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“Bio”-Plastics – Background

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Introduction

The production and use of plastics have expanded massively over the past decades. The main driver of this development is the strongly supply-driven market for plastics. The fossil raw materials used to produce plastics are readily available at low cost, leading to an oversupply of cheap virgin plastic (Röchling Foundation/Wider Sense 2020). Due to the continuous release of plastics into the environment, the term “plastic crisis” has increasingly gained traction in public discourse in recent years to highlight the threat posed to ecosystems, the climate, biodiversity, and human health by ever-increasing plastic pollution (cf. Ekardt et al. 2019).

Against the backdrop of the plastic crisis, so-called “bio-based” plastics are associated with a multitude of expectations for sustainable material use: there is hope that fossil resources can be replaced by renewable ones and that the biodegradability of plastics can contribute to solving the waste problem. However, these hopes can only be fulfilled to a very limited extent by so-called “bio-based” plastics. A neutral discussion of “bio” plastics is also hampered by the fact that the “bio” label is frequently misused as a marketing strategy, raising false expectations among consumers. Furthermore, it is misleading that the EU Organic Farming Regulation (Regulation (EC) No. 834/2007) defines criteria for the terms “organic,” “eco,” “biological,” and “ecological” for agricultural products, but these criteria do not apply to so-called “bio-based” plastics.
Unlike, for example, organic cotton, which comes from controlled organic farming, the plant-based products from which so-called “bio-based” plastics are made largely originate from conventional agriculture.

Accordingly, the terms “bio-plastic” and “bio-based plastic” are used in quotation marks throughout this paper.

In any case, “bio” plastics are not a simple solution to the plastic crisis, because the currently used quantities of (single-use) fossil-based plastics cannot and should not be completely replaced by “bio” plastics, not even in the future. A consistent sufficiency policy, i.e., a significant reduction in consumption, is therefore a prerequisite for the success of any further measures to solve the plastic crisis[3] and must always be considered and integrated into the debate about “bio” plastics as potentially “better plastics.”[4]

The “bio” plastics market is still small: in 2020, they accounted for approximately 1% of plastic consumption across Europe. However, as with conventional plastics, the production of “bio” plastics is growing steadily, in some cases even significantly faster. About half of “bio” plastics are currently used for packaging – compared to about 30% of fossil-based plastics used for packaging (European Bioplastics 2020). Therefore, the following discussion will focus on the packaging sector. Other significant applications of “bio” plastics include agricultural films and single-use consumer goods such as tableware and cutlery. In principle, however, various “bio” plastics are also

[1]*For the definition of sustainability favored by BUND, see BUND 2021a and BUND Position 49 on the understanding of sustainability in waste management (BUND 2010).*

[2]*As is common in German usage, the terms "plastic" and "plastics" are used synonymously in this article, although not all plastics are plastic.*

[3]*Last but not least, the discussion about "bio"-plastics must be understood as part of a sustainable materials policy that needs to be shaped (cf. BUND Position 69 on sustainable materials policy (BUND 2019) and BUND's plastic avoidance strategy (BUND 2021b)).*

[4]*The risks associated with the production, use, and disposal of plastics, and thus also "bio"-plastics, are not locally limited and affect society as a whole. Therefore, in this context, we speak of systemic risks (Kramm et al. 2020, p. 10). These risks do not arise from an accident or a natural disaster, but from our everyday handling of plastic products. This means considering the use of "bio"-plastics in comparison to other materials, including conventional plastics, and examining possible solutions along the entire value chain. Such an integrative approach brings systemic changes (e.g., promoting avoidance and sufficiency strategies) into focus, and supposedly quick solutions that only treat the symptoms (so-called end-of-pipe solutions) can be avoided (cf. Kramm et al. 2020).*

suitable for the production of high-quality plastic components (e.g., furniture, technical parts for electrical engineering and the automotive industry).

The paper is structured as follows: First, it explains which product groups are included under the term "bio-based" plastics. The paper then examines bio-based and biodegradable plastics in more detail, as well as the criticisms currently associated with these materials. This is followed by a discussion of recycling possibilities, before the paper concludes with BUND's demands and principles regarding bio-based plastics.

Definition of "bio-based" plastics

The term "bio" plastics encompasses two different groups of products:

- bio-based plastics and
- biodegradable plastics.

Bio-based plastics are partially or entirely derived from renewable resources, such as those found in corn, sugarcane, or potatoes. Chemically, they often correspond to conventional plastics, such as bio-PE (polyethylene) or bio-PET (polyethylene terephthalate). Bio-based plastics can be biodegradable – but often are not. Biodegradable plastics, such as the bio-based PLA (polylactide, "polylactic acid") and the fossil-based PBAT (polybutylene adipate terephthalate), are characterized by their ability to be broken down into CO_2 and water under certain conditions through microbial processes. Biodegradability does not depend on the original raw material used, but solely on the chemical structure of the final product (German Bundestag 2016). Therefore, biodegradable plastics can be of either fossil or biological origin.

Figure 1 illustrates the classification of various plastics based on the origin of their raw materials and their biodegradability.

In addition to the two groups mentioned above and primarily considered in this paper, other materials exist that are generally considered "bio-plastics":

- Composite materials, often with a fossil-based plastic matrix, that contain bio-based fillers or reinforcing materials from wood or natural fibers, and
- Thermosetting or elastomeric "bio-plastics," particularly polyurethanes and epoxies.

While these materials represent significant quantities, they are not included in the statistics on "bio-plastics" presented here.

