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Discussion about suitable applications for biodegradable plastics regarding their sources, uses and end of life

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Abstract :

This opinion paper offers a scientific view on the current debate of the place of biodegradable plastics as part of the solution to deal with the growing plastic pollution in the world's soil, aquatic, and marine compartments. Based on the current scientific literature, we focus on the current limits to prove plastic biodegradability and to assess the toxicity of commercially used biobased and biodegradable plastics in natural environments. We also discuss the relevance of biodegradable plastics for selected applications with respect to their use and end of life. In particular, we underlined that there is no universal biodegradability of plastics in any ecosystem, that considering the environment as a waste treatment system is not acceptable, and that the use of compostable plastics requires adaptation of existing organic waste collection and treatment channels.

Highlights

► Biodegradable plastics are relevant for selected applications. ► Better certification and clearer instructions are needed to improve waste management. ► Methodological limits hamper the evaluation of plastic biodegradability and toxicity. ► Considering the environment as a waste treatment system is not acceptable.

Keywords : Keywords, Plastic, Biodegradable, Ecosafety, Waste management

1. Introduction

The plastic industry is facing several major problems, spanning from the synthesis of plastic products from petroleum to their long-term accumulation in all environmental compartments. These include the growing scarcity of oil resources, CO_2 emissions from plastics manufacture, and environmental impacts throughout their life cycle. As a partial solution, it has been proposed to manufacture plastics that would be both biobased, i.e., made from renewable resources such as agricultural waste, and biodegradable in a given environment (compost, soil, water) over a reasonable amount of time (weeks, months). These alternatives to “conventional” plastics have generated a considerable research effort to design new materials and establish norms that ensure their biodegradability and the absence of toxicity in the surrounding environment (e.g., ISO 17088, NF EN 13432, NF T51-800, NF ISO 17033). Although these standards are not yet mandatory, this represents a remarkable effort that has never been made for conventional plastics. A wide range of biodegradable plastics are available on the market, including those that are suitable for industrial and home composting, or soil degradation such as films for agricultural and horticultural purposes. However, most households do not discriminate biodegradability under composting (“compostable”) from “biodegradable” (Table 1), which gives the misleading idea that all biodegradable plastics can be released into the environment with no harm done and fast degradation (Dilkes-Hoffman et al. 2019). Furthermore, the term “bioplastic” is prone to send misleading messages as it is used to designate different products: plastics that may be biobased, biodegradable or both biobased and biodegradable (Table 1). All these elements lead to confusion among the general public and inappropriate end-of-life management.

Overall, designing a material with properties like those of conventional plastics but that would completely disappear in all type of environment in a reasonable amount of time (i.e. similar to natural organic matter, from months to years; Vahatalo et al. 2010) without having any harmful properties during its decomposition process is probably out of reach in the current state of knowledge. To approach this goal would involve outstanding technological developments that are currently limited by multiple technological barriers, which we discuss below.

