The role of waste management in reducing bioplastics' leakage into the environment: a review

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Abstract

Bioplastics are becoming more and more widespread as substitutes for petroleum-derived plastics due to their biodegradability. Bioplastics degradation under different environments has been described and reported to depend mainly on bioplastics' compositions and the environmental conditions. Incomplete degradation during waste management processes and leakage of bioplastics into the environment are becoming major concerns that need to be further investigated. In this context, the present paper aimed to review recent literature dealing with biodegradation of bioplastics under industrial (e.g. anaerobic digestion and composting) and natural (e.g. soil and water) environments, and to link it to the potential bioplastics' leakage into the environment. Reviewed data were used to estimate the potential role of waste management processes in decreasing the potential leakage of bioplastics. Depending on bioplastics' type and processing conditions, waste management can effectively reduce bioplastics' potential leakage, decreasing the concentration of these materials that can reach the natural environments.

Keywords

Anaerobic digestion; Bioplastic; Biodegradation; Composting; Leakage.

1. Introduction

About 60 million tonnes of petroleum-derived plastics were produced in 2019 in Europe, whereas the worldwide production accounted for 368 million tonnes (PlasticsEurope, 2020). Europe's plastics demand in 2019 (about 50 million tonnes) was mainly related to packaging (39.6 %), building and construction (20.4 %), and automotive (9.6 %) purposes. Nowadays, about 32 % and 43 % of plastic wastes are recycled or processed for energy recovery in Europe, respectively, with the residual plastic being landfilled (PlasticsEurope, 2020). Although the quantity of plastics wastes sent to recycling has increased by 92 % in Europe since 2006 (PlasticsEurope, 2020), concerns about the sustainability of petroleum-derived plastics have arisen in recent decades. Indeed, besides being produced from a non-renewable raw material (oil), plastic wastes have been recognized as one of the most dangerous pollutants for the environment due to their poor degradability and to their tendency to fragmentation and the production of microplastics that accumulate in the environment (Bellasi et al., 2020). Oxo-degradable plastics, which were first introduced as eco-friendly substitute of petroleum-derived plastics, were recently recognized to give rise to serious environmental issues, i.e. fragmentation into non-degradable microplastics, potential toxic effects of the oxidising additives (Abdelmoez et al., 2021, European Commission, 2018). In addition, polymers produced by renewable biomass such as bio-polyethylene have been reported to be non-biodegradable (Mendieta et al., 2019).

In this context, bioplastics have been introduced in recent decades as environmentally friendly and sustainable alternative materials to petroleum-derived plastics.

The global bioplastics production capacity is foreseen to increase from around 2.1 million tonnes in 2020 to 2.8 million tonnes in 2025 (European bioplastic, 2020).

The rapid increase in bioplastics use is mainly related to policy changes and to a positive perception of bioplastics by the end-users. From the policy side, the European Union planned to ban the most common single-use plastic items by 2021 (European Parliament, 2019) as one of the strategies to achieve the 17 Sustainable Development Goals described by United Nations (Fonseca et al., 2020). On the other side, besides a generally poor knowledge of bioplastics, the general public's perception of bioplastics and their biodegradability is positive (Dilkes-Hoffman et al., 2019, Taufik et al., 2020). Bioplastics are a wide family of compounds that comprise (i) biodegradable and bio-based materials (e.g. starch-based polymers, polylactic acid – PLA, polyhydroxyalkanoates - PHAs), (ii) biodegradable and petroleum-derived materials (e.g. polycaprolactone – PCL, polybutylene adipate terephthalate - PBAT) and (iii) non-biodegradable bio-based materials (e.g. bio-polyethylene) (Abraham et al., 2021, Bátori et al., 2018). Within all the bioplastics, PHAs, PLA and starch-based bioplastics represent about 70 % of the entire bio-based biodegradable bioplastics produced and used in 2020 (European bioplastic, 2020). Sources, main applications and production capacity of these three bioplastics are reported in Table 1. Commonly, bioplastics are composite material made of one main component (e.g. starch, PLA) blended with other components and additives. Due to that, in the present review the three bioplastics studied (PHAs, PLA and starch-based bioplastics) were reported as *blends*, meaning that they were made of composite materials. However, in this review only bioplastics blends made of biodegradable components have been considered.