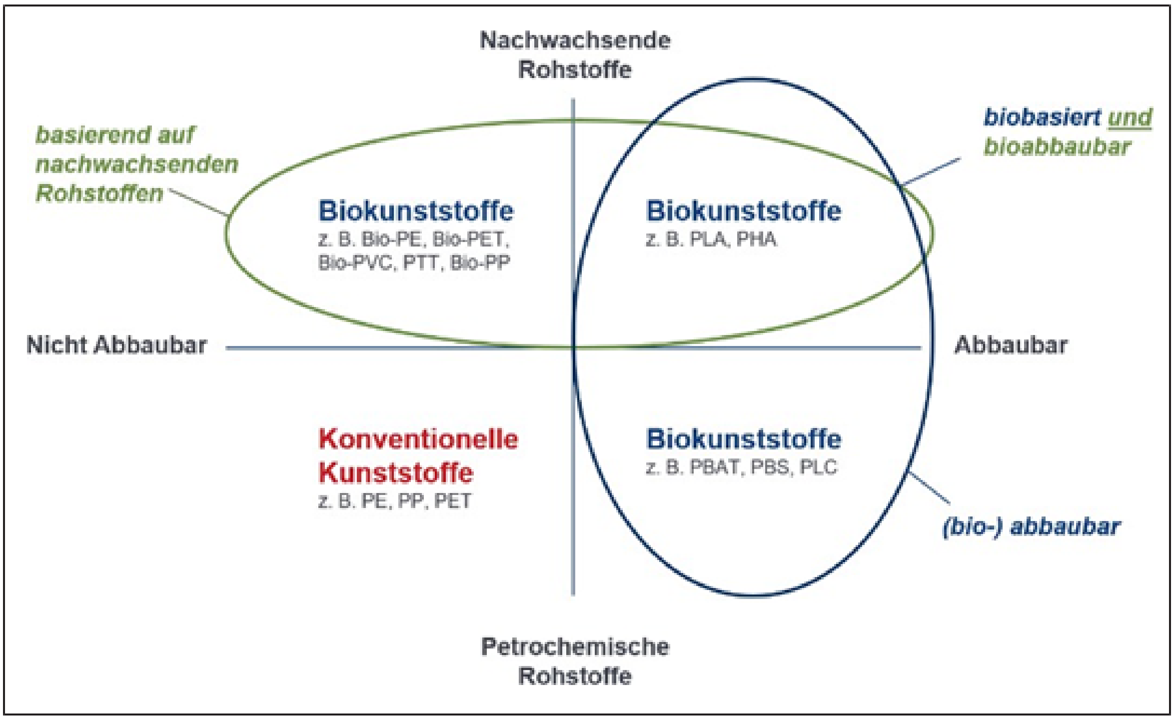

Figure 1: Classification of plastics according to their origin (fossil or bio-based) and biodegradability (Kreutzbruck et al. 2021)

Although "bio" plastics are often touted as a better alternative to conventional plastics, they exhibit similar chemical complexity and contain a similar number of additives as conventional plastics.

Figure 2 illustrates the global production capacities for "bio" plastics by application (European Bioplastics 2020). The largest share of "bio" plastics is used for flexible packaging, followed by rigid packaging; together, these account for approximately 47%. Capacities of just under 700,000 tons are available for consumer goods, textiles, agriculture, and transportation. Particularly in flexible packaging and agriculture, the share of inherently biodegradable plastics outweighs that of non-biodegradable plastics. In rigid packaging, a large proportion

[5] *Substance or mixture of substances in an unprocessed or minimally processed state that can be used in a production process (UBA 2012).*

consists of PET containers; however, PLA and PBAT applications are gaining ground here, as in other applications. A total growth of 7% between 2020 and 2025 is projected for these two types (Renewable Carbon Publications 2021). Some "newcomers" among "bio" plastics are experiencing considerable growth, starting from small market shares, such as PP with a projected growth of 34% by 2025.

Bio-based Plastics

Bio-based plastics consist entirely or partially of renewable, mostly plant-based raw materials.

They are further subdivided into drop-in solutions and novel biopolymers. Drop-in solutions refer to bio-based plastics that are chemically identical to the already known petroleum-based materials. Examples include bio-PET (polyethylene terephthalate) and bio-PA (polyamide). These "bio" plastics are just as non-biodegradable as their corresponding petrochemical "originals." Examples of bio-based, chemically novel polymers that are not structurally identical to conventional plastics include PLA (polylactide) and PHA (polyhydroxyalkanoate) (German Bundestag 2016).

Most "bio" plastics are not 100% bio-based. Many of them are based partly on fossil fuels and partly on renewable raw materials.

In addition, there are blends in which different bio-based plastics are mixed with a fossil-based polymer; common examples include starch blends, which are frequently used for packaging and consumer goods.

Various standards exist for the certification of bio-based plastics, such as the international standard ISO 16620, the European standard CEN/TS 16137, or the German standard DIN EN 17228, which was adopted from the EU. Based on these standards, DIN CERTCO (a certification company of the TÜV Rheinland Group) awards seals depending on the bio-based content. Figure 3 shows examples of the DIN CERTCO seals, which classify "bio-based" plastics into three different groups according to their bio-based content (DIN CERTCO 2021a). The C14 method (also known as the radiocarbon method) is used as a testing procedure to determine the proportion of bio-based carbon atoms (DIN CERTCO 2017). Since C14 atoms decay over very long periods, they are no longer present in fossil sources.

In addition, DIN EN 17228 specifies characteristics of bio-based plastics. The bio-based carbon content must be at least 20%. Other certifications are awarded by TÜV Austria or Biobasedcontent.

A large proportion of the "bio" plastics available today come from smaller producers.

In contrast, in large-scale industry, which manufactures mass-produced plastics (e.g., in the form of pellets), the use of bio-based materials is less common.

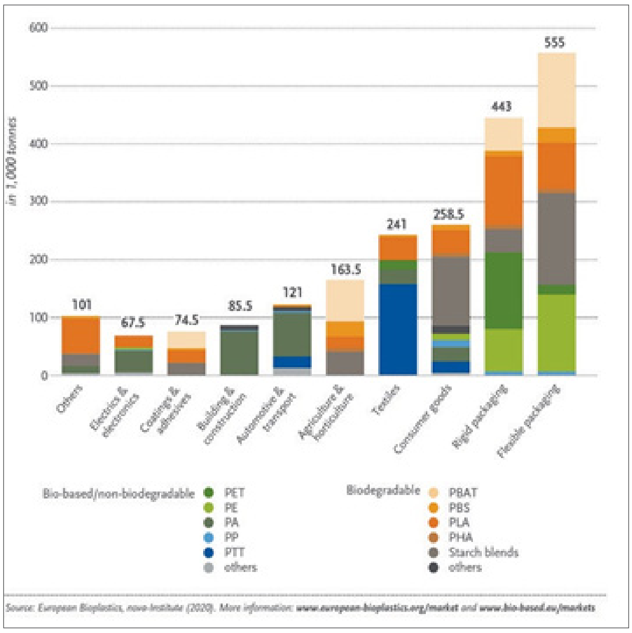

Figure 2: Global production capacities of "bio-based" plastics by application area. Source: European Bioplastics (2020)