2. Applications for which the use of biodegradable plastics is justified owing to their use and end of life

Biodegradable materials have clear advantages either for specific applications (packaging, mulch) or for sectors with high added value (e.g., 3D printing, biomedical). A distinction must be made between collectable and non-collectable items, as their fate will likely differ (Figure 1). Using biodegradable material for plastics for which collection at the end of life is not possible or extremely difficult constitutes a relevant alternative only if the final destination of this plastic waste is well identified. Examples of such applications are the plastic items widely used in the agricultural, horticultural and forestry sectors (strings, clips, bale, and mulching film). These cannot be easily retrieved because of intense fragmentation under UV light and they can end up contaminating soils or waters for decades. Biodegradable mulch film, for instance, starts to degrade as soon as it is laid in the field, notably because of photo-oxidation. The time when its use is no longer necessary usually coincides with the loss of its integrity (Touchaleaume et al. 2016, 2018). It is then buried to accelerate its biodegradation in the soil. Plastics that are biodegradable in soils (e.g. PBAT, PHA, starch blends, cellulose films; Figure 1) are to be distinguished from oxo-degradable plastics that integrate prodegradant additives in conventional plastics to degrade faster, but for which the complete biodegradation remains in doubt in the environment (Abdelmoez et al. 2021). Indeed, after the European Parliament's ban decision, many concerns have been raised about the toxicity of oxo-degradable plastics as they are not biodegradable according to current international standards (EU, 2018). Another example of plastics for which collection at the end of life is not possible or difficult concerns the plastic gears used in marine applications. Fishery gears and aquaculture equipment that are likely to degrade over time and/or be lost at sea could have less long-term impacts on marine fauna (e.g., entanglement, ghost fishing, wounds) if they were made of marine biodegradable materials (e.g. based on polyhydroxyalcanoate, PHA). However, such marine biodegradability remains to be evaluated with regard to the effectiveness in fishing of such biodegradable gears under real conditions, especially when the biodegradation must occur in the same environment as their use, i.e. the seawater. Ideally, they should be retrieved from water and collected after their use time (e.g., following the loss of their mechanical properties) to be thrown in compost on earth. Alternatively, the use of non-biodegradable nets that one would equip with captors and systematically retrieve from the marine environment might be just as efficient (Fielstad, 1988; McElwee et al. 2012). Other examples include the plastic particles and water-soluble polymers used in care products (e.g., cosmetics, detergents) (Sahlan et al. 2020; Volant et al. 2021), or the microfibers used in textiles (Figure 1). When their complete removal from the user product is not feasible, their substitution by materials biodegradable in aquatic systems would be relevant as they are not effectively retained by wastewater treatment plants and may contaminate fresh and saltwater ecosystems in the long term (Edo et al. 2020; Murphy et al. 2016).

Regarding collectable items, biodegradable plastics are not initially designed to be mechanically recycled as they are not able to withstand multiple extrusion cycles while retaining their original properties. Nevertheless, some of them such as PLA could be recycled (Maga et al. 2019, Piemonte et al. 2013, McKeown and Jones 2020) but there are currently not enough recovered resource to consider this end-of-life option that is to be monitored in the future. In addition, if these compostable or biodegradable plastics are not collected separately, they can contaminate plastic recycling (PET, PE and PP) resulting in technological and economic burdens (lack of homogeneous surfaces, undesired opaqueness, defects or failure during injection molding) (Gere and Czigany 2020). However, several automatically sorting technologies (e.g. based on gravity, triboelectrostatic, spectral (NIR)) are currently available and have potential to avoid the cross-contamination of conventional plastic recycling by compostable ones (Taneepanichskul et al. 2022). The only end-of-life scenario being considered at present is the organic recycling through composting and anaerobic digestion of some biodegradable packaging that could be collected with organic waste. For disposable dishes, food packaging films, and bio-waste collection bags, the use of biodegradable material could be relevant, provided that effective education, collection, and sorting processes are concurrently developed to ensure proper management of this waste. The use of compostable plastics requires an adaptation of existing organic waste collection and treatment channels.

3. The use of compostable plastics requires an adaptation of existing organic waste collection and treatment channels

Compostable polymers designed for biological treatment are especially promising for food packaging or service ware, when these are collected together with food waste (Law and Narayan, 2021). Food packaging materials must meet the dual requirement of retaining all their properties throughout their use and not degrading or biodegrading in contact with food during their shelf life. Once they become waste, these plastics can be collected together with food waste and sent to an industrial composting stream where all the conditions are met for them to biodegrade very quickly. The success of this model is conditioned by (1) the strict prevention of the collection of non-compostable materials that would contaminate the compostable waste and (2) the existence of a nearby biological treatment facility (industrial composting plant or aerobic digesters; Figure 1), ensuring not only that the carbon in the plastic can be fully metabolized but also that this happens on a timescale allowing its full mineralization into CO_2. Recent papers have pointed out that the vast majority of commercially biodegradable polymers (e.g., blends made of PHAs, PLA or starch-based) are compostable under thermophilic conditions as those found in industrial composting platforms (Chinaglia et al., 2018, Cucina et al. 2021a, De Gisi et al. 2022, Folino et al. 2020, Ruggero et al., 2021). According to Cucina et al. 2021a, the time estimated for complete degradation of PLA, PHAs and starch-based blends was 84 ± 47 days, 124 ± 83 days and 119 ± 43 days, respectively. These results are consistent with the recent study of Edo et al.(2021), which demonstrates that no debris from compostable biodegradable plastics were found in any of the samples, meaning that if correctly composted their current use does not contribute to the spreading of anthropogenic pollution. This suggested that the use of compostable polymers and the implementation of door-to-door collection systems could reduce the concentration of plastic impurities in compost from organic fraction of municipal solid wastes (OFMSW). This is why the composting process is one of the most preferable options when it comes to the biodegradable plastics disposal (Folino et al. 2020).