PHAs biopolymers are obtained through microbial synthesis from carbohydrates and then they are accumulated in the cell (Ganesh Saratale et al., 2021). PHAs are biodegradable polyesters characterized by physico-chemical properties not far from those of petroleum-derived plastics (Papa et al., 2020), and their main applications are represented by packaging and agricultural/medical goods production. Although PHAs production is actually limited by the high costs of substrates and the use of pure microbial cultures, several studies are focusing on the use of mixed microbial cultures to reduce costs, which should permit enhanced PHAs usage (Villegas Calvo et al., 2018). Since PHAs blends entered the market, the share of this biopolymer family continues to grow and production capacities are set to increase successfully almost seven times by 2025 (Table 1) (European bioplastic, 2020).

PLA is obtained through the microbial fermentation of carbohydrates and subsequent polymerization (Folino et al., 2020). PLA is mainly used for the production of durable and disposable goods (cutlery, glasses, dishes, and packaging) but is also used in building and construction, agricultural, medical applications and fibres production. The production of PLA blends is also expected to grow due to new investments in PLA production sites in China, the US, and in Europe and it is expected that these biopolymers will represent the most produced bioplastics in 2025 (Table 1).

Starch-based blends are made of starch obtained from different crops (e.g. corn, rice, potato) processed with plasticizers, and find their main applications in the production of films, carrier bags and waste-collection bags (Abraham et al., 2021). Starch-based blends were the first bioplastics to be widely used in common applications and they still represent the most produced bioplastics, representing about 20 % of the bioplastics produced in 2020.

Bio-based biodegradable bioplastics present different advantages, with the biodegradability being the most important (Pilla, 2011). Biodegradation of bioplastics involves biotic and abiotic factors that lead to a complete degradation of the material

(Emadian et al., 2017). Generally, abiotic factors (e.g. temperature, water and sunlight) lead to an initial chain scission in the bioplastic polymer, producing shorter oligomers that can pass through the cell walls of microorganisms. Microbial processes then complete the biodegradation of these shorter units into other compounds, depending on the metabolic pathway of the microorganism (aerobic or anaerobic) (Bátori et al., 2018).

Bioplastics biodegradation can be assessed by using international standard methods. The ISO 14855 (2018), ISO 17556 (2019), ISO 14851 (2019) and ISO 13975 (2019) can be used to define whether a bioplastic is biodegradable or not in composting, soil, aqueous and anaerobic digestion environments, as reviewed by Arikan and Ozsoy (2015). Bioplastics usually showed a linear biodegradation and this was an indication that reaction rates were obeying a pseudo-zero order kinetic and that biodegradation rates were constant and independent of the bioplastic amount (Barbale et al., 2021, Chamas et al., 2020, Chinaglia et al., 2018, Degli Innocenti and Breton, 2020). The constant rate of biodegradation could be explained by considering that the biodegradation rate depended on the available C-polymer at the surface and not on the total C-polymer (Chinaglia et al., 2018). Similar considerations were reported by Modelli et al. (1999) who studied the degradation kinetic of PHA sheets.

Whilst the substitution of petroleum-derived plastics represents a major goal to be achieved, the fate of bioplastics in natural and industrial environments has still to be explored. In fact, some recent papers have pointed out that degradation kinetics of bioplastics are often incompatible with waste management systems (Battista et al., 2021, Folino et al., 2020, Zhang et al., 2018). Moreover, degradation kinetics appeared to be really slow in natural soils and aquatic environments, leading to possible environmental concerns (i.e. bioplastic accumulation and fragmentation into

microplastics) (Bátori et al., 2018, Bhagwat et al., 2020, Emadian et al., 2017, Folino et al., 2020, Shruti and Kutralam-Muniasamy, 2019, Thakur et al., 2018).
In this context, the aim of the present paper is to review recent knowledge of biodegradation of bioplastics under controlled (e.g. waste management) and natural environments, paying particular attention to the effect of waste management in reducing the potential bioplastics' leakage into the environment.

2. Bioplastics in waste management

Bioplastics enter the so-called *technosphere* after their production, through their collection and subsequent treatments in *ad hoc* plants (Degli Innocenti and Breton, 2020). Bioplastics degradation in the *technosphere* is crucial since bioplastics that are not processed and degraded can reach the biosphere.