Legend / Abbreviation	Chemical Name	Typical Applications / Remarks
PET	Polyethylene terephthalate	Rigid packaging
PE	Polyethylene	Packaging of all kinds, pipes, cables
PA	Polyamide	Many chemically different types, engineering material
PP	Polypropylene	Packaging and engineering material; small market share as bioplastic, strong growth
PTT	Polytrimethylene terephthalate	Fiber material
PBAT	Polybutylene adipate terephthalate	Films for packaging and agriculture; mainly fossil-based; high market share
PBS	Polybutylene succinate	Packaging, mulch films
PLA	Polylactic acid (Polylactic acid)	Very broad range of applications; high market share; strong growth
PHA	Polyhydroxyalkanoate	Various types; broad range of applications; small market share; strong growth
Starch blends	Starch blends	Packaging, consumer goods; high market share

Figure 3: DIN CERTCO seal for bio-based plastics; Source: DIN CERTCO 2021

With renewable raw materials, the so-called mass balance approach is increasingly being implemented. Due to the highly branched material flows, a separation of bio-based and fossil material streams is practically impossible. The construction of so-called "dedicated" production facilities that exclusively manufacture bio-based products throughout the entire process chain is currently not being considered for economic reasons.

Using mass balancing, the renewable raw materials used – currently in very small quantities – are mathematically allocated to the products. Plastics are considered mass-balanced if bio-based raw materials or precursors were demonstrably used in their production within a clearly defined accounting period (VCI 2017). This is similar to the approach used for feeding renewable electricity into the grid. Thus, a portion of the products is assigned 100% renewable raw materials, and the other portion 100% fossil fuels, even though in reality both are a mixture.

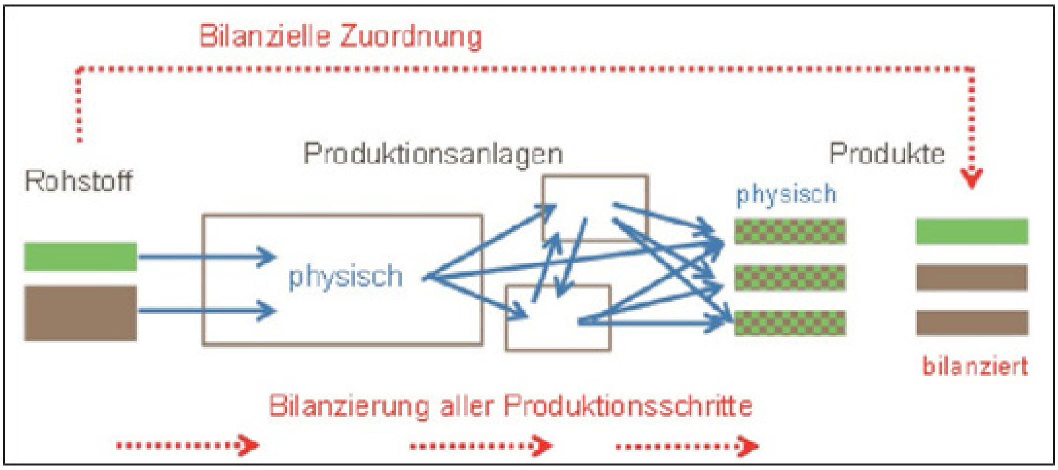

Figure 4: Principle of mass balancing (VCI 2017)

In the same process, the biogenic carbon content in the plastic can fluctuate over time. Dilution effects, as well as production and distribution at regional manufacturing sites with varying raw material supplies, can also make it impossible to detect biogenic carbon. Plastics to which renewable raw materials have been allocated through mass balancing are, according to the definition of the CEN/TC "Bio-based Products," not bio-based (VCI 2017). To avoid misleading consumers, there must be clear guidelines for providing information about these products, as they are not actually bio-based but rather based on 100% renewable raw materials according to mass balancing. Standards (e.g., from TÜV Süd) should be observed, and further standards should be developed if necessary. Emphasis should be placed on easily understandable communication. A clear distinction must be made between these products and truly bio-based products.

In the future, it remains to be seen to what extent mass balancing – which is increasingly being used, including in the application of different recycling processes – can be reconciled with transparent raw material sourcing that is understandable to consumers.

The Origin of Raw Materials for the Production of Bio-Based Plastics

The bio-components for bio-based polymers are currently obtained almost exclusively from cultivated biomass. Table 1 shows a list of the regions and raw materials for these biopolymers. In some cases, the cultivation area and the location of processing ("capacities") are not identical; for example, bio-PET is mainly produced in India, but the raw material comes from Brazil.

The agricultural land required for cultivating the renewable raw material for the production of "bio" plastics is estimated at 0.7 million hectares for the year 2020. This corresponds to 0.015% of the global agricultural area of 4.7 billion hectares. The share of land use for "bio" plastics will increase to 0.02% in the next 5 years (European Bioplastics 2020). Even though the share of global cultivated land for the production of bio-based plastics seems very small, the use of cultivated biomass for plastic production is already a central point of criticism. In the context of the bioeconomy discourse, the cultivated land for various uses (food production, pasture land and fodder cultivation, biofuels, etc.) is already highly contested and in some cases planned for multiple uses. In addition, there is increasing pressure on extensively used areas and protected areas (BUND 2021c). Globally known companies[6] are advertising many new "bioplastic" products. The current cultivation methods of industrial agriculture for the aforementioned crops used for these many new products are massively driving the widespread destruction of natural resources. Industrial agriculture is one of the main drivers of climate change and the loss of biodiversity. Furthermore, it degrades soil quality, and maize cultivation in monocultures, in particular, contributes to soil erosion. The intensive use of mineral fertilizers and chemical pesticides – which are often not even permitted in the EU for good reasons (Heinrich Böll Foundation/BUND 2019) – poses a threat to the environment, human health, and insects, and also leads to the pollution of groundwater and surface water. The increased cultivation of genetically modified plants also poses a risk.

The cultivation of sugarcane in Brazil, driven by current high demand (2020) and unequal land distribution, is leading to a wave of conversion of former cattle pastures into intensively farmed monocultures by a few large corporations, with serious negative impacts on the indigenous population, the local environment, and the climate. Even if sugarcane cultivation itself is only.