In contrast, with the exception of PHA blends the degradation kinetics of biodegradable polymers are often incompatible with anaerobic digestion at mesophilic temperature (Battista et al. 2021, Cucina et al. 2021b), but as pointed out in recent literature, thermophilic temperatures (55 ± 2 °C) significantly accelerated PLA and starch-based blends’ degradation. (Calabro et al., 2020, Cazaudehore et al., 2021, Folino et al., 2020). Studies on improving the biodegradability of PLA by applying thermo-chemical pretreatment are currently being investigated (Calabro et al. 2020 Cazaudehore et al. 2022). On another hand, the chemical modification of natural polymers can also inhibit the degradation process. For instance, while cellulose undergoes rapid biodegradation in most of environments and is widely used as a positive control for assessing biodegradation in thermophilic and mesophilic environments, such as compost or soil, as stated in ASTM and ISO standards (Bher et al. 2022), its chemical modification may significantly impair its biodegradability. For instance, a high degree of acetylation in cellulose acetate (CA), a widely used cellulose-based polymer, lowers its biodegradability through conventional organic waste treatment such as industrial composting (Yadav & Hakkarainen, 2021) or mesophilic anaerobic digestion even when combined with composting (Gadaleta et al. 2022). Overall, these biological treatment processes are not affected by the presence of CA but an increase in compost impurity is reported (Gadaleta et al. 2022). Biodegradability of cellulose esters under industrial composting and anaerobic digestion plants then depends on the interplay between the chemical composition of the bioplastics and the condition of the degradation environment (Yadav & Hakkarainen, 2021), which undermines the suitability of such treatment for such cellulose-based bio-plastics. Thus, a better understanding of the suitable processing conditions for each biodegradable plastics' type is needed to successfully optimize the use and end of life of biodegradable plastics. Overall, with the up-coming generalization of sorting at the source and separate collection of biowaste, dedicated collection channels should be set up (or expanded where it already exists) to support industrial composting and anaerobic digestion platforms. Such facilities have the advantage of being present in large numbers throughout most European countries. For instance, about 720 industrial composting platforms were listed in France in 2020 (sinoe.org) which is seven times more than the number of energy recovery and incineration plants.

On the consumer side, awareness campaigns and clear recommendations to users must be set up to differentiate between recyclable, home compostable, and industrially compostable items, so as to avoid contamination of the recycling or composting streams by inappropriate materials. Indeed, separate collection of biodegradable plastics with organic fraction of municipal solid wastes (OFMSW) has been recommended in Europe since 1994, but better certification and clearer instructions are still needed to decrease the error disposal rate that is higher compared to other plastics (Taufik et al., 2020). Developing a system of identification, labeling or marking (such as the grid pattern or QR code currently used in France and Switzerland to identify compostable plastics; e.g., https://rsb.org/; https://bioapply.com/) combined with clear instructions on using and disposing of such plastic items is of utmost importance to guide the consumer. Along this line, clear rules on labelling of "compostable" or "biodegradable" plastics (Table 1) are needed to avoid the misleading idea that such collectable biodegradable plastics can be thrown away into the environment. For example, in France, the AGEC law forbids, since January 2022, to use the term "biodegradable" or "respectful of the environment", while compostable material will have to be marked with the warning "not to be thrown into the environment".

The triptych of "education-collection-sorting" probably requires a large financial investment and an adaptation of consumption habits. If successfully implemented, the use of compostable plastics for food waste collection may be an excellent option to reduce the inconvenience for householders (odors, insects, leaks), and to increase in the amount of organic waste collected and transformed into good quality biogas, bioproducts or compost to be used in local gardens, parks, and agricultural lands as observed in Italy (Ellen MacArthur Foundation, 2016). This has also the benefit of reducing the tonnage of waste entering conventional waste streams (landfills and incinerators) and the leakage of compostable plastics towards the environment where it will likely not degrade.

