) a lack of methods for MP extraction and analysis and (2) the fact that standard test methods measuring degradation do not require MP analysis. It has, however, been demonstrated that MP production from biodegradable plastics increases with increasing disintegration rates[22], emphasizing the importance of such investigations.

The focus of this study is to address these gaps by investigating the disintegration of commercial biodegradable plastics. Specifically, this research aims to (1) assess the compostability of a wide range of commercially available biodegradable plastic products by evaluating their disintegration using the standardized method ISO 20200 and (2) assess the potential production of MPs after disintegration.

ISO 20200 is conducted under laboratory-scale conditions with controlled temperature, moisture, and small pre-cut samples, providing an optimized environment for disintegration. In contrast, compostability certification relies on pilot-scale testing, such as the requirements for EN 13432 certification, where whole products or larger pieces are tested under less controlled and more variable conditions[23,24]. While the laboratory results cannot directly confirm compliance with compostability certifications, they serve as an effective screening tool. Since disintegration degrees observed under laboratory conditions are generally expected to be higher than those under pilot-scale conditions[25], results of lab-scale disintegration testing offer insight into whether the products are likely to meet compostability claims. Supporting an informed discussion on the future role of bioplastics as an alternative to conventional plastics, the study provides insights into the performance of commercially available 'real world' biodegradable plastics, including their potential to act as a source of MPs into the environment.

This study adheres to the standardized test method ISO 20200 without any modifications. This approach facilitates a comparison between our disintegration outcomes and those from other tests that comply with the same protocol. Standardized methods, often developed with regulatory applications in mind, serve as a cornerstone for frameworks like the OECD Mutual Acceptance of Data[26]. While they offer benefits, e.g., by enhancing study reliability, it is important to acknowledge that standard test methods are not required in scientific studies. The primary motivation for applying a standardized method in this study is to allow prospective and retrospective data comparability.

The study focused on biodegradable plastic products that are likely to be processed in industrial composting as part of their end-of-life/waste management. These products included waste bags (including drawstrings), food bags, flower pots, food containers, plates, and lids. The tested products were declared to be based on PLA, PHA, and starch, including both flexible and ridgid plastics. To provide a comprehensive comparison, two conventional plastics (flexible low-density polyethylene (LDPE) and rigid polystyrene (PS)) were included as negative controls, while cellulose filter paper served as a positive control. This approach aimed to assess disintegration processes in a composting context, providing a clear understanding of how different materials break down and contribute to environmental pollution through MP formation.

Material and methods

For this study, a disintegration test was carried out according to ISO 20200:2015, *Plastics—Determination of the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test*[27]. This method was selected to assess the disintegration in a laboratory-scale composting environment. In contrast, other standard methods, such as ISO 16929 and ISO 14045, are designed for evaluating disintegration in pilot-scale composting tests[23,24]. The study aimed to determine the degree of disintegration of different commercial biodegradable plastic products available on the European market. General information on expected polymer composition was obtained based on information from the producer and literature. However, obtaining exact information is challenging due to the lack of transparency from plastic producers[15,28]. Thus, Fourier-transform infrared (FTIR) and differential scanning calorimetry (DSC) analyses were performed to obtain further information on the composition of the tested products. Furthermore, FTIR analysis was applied to investigate potential changes in the properties of the tested plastics after composting. The disintegration test was conducted under laboratory conditions simulating an industrial composting process in terms of temperature, moisture, and aeration. The experiment was carried out in triplicates for ten biodegradable plastic products, along with positive and negative controls, as described in section "Selection and preparation of plastic samples". Additionally, a reference sample containing only synthetic waste was included. After the termination of the disintegration test, a visual inspection was performed to determine the presence of MPs in the compost. The MP inspection aimed to assess if MPs are produced as plastic degrades.

Selection and preparation of plastic samples

The commercial products examined in this study were obtained from the European market, specifically from Denmark or Italy. In the quest for biodegradable plastic products, the focus was on sourcing items representing a variety of polymer compositions, aiming to explore beyond the commonly studied PLA and starch. The search spanned multiple venues, including supermarkets, retail shops, hardware stores, and garden centers. The biodegradable plastic products obtained are labeled as comprising PLA, starch, biodegradable polyester/starch, or PHA (Table 1). Furthermore, some of the obtained products only indicated their biodegradability/compostability without specifying the polymer type. Despite efforts, products labeled as PBAT or PBS were not found while searching for biodegradable products. The obtained products were all related to food and garden waste, representing items that could realistically end up in industrial composting facilities as part of biowaste collection and treatment processes.

Among the ten tested products, nine were marketed as compostable (Table 1). Of these, six products (Waste Bag (1), Drawstring, Waste Bag (3), Food Container, Plate, and Flower Pot (2)) were certified under the European standard EN 13432 for compostable packaging. Two products (Food Bag and Waste Bag (2)) were certified under TÜV Austria's "OK compost home" label. One product (Lid) was labeled as compostable but lacked certification. Additionally, one product (Flower Pot (1)) was labeled as 100% biodegradable but lacked certification, with no indication of the environmental conditions required for its biodegradation. The experiment of this study included rigid (one food container, one lid, one plate, two flower pots) and flexible (three waste bags, one waste bag drawstring, one food bag) biodegradable plastic products (Tables 1 and S1).

Since the thickness of the test materials was less than 5 mm, all samples were cut into pieces of 2.5 cm × 2.5 cm. The thickness of each sample was measured using a ZEISS Axioscope microscope with an Axiocam 305 color camera (Tables 1 and S2). FTIR and DSC analyses were conducted on all tested products to provide a

Sample no.	Test product	Flexible/rigid	Stated material composition on product label	Product claim/composting certification
1–3	Reference Sample	–	–	–
4–6	Cellulose Filter Paper (positive control)	–	Cellulose	–
7–9	Freezer Bag (negative control)	Flexible	100% LDPE	–
10–12	Weighing Boat (negative control)	Rigid	PS	–
13–15	Food Bag	Flexible	PHA bioplastic and organic GMO-free corn	Home compostable. Certified with TÜV AUSTRIA's "OK compost HOME"
16–18	Waste Bag (1)*	Flexible	100% corn starch	Compostable. Certified according to EN 13432
19–21	Drawstring*	Flexible	100% corn starch	Compostable. Certified according to EN 13432
22–24	Waste Bag (2)	Flexible	PHA from agricultural waste and organic GMO-free corn	Home compostable. Certified with TÜV AUSTRIA's "OK compost HOME"
25–27	Waste Bag (3)	Flexible	Mater-Bi**	Compostable. Certified according to EN 13432
28–30	Food Container	Rigid	PLA	Biodegradable. Compostable. Certified according to EN 13432
31–33	Plate	Rigid	Mater-Bi**	Compostable. Certified according to EN 13432
34–36	Lid	Rigid	PLA made from Ingeo biopolymer	Commercially compostable only
37–39	Flower Pot (1)	Rigid	N/A	100% biodegradable
40–42	Flower Pot (2)	Rigid	Consisting of raw materials such as calcium carbonate, sugar cane, and rapeseed	Compostable. Certified according to EN 13432

Table 1. Overview of biodegradable plastics and control samples investigated in the disintegration test. * Sample 16–18: Waste bag (1) and sample 19–21: Drawstring, originates from the same consumer product. The product consists of a waste bag with a drawstring. The waste bag and the drawstring differed in color and thickness and were thus tested separately. Pictures of the original products are available in Fig. S1 in Supplementary Information S1. ** Mater-Bi is a bioplastic produced by the Italian Company Novamont; based on the literature, Mater-Bi is a copolymer of starch and biodegradable polyester[29].

chemical characterization of the biodegradable plastics under investigation, thereby used to confirm or refute the information on the product label (see section "Chemical characterization"). In addition to samples containing biodegradable plastics, the experiment included reference samples (containing only synthetic waste), positive controls (synthetic waste + cellulose filter paper), and two negative controls (synthetic waste + conventional plastics). The composition of the synthetic waste is described in section "Plastic disintegration during composting". The negative controls included one flexible (LDPE freezer bag) and one rigid (PS weighing boat) plastic product.