Plastic Type	Main Production Capacities	Smaller / Growing Capacities	Biogenic Raw Material
Starch blends	Europe	--	European corn (maize)
PLA	USA	China, Thailand	U.S. corn (Asian sugarcane)
Bio-PE	Brazil	--	Sugarcane
Bio-PET	India	Turkey	Sugarcane from Brazil
Bio-PA	Europe, North America, Asia	--	Castor oil, soybean oil, rapeseed oil, possibly sugar
Biodegradable copolyesters	Europe and Asia	--	Castor, milk thistle, sugar

Table 1: Regions and raw materials for various biopolymers; Source: Detzel et al (2019), p. 29

Although it takes place only marginally in rainforest areas, it contributes to the expansion of cattle farming in the Brazilian Amazon (Fatheuer 2020).

In addition to using cultivated bi

omass, agricultural residues can also be utilized for biomass production. However, competing uses, especially for animal feed production, cannot be ruled out (Detzel et al. 2019). When using agricultural "residues," it is important to consider, from an ecological perspective, that leaving these residues on the field fulfills important functions for soil health, including humus formation and thus climate protection.

Life Cycle Assessment of Bio-Based Plastics

In principle, bio-based plastics do not have a clearly better environmental footprint than conventional plastics. This is shown by studies from recent years (Detzel et al. 2019; UBA 2014; UBA 2017). These studies examined, for example, PE carrier bags, PET bottles, and PLA hinged-lid containers, each compared to a conventional plastic. The following impact categories were considered: cumulative energy demand, greenhouse gas potential, acidification potential, eutrophication potential, and land use. Advantages for bio-based plastics generally arise in terms of conserving non-renewable energy resources and contributing less to the greenhouse effect, and in some cases also to summer smog. Disadvantages arise in the areas of terrestrial and aquatic eutrophication, human toxicity, and acidification.

Biodegradable Plastics

"Biodegradability encompasses the property of a substance to be decomposed by microorganisms in the presence of atmospheric oxygen into carbon dioxide, water, biomass, and minerals, and under anaerobic conditions into carbon dioxide, methane, biomass, and minerals, without a defined time period" (DIN 16208).

The main areas of application for biodegradable plastics are in the packaging and catering sectors. There are also applications in horticulture and agriculture (e.g., mulch films, seed tapes, plant pots, etc.).

The degradation is carried out by special microorganisms whose enzymes break down the polymer chains of the material into small parts. These can then be further degraded by bacteria – possibly together with other organic material. After degradation, only water and carbon dioxide remain from the plastic itself; however, additives and other components are also released.

Typical degradation times for biodegradable plastics are shown in (UBA 2018, pp. 89 ff.). Industrial composting of PBS, for example, resulted in 90% degradation at 58 °C only after approximately five months; a PBS-starch film composted completely after 45 days (also at 58 °C). A PHB film degraded in soil (at 25 °C) by more than 90% within approximately four months. In addition to the type of material, the physical form (thin film, thicker parts) is particularly influential.

[6]*Coca-Cola is promoting the "PlantBottle," Pepsi, together with Nestlé and Danone, is promoting the "NaturAll Bottle," LEGO plans to switch its entire product range to "bio-based" plastic in a few years, and IKEA is also promoting "green" products (Denkhaus Bremen 2021).*

If a plastic is to be designated as biodegradable, a manufacturer can have its product certified according to various standards (Table 2). Specific criteria are applied for degradation in industrial composting facilities, home composting, and soil composting in agriculture. For degradation in freshwater environments, there is only one procedure, based on the standard for industrial composting. For degradation in saltwater, it is particularly difficult to define realistic conditions that can be replicated in the laboratories of the certification institutes. A common feature of all these testing standards is that they do not require complete degradation.

The biodegradation of a material being tested is determined in comparison to a reference material; therefore, the choice of the reference material influences the test result. Microcrystalline cellulose is frequently used as a test material, but depending on the test conditions (temperature, humidity, available microorganisms), it is usually slower to degrade than, for example, polyhydroxybutyrate (PHB). Therefore, harmonization of the standards regarding the test material is necessary.

According to the best-known and most widely used certification standard for compostability in an industrial composting facility (i.e., at approximately 60 degrees Celsius), the following requirements are placed on biodegradable plastics (cf. DIN EN 13432):

- Biodegradation – at least 90% of the polymer mass must be converted into carbon dioxide within 180 days.
- Disintegration – after three months (12 weeks) under industrial or semi-industrial composting conditions, no more than 10% of the dry mass should remain on a sieve with a mesh size of <2 mm.
- The heavy metal content and ecotoxicity of the compost must be below specified limit values.

The certification labels for industrial composting commonly used in Germany (“seedling” or DIN seal

“industrially compostable”, see Table 2) are based on DIN EN 13432. Although there are some product certifications for home composting, this is not possible for the vast majority of “bio” plastics because the products are not suitable for home composting.

Habitat	**Standard**	**Degradation & Disintegration Criteria**	**Logos**
Industrial composting	EN 13432	• Complete biodegradability (90% absolute or 90% relative to a suitable reference substrate) → max. 6 months at 58 ± 2 °C • Disintegration test: max. 10% of the original dry weight of the test material may remain in a sieve fraction > 2 mm → max. 3 months	
		Requirements for the recovery of packaging through composting and biological degradation – test scheme and evaluation criteria for classifying packaging	
		Comparable, among others, to: EN 14995	
Home & garden composting	AS 5810	• Complete biodegradability (90% absolute or 90% relative to a suitable reference substrate) → max. 12 months • Disintegration test: max. 10% of the original dry weight of the test material may remain in a sieve fraction > 2 mm → max. 6 months at 25 ± 5 °C	
	NF T 51-800	Plastics – Specifications for plastics suitable for home composting	

Table 2: Standards for the degradation behavior of biodegradable plastics; expanded with logos, based on sources: Burgstaller et al. 2018, page 6, logos from DIN CERTCO 2021, Fischer 2021, FNR 2021, TÜV Austria 2018

Habitat	Standard	Degradation & Disintegration Criteria	Logos / Certification
Biodegradation in soil (mulch films)	EN 17033	"*Biodegradable mulch films for use in agriculture and horticulture – Requirements and test methods*" (published 2018) • **Complete biodegradability (90% absolute or 90% relative to a suitable reference substrate)** → max. **2 years at 20–28 °C** (±2 °C; preferably 25 °C) • **No disintegration test required**.	
Degradation in freshwater	EN 13432 and EN 14995 (adapted for degradation in freshwater)	• Complete biodegradability **(90% absolute or 90% relative to a suitable reference substrate)** → max. **56 days at 20–25 °C** • **No disintegration test required**	
Biodegradation in the marine environment	ASTM D7081-05	*Standard Specification for Non-Floating Biodegradable Plastics in the Marine Environment (Withdrawn – test methods still in use)* • Complete biodegradability (90% absolute or 90% relative to a suitable reference substrate) → max. 6 months • Disintegration test described under TS-OK-23	

The materials cannot be properly broken down in typical compost piles. The high temperatures required for the decomposition of most "bio" plastics are not reached there for sufficiently long periods (see Table 2).