4. Plastics designated as biodegradable have controversial proof of biodegradability in the natural environment

We do not yet have the tools to properly evaluate either the fate of biodegradable material or its rate of biodegradation in the natural environment, which is by definition both an open and uncontrolled environment. Indeed, the standard test methods currently available to assess plastic biodegradation (ISO tests) are all respirometry tests based on the measurement of microbial respiration (i.e., O_2 uptake or CO_2 release) that cannot be accurately measured in an open environment. Therefore, the ability of materials to degrade in soil or water is mostly measured in miniaturized closed systems, under controlled laboratory conditions designed to ensure quantitative measurements and to guarantee the reliability and reproducibility of the tests, thus meeting the requirements of standardization and regulation. As these conditions are far from those encountered in natural environments, these test methods should be considered primarily as “screening tests” providing consistency and reproducibility to determine the intrinsic biodegradability in a given environment. Several limitations and bottlenecks, which we will present in turn, would need to be overcome to consider these tests as more representative of natural conditions, particularly in the marine environment, which is by far the most complicated to simulate on a laboratory scale.

- “Bottle effect”. A sample taken in a natural environment evolves differently when it is no longer in contact with the open environment, e.g., in terms of bacterial community growth, dissolved O_2, and nutrients (Pernthaler & Amann, 2005). Although such experiments are indispensable for determining and obtaining quantitative data on the actual biodegradation of a material, the nature of this evolution and its influence on biodegradation are complicated to identify.

- Choice of inoculums. The use of a single or a small number of microbial strains in a sterile environment is necessary to understand the mechanisms of biodegradation but does not reflect the richness and diversity of the natural communities present in the marine environment (Zhang & Xu, 2008). Furthermore, tests considering the spatial and temporal variation of inoculum that originated from natural communities attached to plastic in soil or aquatic conditions still require development (Jacquin et al. 2019).

- Carbon sources. In laboratory assays specific to marine or aquatic environments, the organic matter present at a low concentration in the sample will be rapidly consumed. As a result, the plastics present will then become the only source of carbon for the microbial community to live on and develop, which is not the case in the natural environment where natural or anthropogenic organic matter becomes continuously attached to the plastic (Li et al. 2018). In the marine environment, the largest part of the carbon source comes from natural organic matter, while plastic is present in far smaller proportions (Ter Halle & Ghiglione, 2021). Natural autotrophic and heterotrophic activities of the microorganisms growing on plastics that play a role in the evaluation of biodegradation is not yet considered (Jacquin et al. 2019).

- Methodological constraints to representing real biodegradation in the environment. Most of the available methods focus on the last mineralization step of biodegradation after several months of incubation in a small bottle, which provides information on the potential activity of the initial inoculum to completely transform the polymer into CO_2 under laboratory conditions (Harrison et al. 2018). The lack of methods that can evaluate biodegradation in situ renders the estimation of the percentage of biodegradation of a polymer over a given time largely uncertain.

- **Lack of specification standards for anaerobic, freshwater and seawater environments.** The claim that a plastic is biodegradable is regulated by many standards, which require the demonstration of microbial use of the plastic as carbon source for their growth through respirometry measurements. Such standards provide detailed and accurate guidance for conducting and reporting respirometry tests in specific natural or controlled environments. In brief, the certification scheme of biodegradable plastics is based on two types of standards called “specification standard” and “test method standard”, which are closely linked to each other. To be considered as biodegradable, a plastic must meet several requirements, which are specified in specification standards. For each requirement, the specification standard indicates the test method standards to be applied, the thresholds to be reached, the duration of the test, and certain modifications of the method if specific conditions are necessary. Thus, the specification standards are essential to define the requirements describing the biodegradability of a plastic in a given environment, while test method standards drive analytical techniques and method validations (ADEME 2020). To date, specification and test method standards covering the certification of “biodegradable plastics” only exist for industrial and home composting conditions, as well as for soil environment (Supplementary Table 1; ADEME 2020). All the other environments (methanization, freshwater and seawater) have only test method standards that are not sufficient as such to establish the biodegradability of a plastic (ADEME 2020).”