2.1 Bioplastics collection

Separate collection of bioplastics is mandatory to allow for a better recycling of these products after usage. In Europe, separate collection of bioplastics with bio-waste, i.e. with the organic fraction of municipal solid wastes (OFMSW), was prescribed initially in 1994 (Pagga, 1998) and it is actually recommended (Dubois et al., 2020).
Nevertheless, the importance of a better system of certification and clearer instructions for handling of bioplastics is needed. Indeed, it was recently pointed out that, beside the positive appeal of bioplastics packages for consumers, lower correct disposal rates for bioplastics packaging were recognized if compared to petroleum-derived packaging (Taufik et al., 2020). This was probably related to the fact that consumers positively evaluate the biodegradability of bioplastics packaging (Magnier and Crié, 2015),

leading to a less careful collection and disposal of these products. However, an adequate management of such bioplastics by consumers is mandatory to capitalize on the environmental benefits of bioplastics. Due to the general recommendation of discharging bioplastics with OFMSW, the concentration of these products in the bio-waste stream is rapidly increasing and is expected to reach high values in the coming years. For instance, bioplastics in Italy represented about 1 -2 % and 3 - 4 % (weight basis) of OFMSW in 2017 and 2019, respectively (ISPRA, 2020), and this value is expected to increase rapidly in future years, possibly reaching a concentration of 8-10 % (weight basis, forecast for 2030). Therefore, the knowledge of the fate of bioplastics during OFMWS management, i.e. through anaerobic digestion (AD) and composting, is becoming a major issue.

2.2 Anaerobic digestion

AD anaerobically degrades organic wastes to biogas and digestate through four successive phases, (1) hydrolysis, (2) acidogenesis, (3) acetogenesis and (4) methanogenesis (Wang et al., 2018). Biogas is a gas mixture mainly composed by methane and carbon dioxide (55-70 % and 30-45 %, v/v), as well as small amounts of other gases (oxygen, sulphuric acid, hydrogen) (Liu et al., 2019). Biogas can be used as an alternative energy source through its combustion in boilers or combined heat and power units; however, the interest in biogas conversion to high-value products has been increasing recently (Patel et al., 2020, Wu et al., 2016). Digestate is widely considered as a potential organic fertilizer, being rich in plant macronutrients (N, P and K) and organic matter (Castro et al., 2017, Peng et al., 2020, Tambone et al., 2017). AD can be operated at psychrophilic (18-20 °C), mesophilic (35-40 °C) and thermophilic (50-60

°C) temperature regimes (Hupfauf et al., 2018), with the last two conditions being the more effective for organic matter degradation and biogas production.

Recent literature concerning bioplastics degradation during AD was reviewed and summarized in Table 2. In addition, the kinetic constant of biodegradation and the time for complete degradation under anaerobic conditions were estimated using a pseudo-zero order kinetic model (Chinaglia et al., 2018). PHAs blends were recognized to degrade faster than the other bioplastics during AD, and their biodegradation was not strongly influenced by the temperature regime (Yagi et al., 2014, Yagi et al., 2013). Indeed, the estimated time for complete degradation of PHAs blends during AD was found to be 31 ± 20 days under mesophilic conditions and 36 ± 28 days under thermophilic conditions (Table 2). These results were in accordance with Noda et al. (2010) and Siracusa et al. (2008) who reported that PHAs can completely degrade under anaerobic conditions in 5 - 6 weeks. PLA and starch-based blends showed a slower degradation during AD in comparison with PHAs blends. PLA blends were found to degrade completely in 423 ± 76 and 116 ± 48 days in mesophilic and thermophilic conditions, respectively (Cazaudehore et al., 2021, Zhang et al., 2018). Similarly, temperature also played a key role in starch-based blends' degradation during AD. These bioplastics showed a significant reduction of time needed to complete degradation when AD was performed under thermophilic instead of mesophilic conditions (- 60 %) (Calabro' et al., 2020, Cazaudehore et al., 2021).

Summarizing, the biobased biodegradable bioplastics studied showed a decreasing degradation under anaerobic conditions following the order: PHAs blends > starch-based blends ≥ PLA. These differences can be related to the differences in chemical composition of the different bioplastics. Siracusa (2019) suggested that the degradation process is more easy and natural for PHAs polymers and copolymers since they are produced directly from microorganisms. Conversely, the number of organisms able to degrade the chemical structure of synthetic biopolyesters (e.g. PLA) is limited. Therefore, the degradation of such synthetic biopolyesters depends on the environment and microbial population. In anaerobic conditions, fewer enzymes are present and the growth of microorganisms is slower, leading to a slow degradation of bioplastics.