In practice, waste in most industrial composting plants only has a few weeks to decompose, so that biodegradable plastics (such as biodegradable plastic waste bags), despite appropriate certification, do not decompose sufficiently (Burgstaller et al. 2018). Extending the composting process is generally not economically viable and is therefore not foreseeable. Consequently, the biodegradable plastics used in Germany are sorted out by the majority of composting plants and currently end up almost exclusively in incineration, as they cannot be easily distinguished from conventional plastics and other "contaminants." A smaller number of composting plants do compost waste bags certified according to DIN EN 13432, but it remains unclear to what extent these certified biodegradable waste bags are nevertheless sorted out as contaminants during post-sorting and thus also end up in incineration (Scientific Services of the German Bundestag, 2021).

For biodegradable plastic packaging in Germany, even with certification according to DIN EN 13432, it is explicitly stated that they are not permitted for industrial composting or anaerobic digestion. Instead, according to the German Packaging Act, they are to be recycled by the dual systems, just like other packaging. Legally, only DIN-certified biodegradable waste bags are permitted for industrial composting. However, most German municipalities prohibit these waste bags for use in the organic waste bin for the reasons mentioned above.

Last but not least, the decomposition of biodegradable plastics does not produce any humus-forming substances. Therefore, energy must be supplied from an external source to produce new biodegradable products. Consequently, the process in the industrial composting plant is, strictly speaking, not composting, but merely waste disposal (Heinrich Böll Foundation/BUND 2019).

As mentioned above, DIN EN 13432 permits a 10% proportion of residues from the sieve fraction < 2 mm (thus, thin and significantly longer fragments may remain). In principle, it can be assumed that this material will also decompose over a longer period. However, the fresh compost contains these residues, which are to be considered contaminants. Accinelli et al. (2020) investigated the formation of microplastics from compostable waste bags and suggest that soil quality could be temporarily negatively affected as a result of shifts in the soil's microbial flora.

With products like mulch films, there is ongoing discussion about whether leaving appropriately certified films in the soil can be tolerated to a limited extent (UBA 2018). This is because, due to the sometimes high levels of contamination, this process currently involves considerable technical effort and is rarely practiced. Since 2018, a standard has existed that goes beyond the general standards mentioned above. EN 17033, which addresses biodegradable mulch films, incorporates improved ecotoxicological tests (plant, earthworm, and microorganism tests) and further restrictions on ingredients (metals, substances of very high concern) (European Bioplastics 2018).

Mulch films are used, on the one hand, to extend the growing season, but on the other hand, they are also an important tool in both organic and conventional farming for protecting crops from pest infestations. Without their use, reducing pesticide use in vegetable and specialty crop cultivation is significantly more difficult. In some cases, return and recycling systems for used films already exist. Further developments regarding the recycling and biodegradability of mulch films remain to be seen.

[7]*The ASTM D 7081-05 standard was withdrawn in 2014, yet TÜV Austria still certifies based on this standard. The label was formerly issued by Vinçotte (UNEP 2018, p. 70).*

Excursus: Oxo-degradable Plastics

Oxo-degradable plastics may be produced from either fossil-based or bio-based raw materials. Specific additives are incorporated into these plastics to accelerate their degradation process in the environment through exposure to light, heat, or mechanical stress. However, they do not undergo complete biodegradation; instead, they fragment into small particles, resulting in microplastics (Burgstaller et al., 2018).

In June 2019, as part of the **EU Single-Use Plastics Directive** (implemented in Germany through the **Single-Use Plastics Prohibition Ordinance**), a ban on oxo-degradable plastics was adopted. This ban **entered into force in July 2021**.

Recycling of "bio" plastics

According to the European waste hierarchy, waste prevention and reuse are the first and second priorities for achieving a functioning circular economy. Recycling (also known as material recovery) follows in third place. The recycling of plastics (and consequently also "bio-based" plastics) is therefore an important building block for a functioning circular economy, but by no means the solution to the plastic crisis.

Many "bio-based" plastics (i.e., those used for packaging and therefore primarily addressed in this paper) are thermoplastic8 and can therefore, in principle, be recycled. Drop-in polymers such as bio-PE and bio-PET can be recycled together with their corresponding fossil-based plastics, as they are, as already explained, chemically identical. Accordingly, recycling of these "bio-based" plastics is already taking place today. As for new biopolymers (such as PLA), their share of the total packaging volume is currently so small that they are not collected within the dual system because it is not economically viable. They are usually sorted out in sorting plants and end up in incineration plants (Burgstaller et al. 2018).

Against this background, it would be sensible to limit the number of different "new" biopolymers used in products in order to achieve material flows that allow for economically viable recycling.

Additives in "bio-based" plastics and their human and ecotoxicological effects

Like other plastics, "bio-based" plastics contain various additives: substances that provide the desired properties (plasticizers, flame retardants, antioxidants and UV stabilizers, lubricants, dyes, antistatic agents, biocides, fillers, and reinforcing materials). A distinction must be made between these intentionally added substances (IAS) and other, unintentionally added substances (NIAS).

The former are known to the manufacturers, but they often do not disclose this information. NIAS have no specific function and have entered the product unintentionally. They can arise from impurities, reaction and degradation products during manufacturing and use. Examples of NIAS include short-chain, low-molecular-weight plastic components, degradation products of additives, or contaminants from the recycling process (Koster et al., 2016; Geueke, 2018).

Since "bio-based" plastics are expected to enter the environment in increasing quantities in the future due to anticipated increases in production and improper disposal, an assessment of their human and ecotoxicity, as well as their persistence in the environment, is of great importance.