Chemical characterization

The FTIR analysis had two main objectives: (1) to determine which bioplastics the commercial products consisted of and (2) to compare spectra of the pristine plastics and aged plastics, which remained after 90 days of composting, to evaluate potential chemical changes caused by composting. Variations of peak intensity and wavenumbers provided qualitative information about the chemical change of the polymeric structure and the specific degradation process of the test materials.

Agilent 4300 Handheld FTIR spectrometer with a diamond-ATR was used to obtain spectra of the pristine and aged test material. The FTIR collected 32 scans, and each spectrum was attained within the range of 4000–650/cm with a wavelength resolution of 4/cm. The collected spectra were processed in Spectragryph Version 1.2.16.1 using advanced baseline correction and advanced smoothing. The spectra of the pristine plastics obtained with Agilent 4300 Handheld FTIR spectrometer were compared with Nicolet iN10 µ-FTIR (Thermo Fisher Scientific, Madison, USA) using a dedicated reference library including 20 different bioplastic spectra in the Omnic™ Picta™ software and a few other libraries where the spectra of the positive control (cellulose), negative controls (LDPE and PS) and corn starch were available (Supplementary Information S1).

DSC measurements were performed on a Discovery DSC (TA Instruments, DE, USA) to (1) support the FTIR analysis on determining which bioplastic the different products consisted of and (2) support discussions on achieved degrees of disintegration. DSC measurements were carried out from − 90 to 200 °C for polycaprolactone (PCL), PLA, polycarbonate (PC), and polyethylene (PE) and 290 °C for polyethylene terephthalate glycol (PETG) and polyethylene terephthalate (PET), at a heating rate of 10 °C/min under a nitrogen atmosphere. The degree of crystallinity was determined relative to the enthalpy of fusion (H_f) for each polymer using $H_f = 106$ J/g for PLA[30], 293 J/g for LDPE, 146 J/g as an estimate of PHA[31] (value is given for poly(hydroxybutyrate) (PHB)), and 114 J/g for PBAT[32] (where only the PBAT content was taken into consideration for the starch/PBAT blends). All analyses were conducted using TRIOS TA instruments software.

Experimental setup

Plastic disintegration during composting

The disintegration test was conducted according to ISO 20200:2015[27]. A synthetic waste consisting of sawdust (38% dw), rabbit feed (29% dw), ripe compost (9.6% dw), corn starch (9.6% dw), saccharose (4.8% dw), corn seed oil (3.8% dw), and urea (5.3% dw) was prepared just before the start of the experiment (Table S3). The ripe compost was made from garden waste and collected at the Technical University of Denmark (55°47′29.8′′ N 12°31′37.8′′ E). Before adding the compost to the synthetic waste mixture, large inert objects (e.g., stones, glass, and metal) were removed, after which the compost was sieved through a 5 mm sieve. Distilled water was added to the synthetic waste to achieve a moisture content of 55%. The synthetic waste's carbon/nitrogen (C/N) ratio, pH (in H_2O), and volatile solids (VS) content were 30:1, 7.4, and 88.9% dw, respectively. The methods used were:

- pH was measured according to ISO 10390:2021 *Soil quality—Determination of pH*[33]. 5 mL of compost was mixed with 25 mL of distilled water. The suspension was mixed for 60 min using a mechanical shaker. One hour after the mixing, pH was measured in the suspension at 20 ± 2 °C while being stirred to achieve a homogeneous suspension.
- The total C and N were analyzed by vario Macro cube analyzer (Elementar) in CNHS mode. The combustion was performed at 1150 °C with helium (He) as carrier gas and flow at 600 mL/min. A thermal conductivity detector (TCD) analyzed the C and N, and sulfanilamide was used as a quality control. The data was processed with VarioMacro V4.2.0.
- VS was measured as described in ISO 20200:2015 *Plastics—Determination of the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test*[27]. The measurements were carried out by weighing samples and placing them in the furnace at 550 °C for 2h. The samples were then placed in a desiccator to cool to room temperature, after which they were weighed again.

The disintegration test was conducted in polypropylene (PP) boxes with lids. The PP boxes had a volume of 5 L and the dimensions 28 cm × 20 cm × 14 cm. On both sides of the boxes, 5 mm diameter holes were made to ensure gas exchange between the inner and outside atmosphere. To each box, 1 kg of synthetic waste and 5 g of test material were added, except for the reference sample, which only consisted of synthetic waste (Table S4). The incubation period of the disintegration test was 90 days at 58 °C ± 2 °C in an incubation chamber. During this period, moisture, mixing, and aeration were periodically controlled for each sample while simultaneously observing any alterations in the appearance of the plastic and documenting noteworthy changes.

After 90 days of composting, the samples were dried at 58 °C ± 2 °C in the incubation chamber until a constant mass was reached. Each sample was sieved to separate test material larger than 2 mm. Any test material larger than 2 mm was collected and cleaned from compost. The cleaning was easily done with distilled water for the conventional plastic samples. However, for the biodegradable plastic samples, this was not possible, as these samples were very brittle and easily broken down into even smaller plastic pieces when in contact with water. Thus, compost was carefully removed from the biodegradable plastic samples using a tweezer. However, the complete removal of compost from all biodegradable samples was not reached, thus contributing to a systematic underestimation of the disintegration degree (Fig. 3 and Table S7). After cleaning, the test material was dried in an oven at 40 ± 2 °C under vacuum to constant mass. The final mass was expressed relative to the original mass as an average of the degrees of disintegration obtained for triplicate samples.

Compost that had passed through the 2 mm sieve was collected to measure pH, C/N ratio, and VS (Tables S8 and S9). To validate the test, two criteria should be met: (1) the VS content of the compost should have decreased by at least 30%, and (2) for each sample, the difference between the sample and the average of the three samples should not be more than 20%. The validity of the performed test is demonstrated in Tables S9 and S10 in Supplementary Information S1.

Microplastic identification in compost

The production of MPs during composting was visually assessed to investigate possible correlations between disintegration rates and MP formation. In ISO 20200, any part of the plastic test material passing through a 2 mm sieve is considered completely disintegrated[27]. The test method does not include any additional steps to examine the presence of MPs in the below-2 mm fraction. In this study, the undersieves from the disintegration test were collected for MP analysis. Thus, only particles smaller than 2 mm were considered for the MP analysis, as particles larger than this were included in the non-disintegrated fraction. The compost matrix smaller than 2 mm was further sieved with a 0.85 mm mesh, resulting in two size fractions for the MP analysis: 0.85–2 mm and < 0.85 mm. Initial attempts were made to isolate MPs from the compost matrix using oxidative digestion, employing potassium hydroxide (KOH) and hydrogen peroxide (H_2O_2) as oxidation agents. However, visual detection without prior sample preparation was adopted due to the destructive impact of these chemicals on the tested biodegradable plastics. The two compost fractions were visually analyzed using a Leica MZ5 microscope, from which photos were collected to document the presence of MPs. The MP analysis was qualitative, relying on detecting at least one MP particle in 1 g of compost matrix.