Because of all limitations mentioned above, test methods such as the ATSM D6691 for the "Determination of aerobic biodegradation of plastic in the marine environment by a microbial consortium or natural seawater inoculum" warns against extrapolating laboratory test results to the natural environment as a sufficient criterion for biodegradation. We need to ask how many descriptors would be necessary to characterize the biodegradability of a plastic during a laboratory experiment. In this sense, a recent data-driven approach based on the physical properties and molecular structure of the polymer proposed a hierarchy of parameters to quantify its surface erosion in the marine environment, such as glass transition temperature and hydrophobicity to classify plastics into fast, medium, and slow degradation categories (Min et al. 2020).

5. Universal biodegradable plastics do not exist

It is noteworthy that universal biodegradability in any ecosystem on earth does not exist due to the limitless combinations of environmental conditions (e.g., water content, organic matter, oxygen levels, temperature, pH, turbulence). For instance, parameters favoring biodegradability (mainly O_2, water, nutrients, and temperature) will obviously differ greatly between ecosystems (agricultural land, washed beach, sea surface, deep sea) and latitudes (tropical, temperate, polar) (Bano et al., 2017). Moreover, the required conditions for biodegradation largely differ from one polymer to another (i.e., in practice from one type of use to another), meaning that there are as many biodegradation parameters as there are polymers and formulations (Figure 1). Leakage of biodegradable plastics to the environment can occur accidentally (e.g. littering) and voluntary (e.g. agronomic use of digestate or compost containing residues of biodegradable plastics). When reaching the environment, some biodegradable polymers (such as PLA and PBAT that represent almost 40% of the current production of biodegradable polymers) may not necessarily find their specific degradation conditions to be fully decomposed. This poses a risk that it will persist and contaminate the environment where the plastics are released and other ecosystems through natural connectivity of all the environmental compartments (terrestrial, aquatic, and atmospheric) (Kumar et al. 2021). Owing to its fragmentation into smaller, more easily ingestible particles (Napper & Thompson, 2019) could constitute a threat for terrestrial and aquatic organisms.

6. The innocuity of biodegradable materials remains an open question

Leakage of biodegradable plastics to the environment may create subsequent environmental issues due to the unknown toxicity of the ensemble of degradation products. Research investigating the acute and chronic toxicity of biodegradable polymers is still in its infancy (Zimmerman et al. 2020) and contrasting results exist in the literature depending on the biological model, the tested material and the exposure parameters (Kapanen et al. 2013; Sforzini et al. 2016; De Oliveira et al. 2021; Campani et al. 2020; Zimmerman et al. 2021). This suggests that the term “biodegradable” does not necessarily means harmless as the toxicity of bioplastics appears to be formulation-dependent

(Zimmermann et al. 2020). In this regard, most specification standards with biodegradation criteria for plastics require individual toxicity testing of all constituents present at a concentration greater than 1%, in addition to the final plastic product. This involves two evaluation steps including constituent chemical control for harmful compounds (e.g., Cd, Cr, Hg, Ni, Pb, and substances of very high concern, SVHC) and ecotoxicity tests (plants, worms, nitrifying microorganisms), which have already been implemented in some current ISO standards (e.g., NF EN 17033; ISO 15685:2012; ADEME 2020). However, there is no accredited organization to deliver such compliance certifications (e.g. TÜV, DIN CERCO) since there is still no regulation making them compulsory and this may result in the marketing of unsafe materials. In addition, beyond the testing of biodegradable materials as new/bulk/raw material, the influence of usage, weathering, biofouling, and abiotic and biotic degradation on the release of harmful chemicals and degradation products (e.g., monomers, oligomers, additives, NIAS, particles) must also be considered in ecosafety assessment as it is already required in specification standards for compost and soil medium (NF EN 13432, NFEN 14995, NFT 51800, NF EN 17033). Evaluating ecotoxicity of biodegradable material at the stage of material development and formulation (safe-by-design approach, van de Poel & Robaey, 2017) would ensure the environmental and human safety of products and should be reinforced and extended to all materials including conventional plastics. This method would offer robust scientific support for the design of new and safer materials, keeping in mind that the absence of evidence is not evidence of absence (Leslie & Depledge, 2020).