For example, waste bags certified according to DIN EN 13432 contain an average of about five percent additives (Scientific Services of the German Bundestag, 2021). According to the standard, only substances with a weight percentage higher than 1% need to be tested for biodegradability; at the same time, the standard tolerates up to five weight percent of non-biodegradable components.
The certification standards for biodegradable plastics, DIN EN 13432 and DIN EN 14995, specify maximum limits for heavy metals and other toxic substances, and require an assessment of the ecotoxicological effects of the resulting composts on higher plants. However, this is insufficient, as it does not provide information about potential accumulation in the environment and negative consequences for other living organisms. (Eco) toxicity studies are particularly necessary for "NIAS" (non-intentionally added substances).

Several recent publications have identified numerous substances with hazardous potential in plastics, including "bio"-based plastics and those intended for food contact. Two recent studies investigated everyday products made from conventional plastics as well as "bio"-based plastics in the form of plastic raw materials (pellets) and finished products for their chemical composition and toxicity (Zimmermann et al., 2019, 2020). They were tested for acute toxicity using luminescent bacteria, for the potential to initiate mutagenic or carcinogenic effects ("oxidative stress"), and for endocrine effects using cell-based assays. The majority of the plastics tested – both conventional and "bio"-based plastics – contained toxic chemicals. In both groups, a quarter to a third of the extracts showed no toxic effects.

A follow-up study has shown that even under realistic conditions (leaching of chemicals with water instead of methanol), thousands of chemicals can migrate from the plastics and thus transfer into food and the environment (Zimmerman et al. 2021).

Various research groups have developed so-called biotest batteries that can be used to assess human, terrestrial, and aquatic toxicity (Koster et al. 2012; EFSA, 2019; Koster et al. 2016; Neale et al. 2017; Schmidt et al. 2017; Brack et al. 2019; DiPaolo et al. 2016; Braun et al. 2021). From the multitude of test methods and test batteries, a suitable combination should be developed for all "bio" plastics, especially biodegradable ones, which must then be applied mandatorily based on the precautionary principle.

[8] Thermoplastic plastics can be melted down (without significant material changes).

However, using their test combination, Zimmermann et al. (2019, 2020) found only low inherent toxicity in approximately a quarter of the samples. This selection could be groundbreaking for the future development of a new generation of low-toxicity and environmentally friendly plastics.

Critical aspects of "bio-based" plastics at a glance

In summary, the following statements can be made about "bio-based" plastics:

- The vast majority of bio-based "bio-plastics" are not products derived from organic farming. Furthermore, they often contain fossil-based components.
- Virtually all "bio-plastics" contain additional additives. Toxic effects have been demonstrated for many of these; their toxic potential does not differ significantly from that of fossil-based plastics (Zimmermann et al. 2020).
- Some "bio-plastics" are biodegradable and certified as such. However, since the decomposition times, according to current standards, are significantly longer than the composting time in industrial facilities, decomposition in accordance with the standard is not guaranteed. Moreover, the residual particles tolerated by the standard should be critically evaluated.
- For the "new" biopolymers that are not chemically identical to established plastics (PE, PET, etc.), there are currently no recycling options within existing recycling facilities due to the small quantities produced.
- Approximately half of all "bio-plastics" are used in packaging. There is enormous potential for reducing their use in this area; in other words, many of these plastic applications are unnecessary in a sustainable economy.
- The standards for all "bio-plastics," but especially for those certified as biodegradable, do not include the necessary human and ecotoxicological tests for either intentionally added substances (IAS) or non-intentionally added substances (NIAS).

BUND demands and guidelines on "bio-based" plastics

Given the current circumstances, "bio-based" plastics are currently a false solution to the plastic crisis.

The primary goal in response to the plastic crisis is and remains the avoidance of unnecessary plastic applications, particularly in the packaging and single-use sectors. From the perspective of BUND (Friends of the Earth Germany), the often heated debate surrounding the use and potential benefits of "bio-plastics" primarily distracts from the truly necessary transformation of the packaging and plastics sectors in general. Here, consistency (e.g., reusable instead of single-use) and sufficiency (reduced quantities) must be given greater focus. Necessary, binding reduction targets must also be supported by specific targets and measures; otherwise, they will remain merely symbolic.

The industry, for example, promotes "bio" plastics with the argument that they are a good way to store CO2. In reality, this argumentation resembles other end-of-pipe solutions to climate change, which only address the symptoms. Such arguments lead to the preservation of the status quo for as long as possible and weaken demands for the necessary systemic changes. The large quantities of single-use packaging – whether made of plastic or "bio"-plastic – and the low recycling rates of existing plastic waste are the primary problem that should be addressed. A discussion about "bio"-plastics as a CO_2 storage solution can distract from this.

In the second step, the plastic already in the system must be genuinely recycled in a high-quality manner – this includes prioritizing reuse through the widespread use of reusable systems. Furthermore, all plastic products manufactured must be recyclable not only in theory but also in practice. To achieve this, a product design optimized for recycling is essential (monomaterials, suitable colors, ease of disassembly, etc.) to ensure the highest possible quality of recycled material.

The Central Packaging Register should accordingly remove "bio-based" plastics from its approved list as long as they cannot be recycled in the current market. For the recycling of "bio-based" plastics, this means that, in addition to drop-in polymers that can be recycled with the chemically identical fractions of conventional plastics, a restriction to a few new "bio-based" plastics[9] is advisable in order to increase their proportion and thus make material recycling economically viable. Appropriate political incentives are crucial for this – especially against the backdrop of the need for a socio-ecological transformation, in which economic viability according to today's standards can no longer be the central criterion for or against a measure.

Only then should the question be addressed of whether and where bio-based plastics can meaningfully replace those derived from fossil fuels.

It is questionable whether biodegradability, depending on the application, can actually offer advantages, e.g., in soil-related agricultural applications. This is of central importance because the composting of biodegradable plastics is merely a form of disposal, which contradicts the principles of the circular economy.

Furthermore, labels such as "compostable" or "biodegradable" can lead to these products ending up more frequently in the environment, which is extremely problematic.

The standards for all "bio-based" plastics, but especially for those certified as biodegradable, should be supplemented with necessary human and ecotoxicological tests. In particular, (eco)toxicity studies are necessary for "NIAS" (non-intentionally added substances). Furthermore, harmonization of the standards regarding the reference material is required.