Results and discussion

FTIR and DSC confirmation of polymer composition

The FTIR spectra and DSC analysis results of the tested commercial biodegradable products, along with those for the positive and negative controls are displayed in Tables S5 and S6 in Supplementary Information S1. The FTIR analysis and the following comparisons with the reference libraries confirmed that the positive control was cellulose and that the negative controls were LDPE and PS. As for the biodegradable products, comparisons of FTIR spectra with the dedicated reference libraries, and observations of the functional groups and the fingerprint region, confirmed the composition of the Lid and Food Container as polyesters with a clear carbonyl peak. With a glass transition temperature (Tg) of 56 °C and a melting point (Tm) between 150 and 170 °C, both polyesters were identified as PLA, which is also in accordance with the product label (Table 2). No specific information regarding the plastic type was provided for either flower pot; instead, only the raw materials used were stated on the product label, and this information was solely available for Flower Pot (2) (Table 1). However, from the FTIR spectra of the pristine flower pots, it is clear that both flower pots are polyesters with characteristic carbonyl signals. In addition, both samples exhibit a primary Tg at 56 °C as well as a Tm of 156 °C, which suggests that both Flower Pot (1) and Flower Pot (2) are composed of PLA (Table 2). In addition to the mentioned transitions, both Flower Pot (1) and Flower Pot (2) also contain an additive with a low Tg (− 31 °C), which has not been identified. The Plate was labeled as a starch-blend according to product information, which the FTIR analysis confirms (ester carbonyl signal, as well as characteristic hydroxy group (OH) absorbance from starch) in combination with the DSC analysis that shows a similar combination of thermal transitions as for the other PBAT/starch blends (Tg = − 44 °C and Tm = 114 °C PBAT, and a small Tm = 155–157 °C for starch). These conclusions are supported by comparisons of the obtained FTIR spectra with those from the applied FTIR reference libraries and spectra referenced in prior studies[34–36].

The FTIR analysis further revealed that the complete nature of the polymer blends used in Food Bag and Waste Bag (2) are very similar in that they are both polyesters (ester carbonyl in FTIR). Based on the DSC analysis showing a very low Tg (− 34 °C) in combination with a Tm of 152–153 °C, it is suggested that this is a PHA suitable for film-blowing. Also, comparing the pristine products Waste Bag (1), Waste Bag (3), and Drawstring suggested that these products are all blends of PBAT and corn starch (Tg = − 35 to 36 °C and Tm = 114–125 °C assigned to PBAT, in addition to a strong water presence and a Tm = 155–157 °C, starch), unlike the product information indicating that these products are 100% corn starch (Table 2). Interestingly, despite the material similarities between these three products, only Waste Bag (1) reached complete degradation within 90 days of composting, suggesting that factors other than polymeric composition are decisive for degradability.

Disintegration test results

Alterations in the appearance of the tested plastics were monitored during the 90-day composting period (Figs. 1 and 2). On day seven, rigid plastic pieces from the tested Food Container (samples 28–30), Lid (samples 34–36), Flower Pot (1) (samples 37–39), and Flower Pot (2) (samples 40–42) had started to disintegrate. At this point, the color of both flower pots had changed from dark green to a lighter/grayish green. On day 11, all the tested Food Container plastic pieces had broken down into smaller pieces. On day 14, all plastic pieces from the Lid, Flower Pot (1), and Flower Pot (2) had also broken down into smaller pieces. No visible plastic was left in samples with the Food Container. On day 30, some plastic in samples 31–33 (Plate) had broken down into smaller pieces. No visible plastic was left in samples with the tested Lid, Flower Pot (1), or Flower Pot (2). On day 35, plastic from samples with Waste Bag (1) (samples 16–18), Drawstring (samples 19–21), and Waste Bag (3) (samples 25–27) had broken down into smaller pieces. On day 38, most of the plastic pieces in the samples containing the Food Bag (samples 13–15) and the Waste Bag (2) (samples 22–24) had broken down into smaller pieces. On day 59, no visible plastic was left in the samples with Waste Bag (1). For samples containing the Food Bag, Drawstring, Waste Bag (2), Waste Bag (3), and Plate, there was still visible plastic left on day 90 (Figs. 1, 2 and 3, and Table S7).

Sample no.	Test product	Thickness (µm)	Xc (%) 1st cycle	Declared polymer composition on product label	Suggested polymer composition based on FTIR and DSC analyses
4–6	Cellulose Filter Paper (positive control)	162 ± 15.0	–	Cellulose	Cellulose
7–9	Freezer Bag (negative control)	32.0 ± 1.16	37	100% LDPE	LDPE
10–12	Weighing Boat (negative control)	253 ± 1.48	–	PS	PS
13–15	Food Bag	17.6 ± 1.55	13	PHA	PHA
16–18	Waste Bag (1)	25.7 ± 1.21	NA, H_2O*	Starch	PBAT/starch
19–21	Drawstring	29.1 ± 0.56	NA, H_2O*	Starch	PBAT/starch
22–24	Waste Bag (2)	17.0 ± 2.07	8.9	PHA	PHA
25–27	Waste Bag (3)	14.0 ± 1.27	NA, H_2O*	Mater-Bi (biodegradable polyester/starch)	PBAT/starch
28–30	Food Container	170 ± 1.44	2.6	PLA	PLA
31–33	Plate	255 ± 5.17	37, crystallinity for PBAT**	Mater-Bi (biodegradable polyester/starch)	PBAT/starch
34–36	Lid	272 ± 5.91	34	PLA	PLA
37–39	Flower Pot (1)	131 ± 1.98	1.4	N/A	PLA
40–42	Flower Pot (2)	111 ± 2.24	7.7	N/A	PLA

Table 2. Overview of material thickness, crystallinity (Xc), declared polymer composition on product labels for the tested products, and the suggested polymer compositions based on the FTIR and DSC analyses conducted in this study. *The crystallinity could not be measured for Waste Bag (1), Drawstring, and Waste Bag (3) due to the water content being too high in the samples. ** For the Plate, the measured crystallinity is only for the PBAT part of the sample.