7. Conclusion

The end-of-life options for plastic waste vary depending on the types of materials involved (biodegradable or not) and how easy they can be collected and separated from other waste streams (Figure 1). The use of biodegradable plastics should be restricted to a limited number of applications for which recycling is not an option as long as there are no specific collection schemes in place. The designation “biodegradable” must be clarified to avoid the idea that the natural environment could be considered as a viable waste treatment system. Indeed, there is uncertainty that this term may inadvertently promote littering behavior as already discussed in Napper & Thompson (2019). Indeed, even if consumers are in general concerned about plastics as an environmental issue, they do not necessarily translate their aspiration to reduce plastic use through appropriate behaviors (Dilkes-Hoffman et al, 2019). The certification of compostable/biodegradable materials must be improved based on new standards and evaluation methods more representative of environmental conditions. With respect to conventional plastics, there are still no specification standards assessing their composition and environmental toxicity. Strict regulation is thus urgently needed to make such certifications compulsory for both conventional and biodegradable materials. Finally, we should bear in mind that all routes favoring banning and reduction strategies should be promoted over the use of alternative materials. The first answer to plastic pollution is to reduce its production and usages whenever possible (e.g., use less single use plastic items and avoidable packaging) and favor reusable and recyclable plastics to enhance the recovery of resources before going down the biodegradable path (Bucknall, 2020). The plastic waste hierarchy (refuse, reduce, reuse, recycle) should be kept in mind right from a product’s conception and throughout its entire life cycle, and it is now clear that we must make the transition from a linear “buy-use-throw” system to a circular approach including improved conception (ecodesign), collection, sorting, and recycling schemes (Lau et al., 2020).

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COMPETING INTEREST

The authors declare no competing or financial interests.

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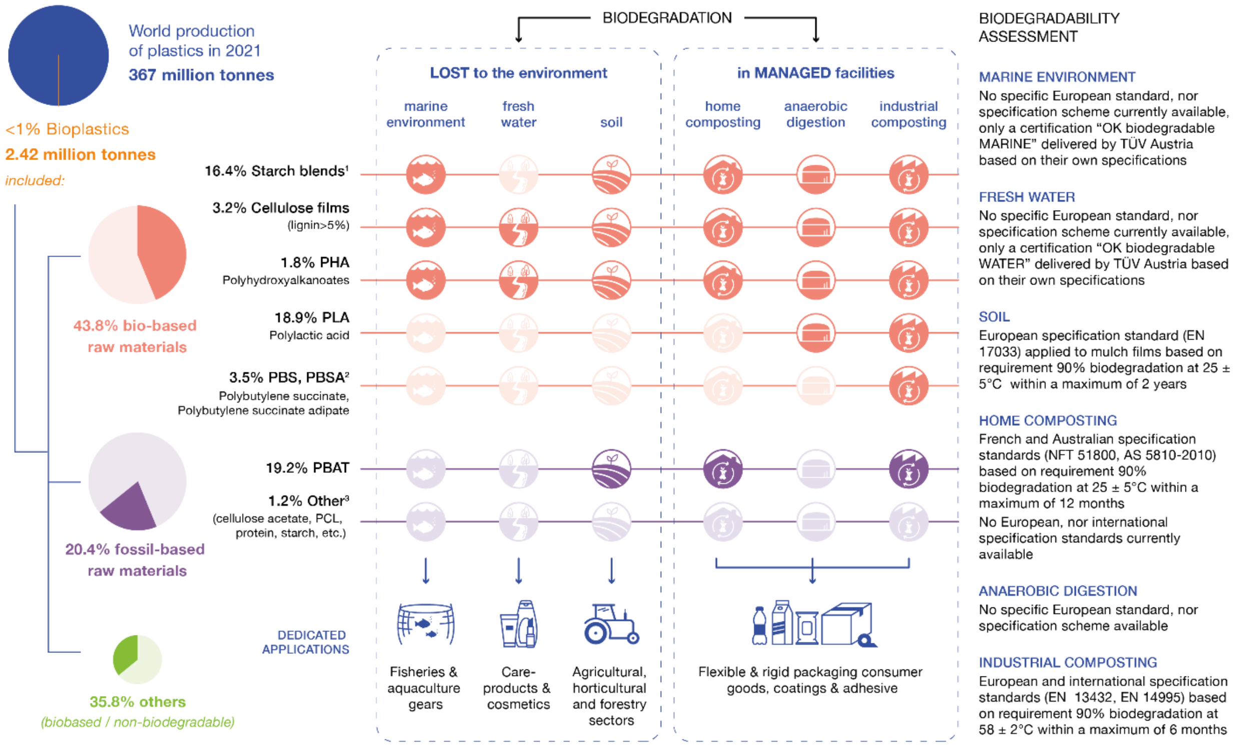
Tables and figures