[9]*Based on the current state of development, these materials primarily include PLA and PHAs, assuming that the volume growth continues as it has in recent years.*

The BUND (German Federation for Environment and Nature Conservation) makes the following demands regarding the use of bio-based plastics:

- The BUND rejects the production of raw materials for bio-based plastics on non-sustainable, dedicated land (e.g., through deforestation, conversion of extensively used land to intensively used land, or displacement of food production).
- Sustainable production of bio-based plastics can only be achieved through the use of raw materials that are regionally available as residues from biogenic products (such as the timber industry, viticulture, or waste cooking oil). Appropriate certification should be in place for the origin of these raw materials. Agricultural "residues" that are beneficial for soil health and CO2 sequestration should not be used for "bio" plastic production.
- The use of bio-based plastics must not lead to conventional plastics gaining a better image in avoidable applications (greenwashing). This applies in particular to plastic products that are only partially made from bio-based raw materials.
- Consumer-friendly, easily understandable communication about the actual bio-based content of products is necessary. Independent standards/certification should be developed for this purpose.
- The German Federation for Environment and Nature Conservation (BUND) makes the following demands regarding the use of biodegradable plastics:
- A fundamental rejection of the use of biodegradable plastics for packaging.
- If demonstrably useful applications for biodegradable plastics are established, conventional plastics should no longer be permitted for these applications.
- Biodegradable plastics must legally contain no additives or only harmless additives. This requires complete transparency regarding all ingredients, as well as toxicity testing for non-intentionally added substances (NIAS).
- They must also be completely biodegradable outside of industrial composting facilities.
- No approval of biodegradable plastic products for disposal via composting plants.
- The use of products such as mulch films should be minimized as much as possible.
- The use of products such as mulch films is, among other things, an important non-chemical pest control method. In the future, its use should be limited either to truly biodegradable plastics or, preferably, to durable films that are returned for recycling.
- Return and recycling systems, ideally based on a deposit system, must be established for the return of films used in agriculture.

Appendix A: Additives in "bio-based" plastics and their human and ecotoxicological effects

Like other plastics, "bio-based" plastics contain various additives: substances that provide the desired properties. More than 10,000 different chemicals have been associated with plastics (Wiesinger et al. 2021). However, due to a lack of transparency, it remains unclear which and how many of these chemicals are present in a given plastic.

A distinction can be made between intentionally and unintentionally added substances (IAS and NIAS). The former are known to the manufacturers, but they often do not disclose this information. The latter are usually unknown even to the manufacturer and are unintentionally present in the final product. These include, for example, by-products (e.g., short-chain plastic components (oligomers)), as well as reaction and degradation products from the manufacturing process (e.g., nonylphenol from antioxidants), and impurities (e.g., mineral oil and substances resulting from the recycling process) (Koster et al., 2016; Geueke, 2018). These can arise from impurities, reaction and degradation products during manufacturing and use, and their risk potential cannot be assessed in most cases due to a lack of data.

Since "bio-based" plastics are expected to enter the environment in increasing quantities in the future due to anticipated increases in production and improper disposal, an assessment of their human and ecotoxicity, as well as their persistence in the environment, is of great importance.

The substances intentionally added for specific functions (plasticizers, flame retardants, antioxidants and UV stabilizers, lubricants, dyes, antistatic agents, biocides, fillers, reinforcing agents) can be broadly categorized into additives intended for plastics used in food or skin contact applications, and additives for technical applications indoors and outdoors. Since many "bio" plastics are used for food packaging, the additives and non-intentionally added substances (NIAS) they contain can migrate into food (and thus generally into the food chain). Such plastics and their components are under particular scrutiny. A positive list from the EU (EU, 2020) containing more than 1000 individual substances has been continuously updated since 2011 ("Union list of authorized monomers, other starting materials, macromolecules obtained by microbial fermentation, additives and processing aids used in the manufacture of plastics"). Some individual substances have been evaluated by the European Food Safety Authority (EFSA). Furthermore, any substance placed on the market with a production volume of more than one ton per year should be registered in the EU. For these substances, a dossier is typically available containing their (eco)toxicological and other environmentally relevant properties.

Groh et al. (2021) investigated food-contact plastics and identified approximately 4700 substances (IAS) in a comprehensive compilation, which are used worldwide as starting materials or additives in food-contact plastics. They found approximately 600 chemicals in the plastics studied that are classified as priority substances on various lists, including those considered hazardous to health and/or the environment (ECHA/Japan), endocrine disruptors, persistent, bioaccumulative, and toxic (PBT), very persistent and very bioaccumulative (vPvB), or persistent organic pollutants (POPs), or that are listed on priority lists in the EU or the USA (California). Identifying such known and unknown substances and substance groups is a first step in recognizing critical substances based on their structures; however, further steps are necessary for a complete assessment. In "bio-based" plastics, over 40,000 substances[10] were found using chemical analysis methods, many of which are non-intentionally added substances (NIAS) (Zimmermann et al., 2020).

After more or less prolonged use, "bio-based" plastics – like plastics made from petroleum – are subject to material recycling, incineration, or landfilling (Hahladakis et al., 2018). However, some of them end up in the environment (litter); for all "bio-based" plastics, the pathway into the terrestrial and potentially aquatic environment is particularly likely. Ideally, the plastics are then completely mineralized into CO_2 and water, but this only happens under favorable laboratory conditions, rarely in the real environment (Haider et al., 2019).

The fate of the intentionally added substances (IAS) and non-intentionally added substances (NIAS) contained in the products remains largely unclear. For example, waste bags certified according to DIN EN 13432 contain an average of about five percent additives; neither these additives and their degradation behavior, nor their ecotoxicity, are adequately regulated by the standard (German Bundestag Scientific Services, 2021). The standard therefore does not rule out an ecotoxic effect of the additives. With an IAS + NIAS content of 1–5%, the 870,000 tons per year of biodegradable plastics produced globally in 2017 (Haider et al., 2019) translate to approximately 9,000 to 40,000 tons of largely unknown chemicals, some of which are released into the environment annually without control.

The certification standards for biodegradable plastics, DIN EN 13432 and DIN EN 14995, specify maximum limits for heavy metals and other toxic substances and require a determination of the ecotoxic effect of the resulting composts on higher plants. However, this is insufficient, as it does not provide any information about possible accumulation in the environment and negative consequences for aquatic or terrestrial organisms. (Eco)toxicity studies are particularly necessary for the "NIAS."

If the added intentionally added substances (IAS) are known and registered, the basic data facilitate an assessment of the human toxicological and environmental hazard potential (EFSA, 2020; Hahladakis et al., 2018) and the identification of particularly critical substances with prioritization (Groh et al. 2021). However, the identification of critical IAS and non-intentionally added substances (NIAS) without existing data sets requires further efforts. Several publications from recent years offer starting points for this.