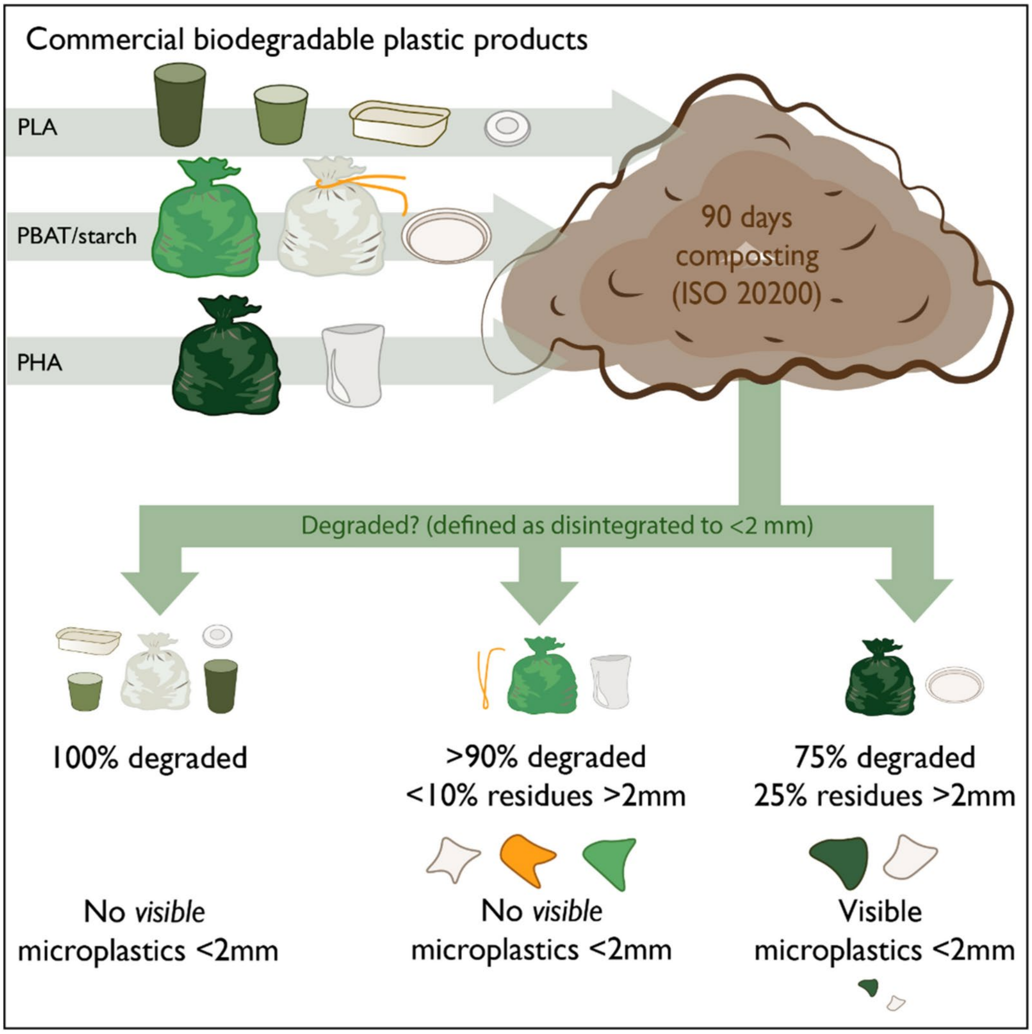

Fig. 1. Graphical representation of the disintegration of the tested biodegradable plastic products after 90 days under simulated industrial composting conditions. The figure also shows subsequent visual inspection for the presence of microplastics. Plastics were classified as non-disintegrated when the sizes of plastic residues exceeded 2 mm, while visual inspection for microplastic was focused on their presence in compost undersieves with particles smaller than 2 mm.

After 90 days of composting, the two conventional plastics (negative controls) reached less than 1% disintegration (Table S8). In contrast, eight of ten biodegradable plastic products tested disintegration degrees exceeding 90% (Figs. 1, 4, and Table S8). To confirm compliance with the EN 13432 standard, pilot-scale disintegration tests should be conducted for these products to verify whether they meet the 90% disintegration requirement under such conditions. However, the remaining two products (Waste Bag (2) and Plate) disintegrated by less than 90%. Notably, despite holding EN 13432 certification, the Plate only reached a degree of disintegration of 75% in this lab-scale test (Figs. 1, 4, and Table S8). This raises doubts about whether the product would meet the 90% disintegration requirement within 90 days under pilot-scale conditions. Waste Bag (2), certified as home compostable, also demonstrated a disintegration degree of 75% within 90 days under industrial composting conditions (Figs. 1, 4, and Table S8). While this performance reflects partial compostability, the product will likely exhibit even lower disintegration under home composting conditions due to less favorable degradation conditions, such as lower temperatures[37]. While home composting conditions may pose more challenges for degradation than industrial conditions, it is essential to acknowledge significant differences in the standard test methods for these two composting environments. Thus, while it could be speculated that Waste Bag (2) would achieve even lower than 75% disintegration after 90 days under home composing conditions, definitive conclusions on home composability would require dedicated tests. Standard methods for testing plastic compostability under home composting conditions include AS 5810-2010, UNI 11183:2006, NF T 51-800:2015, and EN 17427:2022. These tests state that 90% of the material should be degraded within 12 months[38–41], thus applying a more extended test duration than EN 13432. However, previous studies have shown that even when increasing the incubation time from 12 weeks to 12 months, the disintegration of biodegradable plastics is lower under home composting conditions than under industrial composting conditions[42].

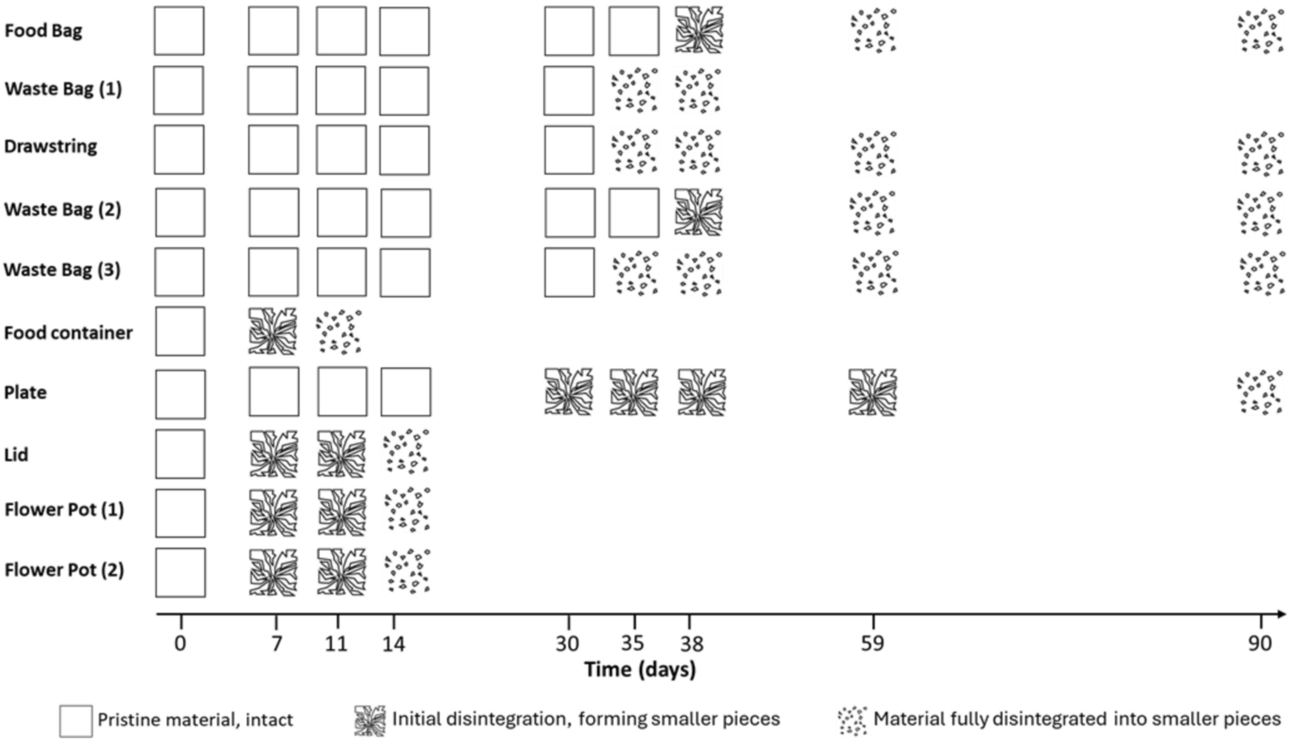

Fig. 2. Graphical representation of the stages of disintegration over a 90-day test period, illustrating the progression from pristine materials (no visible disintegration) to initial signs of disintegration and eventually to all pieces fragmenting into smaller pieces. The stages of disintegration are indicated by the symbols shown in the legend; the absence of a symbol signifies that no visible plastic fragments remained in the compost.