Table 1. Definitions of the common terms used to designate biodegradable plastics and their ability to decompose in a given environment. Sources: ISO 472:2013 Plastics – Vocabulary ; https://www.european-bioplastics.org

Term	Definition
Bioplastic	Bio-based and /or biodegradable plastic in the most commonly accepted sense and in the absence of a standard definition. In France a bioplastic is defined as a bio-based AND biodegradable plastic (JORF n°0297 of 22 December 2016) whereas in English-speaking countries, the term covers bio-based AND/OR biodegradable plastics.
Biodegradable	Ability of an organic material to be fully mineralised by the action of micro-organisms, either in the presence of oxygen by aerobic decomposition into carbon dioxide, water and mineral salts of all other elements present (mineralisation) and the appearance and/or reorganisation of new biomass, or in the absence of oxygen by anaerobic decomposition into carbon dioxide, methane, mineral salts and the appearance and/or reorganisation of new biomass. The process of biodegradation depends on the surrounding environmental conditions (e.g. location or temperature), on the material and on the application.
Compostable	Ability to fully biodegrade in a composting process. From a normative point of view, this claim implies several other specific requirements in addition to the ultimate biodegradation like control of constituents, disintegration and ecotoxicity regarding the degradation products. A distinction is made between industrial (NF EN 13432 for packaging and NF EN 14995 for plastics) and home composting (AS5810:2010, NF T51-800:2015, prEN 17427:2020) to take into account the comparatively smaller volume of waste involved and the lower temperature which leads in a slower degradation and biodegradation process.



MARINE ENVIRONMENT
No specific European standard, nor specification scheme currently available, only a certification “OK biodegradable MARINE” delivered by TÜV Austria based on their own specifications

FRESH WATER
No specific European standard, nor specification scheme currently available, only a certification “OK biodegradable WATER” delivered by TÜV Austria based on their own specifications

SOIL
European specification standard (EN 17033) applied to mulch films based on requirement 90% biodegradation at 25 ± 5°C within a maximum of 2 years

HOME COMPOSTING
French and Australian specification standards (NFT 51800, AS 5810-2010) based on requirement 90% biodegradation at 25 ± 5°C within a maximum of 12 months

No European, nor international specification standards currently available

ANAEROBIC DIGESTION
No specific European standard, nor specification scheme available

INDUSTRIAL COMPOSTING
European and international specification standards (EN 13432, EN 14995) based on requirement 90% biodegradation at 58 ± 2°C within a maximum of 6 months

Figure 1. Distribution, biodegradability and suggested applications for biodegradable plastics. Sources: European Bioplastics, nova-Institute (2021) wwww.european-bioplastics.org/market, www.bio-based.eu/markets, www.renewable-carbon.eu/graphics. Biodegradability assessment (right hand panel) refers to the existence of specification standards in a given environment. [1.] Mater-Bi (Novamont Spa) of 3rd generation (MATER-BI AF03A0 AND MATER-BI AF05S0) are certified as biodegradable in aerobic marine conditions, https://ec.europa.eu/environment/ecoap/etv/aerobic-biodegradation-mater-bi-af03a0-and-mater-bi-af05s0-mater-bi-third-generation-under_en. [2.] PBSA is biodegradable in soil and home composting conditions. [3.] Other refers to different products displaying different ability to biodegrade according to a considered environment. Dedicated applications are suggested whenever complete removal of plastic material is not available. Colors represent biobased biodegradable (orange), petrol-based biodegradable (purple) and biobased non-biodegradable plastics (green). Small icons illustrate the end of life in the environment for biodegradable plastics, and the shading indicates absence of biodegradation in a given environment.