Two recent studies investigated everyday products made from various conventional (petroleum-based) plastics (e.g., polyethylene, polystyrene, polyvinyl chloride) as well as "bio-based" plastics (many of which are intended for food contact) for their chemical composition and toxicity (Zimmermann et al., 2019, 2020). The chemicals contained in the products were extracted using methanol, and the resulting chemical mixture was then tested using cell-based assays. The majority of the plastic products examined – two-thirds of the conventional plastics and three-quarters of the "bio-based" plastics – contained harmful chemicals, including those that are toxic to cells or cause endocrine disruption. The products based on cellulose or starch contained the most chemicals and were the most toxic (i.e., had negative effects in cell-based assays).[11] In both groups, one-quarter and one-third, respectively, showed no toxic effects from the extracts.

A follow-up study has shown that even under real-world conditions (extracting the chemicals with water instead of methanol), thousands of chemicals leach from the plastics and can thus transfer into food and the environment (Zimmerman et al. 2021). To draw conclusions regarding the impact on humans and other organisms, it is necessary to extrapolate the results from the cell-based assays to living organisms and to estimate the actual exposure. For packaging, the extent of migration into food or leaching into the environment must be determined and evaluated based on effect data.

To identify potential effects of plastic components on humans (via food or skin) or on the environment with a reasonable degree of certainty, there is, firstly, the conventional single-substance assessment. This requires prior chemical-analytical characterization of the NIAS (Koster et al., 2012: 10 µg/kg as the lower analytical limit), followed by the identification of substances with particularly relevant toxicological structures (nitrosamines, highly genotoxic compounds, dioxin-like compounds, azoxy compounds, steroids, aflatoxin-like compounds, organophosphates, organometallic compounds), information on potential migration with exposure assessment, and finally, the evaluation of each substance, either through substance-specific tests or broadly according to the TTC concept ("Thresholds of Toxicological Concern") (Koster et al., 2012; EFSA, 2019). The TTC upper limit would result in an exposure of a maximum of 90 µg per person per day (Kroes et al., 2004).

Alternatively – and more simply – the extracts of the plastics could be tested integrally for possible toxic properties using a suitable combination of test methods. Koster et al. (2016) refer to the application of the migration/extraction methods described in EU Regulation 10/2011 (Annexes III and V) for plastics in contact with food. They propose subsequent in-vitro bioassays for endocrine activity, cytotoxicity, and genotoxicity/potential carcinogenicity. A variety of test methods for determining human and aquatic toxicity have been compiled by Neale et al. (2017) and Schmidt et al. (2017). Schmidt et al. (2017) worked with a total of 12 tests for different endpoints (hormone-like, mutagenic/genotoxic and neurotoxic effects, immunotoxicity and oxidative stress, metabolic enzymes

[10]The number of substances/chemicals are approximations and not accurate figures. However, this approximation is more likely to underestimate the number of chemicals/substances contained in or that can leach from the products.

[11]The conventional plastics involved were polyvinyl chloride and polyurethane.

and receptors, phytotoxic and other specific effects). Within the EU project SOLUTIONS and the NORMAN network, a coordinated bioassay battery was developed that uses three organismic in vivo bioassays and cell culture-based in vitro methods for the detection of specific effects such as endocrine activity, genotoxicity, and reactive toxicity (Brack et al. 2019, DiPaolo et al. 2016). This bioassay battery was proposed by a working group on effect-based methods of the EU for implementation in the Water Framework Directive. This bioassay battery, extended to include terrestrial bioassays, is used, for example, within the ERDF project iMULCH or in the UBA project "Plastics in soils - occurrence, sources, effects" (Braun et al. 2021). From this multitude of test methods and test batteries, a suitable combination should be developed for all "bio" plastics, which must then be applied mandatorily based on the precautionary principle.

The concept of "Green Toxicology" is also very effective in the development of new bio-based plastics. This approach employs a comprehensive battery of ecotoxicological and toxicological tests at an early stage of product development to directly rule out adverse effects on humans and the environment and to support the design of the most environmentally friendly products through direct feedback (Crawford et al. 2016, Johann et al. 2021). Ideally, the products are classified as harmless, or further investigations are required, including analytical methods and individual substance assessments. Zimmermann et al. (2019, 2020) found only low inherent toxicity in approximately a quarter of the samples using their test combination. This selection could be groundbreaking for the future development of a new generation of low-toxicity and environmentally friendly plastics. Which extraction agent is suitable and which of the existing test methods are suitable in practice as rapid high-throughput early warning procedures for detecting toxic additives still needs to be clarified in research projects. This must consider both the protection of humans during the use of the plastics (e.g., migration into food from packaging, skin contact) and possible effects from uncontrolled release into the environment.

The maximum limits for heavy metals and other toxic substances specified in DIN EN 13432 and DIN EN 14995, as well as the test for determining ecotoxic effects on higher plants, are insufficient to provide adequate information about potential accumulation in the environment and negative consequences for other living organisms. The standards for all "bio"-plastics, but especially for those certified as biodegradable, should be supplemented with necessary human and ecotoxicological tests. In particular, (eco)toxicity studies are required for "NIAS" (non-intentionally added substances).

For bio-based plastics, a suitable combination of test methods should be developed using existing concepts such as "Green Toxicology" and the publications by Zimmermann et al. (2019, 2020). These methods should comprehensively, yet cost-effectively, assess the potential toxic and ecotoxic properties of products, starting as early as the product development process.

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Standards

DIN EN 13432
Packaging – Requirements for packaging recoverable through composting and biodegradation – Test scheme and evaluation criteria for the classification of packaging; 2000

DIN EN 14995
Plastics – Evaluation of compostability; 2007

DIN EN 17228
Plastics – Bio-based polymers, plastics and plastic products – Terms, characteristics and communication; 2019

DIN CEN/TR 16208
Bio-based products – Overview of standards; 2011

ISO 16620
Plastics – Determination of biobased content – Part 1: General principles; 2015

AS 5810
Biodegradable plastics – Biodegradable plastics suitable for home composting (Australian standard); 2010

ASTM D6400
Standard Specification for Compostable Plastics (U.S. standard); 2019

ASTM D6866
Standard Test Methods for Determining the Biobased Content of Solid, Liquid, and Gaseous Samples Using Radiocarbon Analysis (U.S. standard); 2018