The study results showed differences in the achieved disintegration between the different tested products. Four of the five tested rigid products reached 100% disintegration, all made from PLA (Fig. 4). These rigid PLA samples varied in thickness and crystallinity but consistently disintegrated completely. Thus, for PLA products, the disintegration appears to be more influenced by the polymer type rather than sample thickness and crystallinity. However, the absence of flexible PLA samples in our study prevents a determination of whether the polymer type alone is responsible for the observed disintegration. For PBAT/starch-based products, both flexible and rigid plastics were tested, revealing notable differences in degrees of disintegration. Flexible samples achieved higher degrees of disintegration (95–100%) than the rigid sample, which only reached 75% (Fig. 4). However, this variation in disintegration may be linked to the products' differences in thickness, crystallinity, or water content. The rigid sample had a significantly greater thickness (255 µm) than the flexible samples (14–29 µm) and exhibited high crystallinity (37% for the PBAT component) (Fig. 4). In contrast, the crystallinity of the flexible samples could not be measured due to their high water content. PHA-based products were only tested as flexible plastics. These samples had similar thicknesses but slight differences in crystallinity (8.9% for Waste Bag (2) and 13% for the Food Bag) (Fig. 4). Interestingly, the Food Bag, which had higher crystallinity, achieved 93% disintegration, while the Waste Bag (2) only reached 75% (Fig. 4). These results suggest that factors beyond thickness and crystallinity may significantly influence disintegration for products of the same polymer.

Overall, the findings emphasize that polymer type, thickness, crystallinity, and water content are critical for plastic disintegration. To clarify the impact of these factors, future studies should compare plastics of identical polymer composition with controlled variations in thickness and crystallinity. To facilitate more robust and targeted comparisons, comprehensive market mapping is also needed to identify a broader range of products, including flexible PLA and rigid non-PLA plastics.

FTIR measurements of chemical changes during composting

Positive and negative controls

After composting, the spectrum of remaining pieces of cellulose filter paper did not show any significant changes in the alcohol/water region (3700–3000/cm); on the other hand, the carbonyl region showed a very clear difference with the appearance of new functional groups in the region 1800–1500/cm, which is attributed to oxidation of the cellulose backbone. The spectra of LDPE before and after composting were largely similar, showing only a minor increase in the carbonyl region (1800–1600/cm) attributed to biotic and abiotic oxidation resulting in a reduction in hydrophobicity of the material[43], while there were no indications of appearance of alcohols or other oxygen-based species. According to Alassali et al. (2018), LDPE is generally acceptable for recycling and re-processing even after composting, as material properties are primarily unchanged; this agrees with the observations of the present study. Like LDPE, the spectrum of PS showed minimal changes after

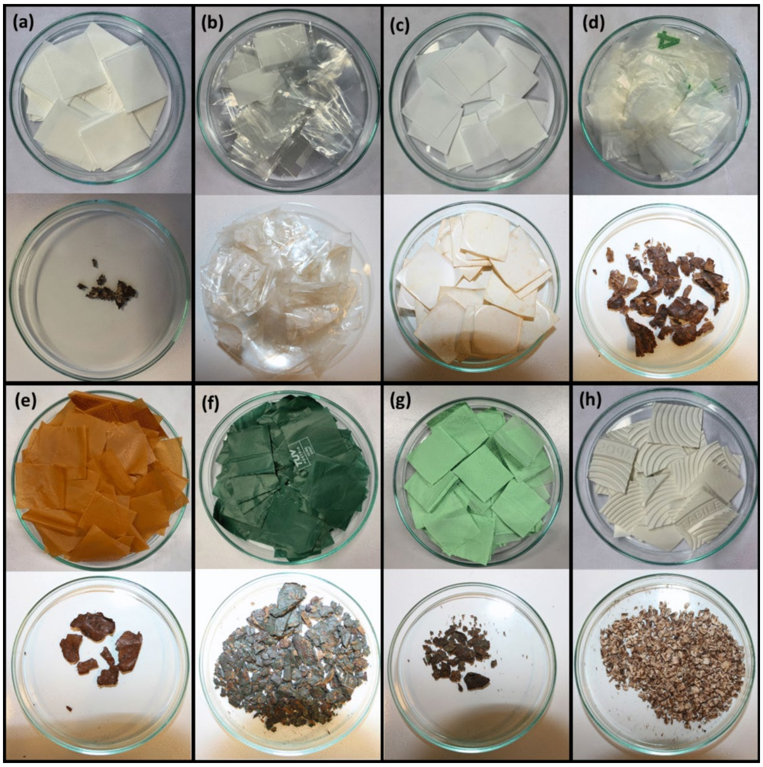

Fig. 3. Examples of test material before (top photo) and after (bottom photo) composting for products that did not fully disintegrate after 90 days of composting. (**a**) Cellulose filter paper, positive control (sample 5). (**b**) LDPE Freezer Bag, negative control (sample 7). (**c**) PS Weighing Boat, negative control (sample 13). (**d**) Food Bag (sample 15). (**e**) Drawstring (sample 19). (**f**) Waste Bag (2) (sample 22). (**g**) Waste Bag (3) (sample 27). (h) Plate (sample 31). The complete overview of all samples after 90 days of composting is available in Table S7 in Supplementary Information S1.

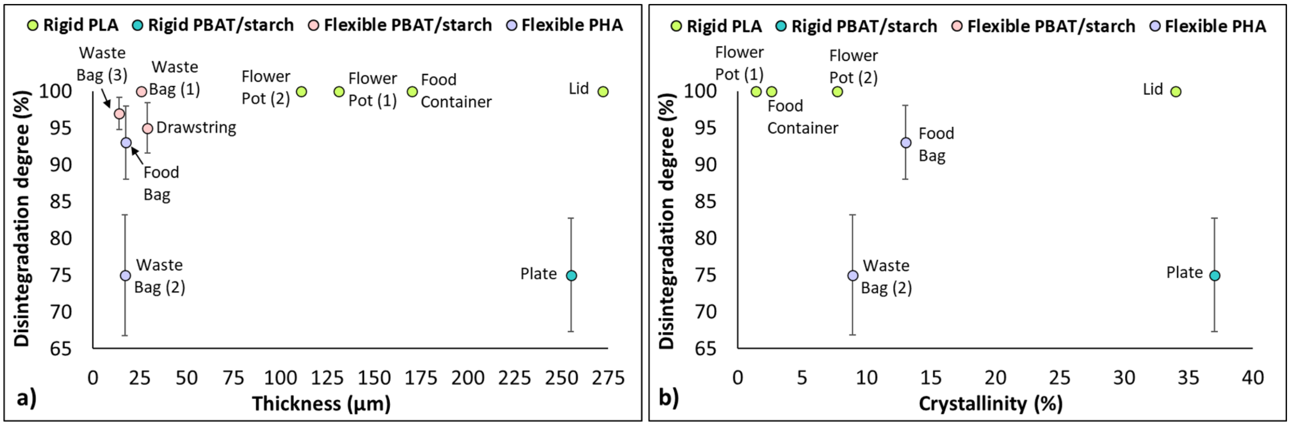

Fig. 4. Disintegration degree as a function of (**a**) material thickness and (**b**) material crystallinity. The disintegration degrees are the triplicate samples' average values, including the standard deviation. Table S8 in Supplementary Information S1 presents the values of the disintegration degrees. Table 2 shows the values of the material thickness and the crystallinity. The polymer composition stated in the figure is based on chemical characterization by FTIR and DSC analyses, as illustrated in Table 2. Crystallinity was not possible to measure for the flexible PBAT/starch samples because of too much water in the samples, and it could thus not be plotted. The rigid PBAT/starch sample (Plate) did not show significant amounts of absorbed water in the original sample (compared to the other PBAT/starch systems). The crystallinity plotted for the Plate is only representative of the PBAT part of the product, as noted in Table 2.

composting, with the appearance of very small peaks between 1800 and 1600/cm. This observation aligns with the findings by Wahl et al. (2024), which underlined the appearance of new bands from 1700 to 1600/cm in PS MPs after compost degradation. These bands likely stem from overlapping multiple C=O bond groups from ketones, aldehydes, or carboxylic acids, indicative of a complex and multifaceted degradation process[44].

Biodegradable plastic products

Five biodegradable plastic products did not fully disintegrate after composting, allowing for comparing their spectra with those obtained before composting. These products, namely Food Bag, Drawstring, Waste Bag (2), Waste Bag (3), and Plate, exhibited various changes when comparing the FTIR spectra before and after composting at specified intervals (Table S5). The observed changes in the spectra can be ascribed to the process of degradation of the plastic products due to hydrolysis and microbial activity[45]. Similar changes were observed for all the products after degradation; specifically, a broad peak centered at 3400/cm indicative of water and alcohol groups was observed for all the products (Table S5). This was observed both for samples that had no absorbance in this region before degradation (Food Bag, Waste Bag (2), and Plate) as well as for the samples that already expressed this before degradation, presumably due to a high initial water content (Drawstring and Waste Bag (3)) (Table S5). The main differences observed for the composted samples were from 1800 to 1550/cm, which is indicative of the formation of carbonyls in various forms due to oxidation (esters, ketones, acids, carboxylates)[45] as a result of the microbial activity in the compost. The findings observed in the examined spectra are corroborated by other studies on the degradation of biodegradable plastics[45,46].

Microplastic analysis

After 90 days of composting, MPs were visually identified in samples from two of the ten tested biodegradable plastic products (Fig. 1). Specifically, MPs were observed in samples 22–24 (Waste bag (2)) and samples 31–33 (Plate) across both collected size fractions below 2 mm (Figs. 5 and 6). Interestingly, within the size fraction < 0.85 mm, it was noted that some particles exceeded the mesh size (Fig. 6), possibly attributed to the three-dimensional structure of the MP particles. The visual observation of MPs in this study suggests that more MP particles are generated from Waste Bag (2) compared to Plate, with flexible plastics (Waste Bag (2)) tending to stick to the compost matrix. This occurrence is particularly evident in images depicting the size fraction between 0.85 mm and 2 mm, where small particles are visibly attached to the compost (Fig. 5).

Notably, no MPs were visible in the samples with conventional plastics. This observation is consistent with the findings of a previous study by Wei et al. (2021), which demonstrated that biodegradable plastics (PBAT) generated a higher MP content compared to conventional plastic (LDPE) in aquatic environments[17]. It is important to note that the lack of visible MPs in samples other than Waste Bag (2) and Plate using light microscopy does not conclusively indicate their absence. The surrounding compost matrix poses challenges for MP detection, mainly if the plastic color is similar to the brown compost. For example, detecting MPs from the sample with the Drawstring would be difficult because of its brown/orange color, resembling that of the compost. To enhance the accuracy of MP analysis, it is essential to extract particles from the surrounding matrix before detection. However, existing extraction methods used for conventional MP extraction often involve harsh chemicals, which can degrade MPs from biodegradable plastics (bio-MPs). Existing methods, including oxidative digestion with KOH and H_2O_2, were evaluated for their efficacy in extracting bio-MPs from compost samples containing pristine and aged biodegradable plastics. While oxidative digestion with KOH degraded pristine biodegradable plastics, H_2O_2 demonstrated non-destructive properties (data not shown). However, degradation was observed when H_2O_2 was applied to aged biodegradable plastics (data not shown). These findings highlight the inadequacy of current extraction methods for samples containing aged bio-MPs. Consequently, there is an urgent need to develop extraction techniques tailored explicitly for bio-MPs. Such methods would enhance detection accuracy and minimize the risk of unintentional bio-MP degradation during extraction.

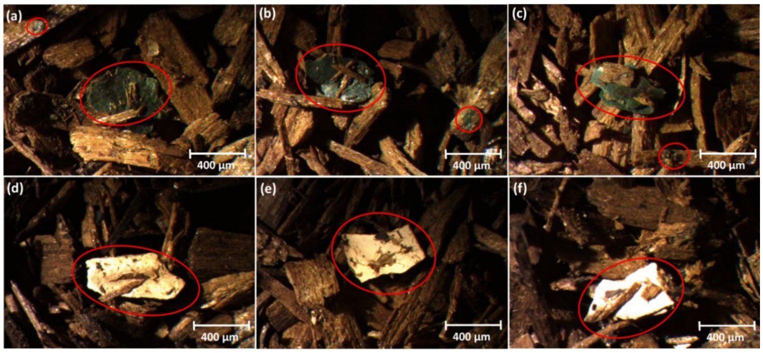

Fig. 5. Microplastic (circled in red) detected in the compost fraction between 0.85 mm and 2 mm after 90 days of composting. (**a**) Waste Bag (2) (sample 22). (**b**) Waste Bag (2) (sample 23). (**c**) Waste Bag (2) (sample 24). (**d**) Plate (sample 31). (**e**) Plate (sample 32). (f) Plate (sample 33).

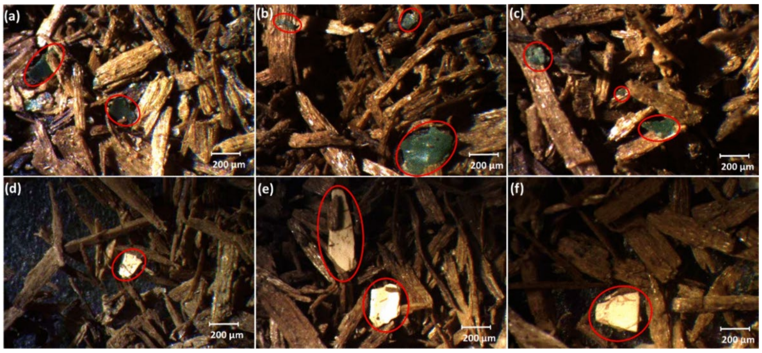

Fig. 6. Microplastic (circled in red) detected in the compost fraction smaller than 0.85 mm after 90 days of composting. (**a**) Waste Bag (2) (sample 22). (**b**) Waste Bag (2) (sample 23). (**c**) Waste Bag (2) (sample 24). (**d**) Plate (sample 31). (**e**) Plate (sample 32). (f) Plate (sample 33).

Discussion summary

Evaluating the disintegration of commercial biodegradable plastics in compost revealed valuable insights into their environmental implications and waste management practices. During the 90-day composting period, significant disintegration of biodegradable plastic products was observed, with most products achieving disintegration degrees exceeding 90% (Fig. 1). However, two of these products (Lid and Flower Pot (1)) did not hold formal composability certifications (Table 1). The lack of certification is problematic as only certified biodegradable plastic products are accepted in industrial composting facilities alongside biowaste[47]. Consequently, biodegradable plastic products claiming to be compostable without certification must be sorted as residual waste, limiting their full potential. Moreover, these uncertified products can confuse consumers about proper waste management practices, potentially resulting in incorrect sorting of biodegradable plastics. While uncertified products may meet the requirements of the EN 13432 standard, the decision not to certify products may stem from factors such as cost, market demand, and regulatory compliance. Certification processes can be expensive, which can be a barrier for smaller producers operating on tight budgets, for which the certification cost may outweigh the perceived benefits[48]. Thus, if consumers do not actively seek products with compostability certifications, producers might find investing in areas other than certification more beneficial. Moreover, if there is no regulatory demand for composting certifications on products claiming to be compostable, producers might not be incentivized to do so.

On the other hand, one certified product (Plate) fell short of the 90% threshold, raising questions about the legitimacy of its compostability claim (EN 13432 compostable). Another product (Waste Bag (2)) certified as home compostable only achieved 75% disintegration in our test, despite the test conditions being presumably more favorable for biodegradable plastic degradation than those typically encountered in home composting environments.

Some of the tested biodegradable products showed incomplete degradation after 90 days of composting with the visible presence of plastic particles smaller than 2 mm (Fig. 1). Despite the degradable properties of these biodegradable plastic particles, they will still fall under the category of MPs[49]. Thus, while industrial composting environments provide optimal conditions for the degradation of biodegradable plastics, and these materials outperform conventional plastics in degradability, incomplete degradation can still lead to bio-MP production. This poses significant risks, including agricultural contamination and accumulation of bio-MPs in the environment. To this, it must be added that if a plastic product fails to degrade under industrial composting conditions, there are slim chances of it degrading in other environments, such as seawater, at lower temperatures[50]. These findings stress the complex dynamics of sustainable plastic management, emphasizing the need for further research on biodegradable plastic degradation. Furthermore, research should focus on developing effective bio-MP extraction methods to facilitate the evaluation of the environmental impacts of bio-MPs. Such efforts are crucial to mitigate the unintended consequences of plastic degradation and prevent regrettable substitutions.

Finally, it should be noted that promoting products as compostable may be misleading in countries like Denmark, where composting of household waste is not integrated into the waste management system. In Denmark, collected biowaste is typically sent to anaerobic digestion plants to produce biogas and sludge[51], which operate under different conditions than industrial composting facilities. This discrepancy in the processing environment implies that compostable plastics, designed for composting, may not degrade efficiently under the anaerobic conditions of the digestion plants. Therefore, careful consideration is needed when labeling products as compostable, especially in regions with distinct waste management practices. The results of this study underscore the importance of critically evaluating compostability claims not only to prevent greenwashing and consumer confusion but also to assess their suitability for specific waste management systems.

Conclusion

This study investigated the degree of disintegration of various biodegradable plastic products on the European market. Chemical characterization with FTIR and DSC analyses were conducted to validate the information on polymer composition stated on the product labels. While some products matched their declared composition, others exhibited inconsistencies, highlighting the importance of accurate labeling for transparency and reliability in the biodegradable plastics market. These findings stress the necessity of coupling degradation test results with chemical analysis to ensure a robust basis for comparison.

The study highlighted significant differences in the disintegration of rigid and flexible biodegradable plastics, with rigid PLA products generally demonstrating higher degrees of disintegration. Among the five rigid products tested, four reached 100% disintegration, all made of PLA. Despite variations in thickness and crystallinity, these PLA samples consistently disintegrated completely, indicating that sample thickness and crystallinity had minimal impact on degradation. In contrast, PBAT/starch products exhibited more variability, with flexible samples achieving higher disintegration rates (95–100%) than the rigid sample (75%). Disintegration of PBAT/starch samples appeared to be influenced by thickness, water content, and possibly crystallinity. For flexible PHA products, however, no clear correlation between disintegration and sample thickness or crystallinity was found, suggesting that other factors should be explored. The rigid PLA products initiated disintegration more quickly, with all breaking down into smaller pieces within 14 days and leaving no visible plastic after 30 days of composting. In contrast, the rigid PBAT/starch product only began disintegration after 30 days, with visible plastic remaining even after 90 days. Flexible PBAT/starch plastics started disintegrating on day 35, with one of the three products showing no visible plastic after 90 days. Flexible PHA products began disintegrating on day 38, with both samples still containing visible plastic after 90 days. Future studies should focus on testing rigid plastics with varying polymer compositions and directly comparing flexible and rigid plastics of the same polymer type to better understand the factors influencing plastic degradation. Additionally, the impact of variations in material properties beyond polymer type, sample thickness, rigidity, and crystallinity on plastic degradation should be further explored.

Standards like ISO 20200 and EN 13432 define disintegration criteria but do not address MPs' potential production during degradation. Current extraction methods for conventional MPs proved inadequate for bio-MPs, leading to unintentional degradation of the particles. This study conducted MP analysis based on visual observations of compost matrices using light microscopy without sample pretreatment. This qualitative confirmation of MPs in samples from two biodegradable plastic products points to the release of bio-MPs to the environment during composting practices. However, this method exhibited limitations, emphasizing the urgent need to develop tailored extraction techniques to improve detection accuracy and minimize unintentional degradation of bio-MPs. Further research should focus on developing standardized methods for extracting and quantifying bio-MPs, as their environmental impact remains a concern.

The EN 13432 standard's lack of requirements for complete degradation raises concerns about MP production from certified biodegradable plastics during waste management practices. While biodegradable plastics demonstrate higher disintegration degrees than conventional plastics in compost, their potential to generate bio-MPs necessitates further investigation into their environmental impact. Current practices of using compost as fertilizer on agricultural land may contribute to bio-MP accumulation in the environment if biodegradable plastics are treated with biowaste in industrial composting facilities. This underscores the importance of further investigations on the potential adverse effects of bio-MPs in the environment, alongside discussions at a political level regarding regulation on the labeling of so-called biodegradable plastic products.

Data availability

All data are available in Supplementary Information.

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References

1. OECD. *Global Plastics Outlook: Policy Scenarios to 2060* (OECD Publishing, 2022). https://doi.org/10.1787/aa1edf33-en.
2. Ritchie Hannah & Roser Max. Plastic Pollution. *OurWorldInData.org* 1–14. https://ourworldindata.org/plastic-pollution#how-much-plastic-does-the-world-produce (2018).
3. Statista. Plastic production worldwide 2020. https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/ (2023).
4. Fogh Mortensen, L. et al. Plastics, the circular economy and Europe's Environment—a priority for action. EEA Report. https://lup.lub.lu.se/search/publication/0bae57b0-51ca-4f4e-9881-72baf2665cc6 (2021). https://doi.org/10.2800/5847.
5. Kumar, R. et al. Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. *Sustainability* **13**, 9963 (2021).
6. Mihai, F. C. et al. Plastic pollution, waste management issues, and circular economy opportunities in rural communities. *Sustainability* **14**, 20 (2021).
7. Flury, M. & Narayan, R. Biodegradable plastic as an integral part of the solution to plastic waste pollution of the environment. *Curr. Opin. Green Sustain. Chem.* **30**, 100490 (2021).
8. European Bioplastics. *Bioplastics market development update 2023*. http://www.european-bioplastics.org/news/publica (2023).
9. European Bioplastics. *Bioplastic Market Development Update 2022* (2022).
10. European Commission. *EU Policy Framework on Biobased, Biodegradable and Compostable plastics—Communication from the Commission to the European Parliament, the Council, the European Economic and Social Commitee and the Commitee of the Regions* 1–14 (2022).
11. European Bioplastics. *Position of European Bioplastics—Compostable Plastics and their Contribution to Soil Health* (Springer, 2022).
12. United Nations Environment Programme. *Revised Draft Text of the International Legally Binding Instrument on Plastic Pollution, Including in the Marine Environment* 34–37 (SAGE Publications, 2023). https://doi.org/10.4135/9781452218557.n533.
13. European Bioplastics. Frequently asked questions on bioplastics (2023).
14. Scientists' Coalition for an Effective Plastics Treaty. Policy brief: the global plastics treaty: what is the role of bio-based plastic, biodegradable plastic and bioplastic? (Possible Core Obligation 8) (2023).
15. Afshar, S. V., Boldrin, A., Astrup, T. F., Daugaard, A. E. & Hartmann, N. B. Degradation of biodegradable plastics in waste management systems and the open environment: a critical review. *J. Clean. Prod.* **434**, 140000 (2024).
16. Wang, C. et al. Biodegradable microplastics (BMPs): a new cause for concern?. *Environ. Sci. Pollut. Res.* **28**, 66511–66518 (2021).

17. Wei, X. F., Bohlén, M., Lindblad, C., Hedenqvist, M. & Hakonen, A. Microplastics generated from a biodegradable plastic in freshwater and seawater. *Water Res* **198**, 117123 (2021).
18. Zimmermann, L., Dombrowski, A., Völker, C. & Wagner, M. Are bioplastics and plant-based materials safer than conventional plastics? In vitro toxicity and chemical composition. *Environ. Int.* **145**, 106066 (2020).
19. De Wilde, B. Biodegradation testing protocols. *ACS Symp. Ser.* **1114**, 33–43 (2012).
20. International Organization for Standardization. ISO 472, Plastics—vocabulary. *ISO 472:2013*. https://www.iso.org/obp/ui/#iso:std:iso:472:ed-4:v1:en (2013).
21. Cristina Lavagnolo, M., Poli, V., Maria Zampini, A. & Grossule, V. Biodegradability of bioplastics in different aquatic environments: a systematic review. *J. Environ. Sci.* https://doi.org/10.1016/j.jes.2023.06.013 (2023).
22. Ruggero, F. et al. Rigid and film bioplastics degradation under suboptimal composting conditions: a kinetic study. *Waste Manage. Res.* https://doi.org/10.1177/0734242X211063731 (2021).
23. ISO. ISO 14045—packaging—evaluation of the disintegration of packaging materials in practical oriented tests under defined composting conditions (2003).
24. ISO. Plastics—determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test (ISO 16929:2021) (2021).
25. Pischedda, A., Tosin, M. & Degli-Innocenti, F. Biodegradation of plastics in soil: the effect of temperature. *Polym. Degrad. Stab.* **170**, 109017 (2019).
26. OECD. Mutual Acceptance of Data (MAD). https://www.oecd.org/chemicalsafety/testing/mutualacceptanceofdatamad.htm (2023).
27. ISO. ISO 20200:2015—plastics—determination of the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test. *Int. Organ. Standardization* **2015**, 1–8 (2015).
28. Crippa, M. et al. *A Circular Economy for Plastics—Insights from Research and Innovation to Inform Policy and Funding Decisions* (2019). https://doi.org/10.2777/269031.
29. Tosin, M., Pischedda, A. & Degli-Innocenti, F. Biodegradation kinetics in soil of a multi-constituent biodegradable plastic. *Polym. Degrad. Stab* **166**, 213–218 (2019).
30. López-Rodríguez, N., Martínez-De-Arenaza, I., Meaurio, E. & Sarasua, J. R. Efficient stereocomplex crystallization in enantiomeric blends of high molecular weight polylactides. *RSC Adv.* **5**, 34525–34534 (2015).
31. Crétois, R. et al. Physical explanations about the improvement of PolyHydroxyButyrate ductility: hidden effect of plasticizer on physical ageing. *Polymer (Guildf.)* **102**, 176–182 (2016).
32. Garalde, R. A., Thipmanee, R., Jariyasakoolroj, P. & Sane, A. The effects of blend ratio and storage time on thermoplastic starch/poly(butylene adipate-co-terephthalate) films. *Heliyon* **5**, e01251 (2019).
33. ISO. ISO 10390:2021 Soil, treated biowaste and sludge—determination of pH. In *International Organization for Standardization* 10 (2021).
34. Chieng, B. W., Ibrahim, N. A., Yunus, W. M. Z. W. & Hussein, M. Z. Poly(lactic acid)/poly(ethylene glycol) polymer nanocomposites: effects of graphene nanoplatelets. *Polym. (Basel)* **6**, 93–104 (2014).
35. Shen, W., Zhang, G., Ge, X., Li, Y. & Fan, G. Effect on electrospun fibres by synthesis of high branching polylactic acid. *R. Soc. Open Sci.* **5**, 180134 (2018).
36. Singla, P., Mehta, R., Berek, D. & Upadhyay, S. N. Microwave assisted synthesis of poly(lactic acid) and its characterization using size exclusion chromatography. *J. Macromol. Sci. Part A: Pure Appl. Chem.* **49**, 963–970 (2012).
37. TÜV AUSTRIA. OK compost, Seedling & REAL. https://www.tuv-at.be/okcert/certifications/ok-compost-seedling-real/ (2023).
38. AFNOR. NF T 51-800 plastics—specifications for plastics suitable for home composting. https://www.boutique.afnor.org/en-gb/standard/nf-t51800/plastics-specifications-for-plastics-suitable-for-home-composting/fa060127/1525 (2015).
39. Australian Standard. AS 5810—biodegradable plastics—biodegradable plastics suitable for home composting. australian standard (2010).
40. European Standard. EN 17427:2022 packaging—requirements and test scheme for carrier bags suitable for treatment in well-managed home composting intallations (2022).
41. UNI. UNI 11183:2006 plastic materials biodegradable at ambient temperature. Requirements and test methods (2006).
42. Adamcová, D., Zloch, J., Brtnický, M. & Vaverková, M. D. Biodegradation/disintegration of selected range of polymers: impact on the compost quality. *J. Polym. Environ.* **27**, 892–899 (2019).
43. Xing, R. et al. Free radicals accelerate in situ ageing of microplastics during sludge composting. *J. Hazard Mater.* **429**, 128405 (2022).
44. Wahl, A. et al. Condition of composted microplastics after they have been buried for 30 years: Vertical distribution in the soil and degree of degradation. *J. Hazard Mater.* **462**, 132686 (2024).
45. Ruggero, F. et al. Degradation of film and rigid bioplastics during the thermophilic phase and the maturation phase of simulated composting. *J. Polym. Environ.* **29**, 3015–3028 (2021).
46. Markowicz, F. & Szymańska-Pulikowska, A. Assessment of the decomposition of oxo-and biodegradable packaging using ftir spectroscopy. *Materials* **14**, 785 (2021).
47. Italian Composting and Biogas Association. What we do—promote separate collection, engaged in quality. https://www.compost.it/en/what-we-do/ (2024).
48. Dansk Erhverv. Certificeringer og mærkninger. https://www.danskerhverv.dk/branche/handel/engroshandel/certificeringer-og-markninger/ (2025).
49. Hartmann, N. B. et al. Response to the letter to the editor regarding our feature 'are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. *Environ. Sci. Technol.* **53**, 4678–4679. https://doi.org/10.1021/acs.est.9b02238 (2019).
50. Ahsan, W. A., Hussain, A., Lin, C. & Nguyen, M. K. Biodegradation of different types of bioplastics through composting—a recent trend in green recycling. *Catalysts* **13**, 1–14 (2023).
51. Vestforbrænding. Fra madaffald til biogas. https://vestfor.dk/bliv-klogere/nyheder/nyhedsoverblik/fra-madaffald-til-biogas (2022).

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Author contributions

This research article was carried out in collaboration between the following authors. S.V.A.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing,

Visualization, Project administration. A.B.: Conceptualization, Methodology, Supervision, Writing - Review & Editing. T.H.C.: Supervision, Writing - Review & Editing. F.C.: Formal analysis, Writing - Original Draft, Writing - Review & Editing. A.E.D. Formal analysis, Writing - Review & Editing. B.R.: Formal analysis, Writing - Original Draft, Writing - Review & Editing. N.B.H.: Conceptualization, Methodology, Writing - Review & Editing, Visualization, Supervision.

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Additional information

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