The role of temperature regimes in bioplastics degradation during AD was pointed out in recent literature (Calabro' et al., 2020, Cazaudehore et al., 2021, Folino et al., 2020). With the exception of PHAs blends, for which temperature did not influence anaerobic degradation, thermophilic temperatures (55 ± 2 °C) significantly accelerated PLA and starch-based blends' degradation. This was probably due to changes in the mechanical properties of bioplastics that can occur only under thermophilic conditions. For example, PLA blends' degradation was enhanced by reaching their glass transition temperature (55-60 °C) that causes PLAs' mechanical properties to change, making them more hydrophilic and accessible for microbial hydrolysis (Marek and Verney, 2016). This was also in accordance with Hamad et al. (2015) who described that elevated temperature (58 °C) is needed to reduce the molecular weight of PLA blends and to start their biodegradation. Similarly, also the biodegradation of starch-based blends was enhanced by thermophilic temperatures. This was probably related to the fact that the polyester component of starch-based blends can be degraded only at elevated temperature, as described by Gil-Castell et al. (2020), who reported that polyesters such as poly(3)-hydroxybutyrate-co-3-hydroxyhexanoate (PHBH) biodegraded effectively only at temperatures higher than 58 °C. Taking into consideration both that AD of OFMSW is commonly performed with short hydraulic retention times (HRT) (20-30 days) to optimise biogas yields and volumes of waste treated (Panigrahi and Dubey, 2019, Shrestha et al., 2020), and the reviewed literature concerning bioplastics degradation during AD, some of the following conclusions can be derived. Only PHAs blends were recognized to be compatible with AD processes conducted with conventional HRT. In fact, 80 % of degradation (weight basis) is usually considered a goal that should be achieved at the end of the HRT for a biomass suitable for AD (Ran et al., 2018), and PHAs blends can satisfy this requirement (Table 2). PLA and starch-based blends required about 10 - 15 times a conventional HRT of 30 days to degrade completely under mesophilic conditions. Moving to thermophilic regimes, the degradation kinetic increased but the objective of degrading 80 % (weight basis) of bioplastics in the HRT cannot apparently be achieved. Similar conclusions were reported by Battista et al. (2021), who observed only a partial degradation of single-use bioplastics under anaerobic conditions and the requirement of a very long retention time to achieve acceptable degradation rates. The high amount of bioplastics' residues in the digestate may also led to difficulties for its subsequent utilization, above all in new applications, i.e. nutrient recovery producing fertilizer-like material to be used in agriculture and /or the use as substrate for micro-algae cultivation.

In particular, the effect of the presence of bioplastic residues in compost and digestate because of their use in agriculture is later described and discussed.

2.3 Composting

Composting aerobically degrades organic wastes to compost and two main by-products (heat and carbon dioxide) (Cerda et al., 2018, Wang and Zeng, 2018). Composting is a self-heating process that proceeds through three main phases, (1) mesophilic (25-40 °C),

(2) thermophilic (55-65 °C) and (3) maturation. Compost is a nutrient-rich organic amendment able to provide N, P, K and organic matter to the soil (Wang and Zeng, 2018). During composting, labile organic matter is mineralized and complex recalcitrant materials tend to concentrate, increasing the organic matter stabilization of the compost (Cucina et al., 2018).

Performances of bioplastics degradation during composting taken from recent literature are summarized in Table 3. Assuming a pseudo-zero order kinetic model for the aerobic degradation of bioplastics (Chinaglia et al., 2018), the kinetic constant of biodegradation and the time for complete degradation under aerobic conditions were estimated and reported in the same Table. Data reported for bioplastics showed higher kinetic constants of degradation under thermophilic composting conditions than those reported for AD (Gómez and Michel, 2013). All the biobased biodegradable bioplastics studied showed a quick degradation, and the kinetic constant of degradation increased following the order: PLA blends < starch-based blends ≤ PHAs blends. Consequently, time estimated for complete degradation of bioplastics was 84 ± 47 days, 124 ± 83 days and 119 ± 43 days for PLA, PHAs and starch-based blends, respectively (Table 3).

Several factors affect bioplastics degradation in composting environments, with temperature and bioplastics chemical composition being the most important (Emadian et al., 2017). The high temperatures of the active phase of composting (> 55 °C) allow reaching the glass transition temperature of the most common bioplastics, leading to the passage from the crystalline status of polymer to the amorphous one, and so increasing polymer hydrophilicity (Amin et al., 2019, Zhang et al., 2007), leading to higher hydrolyzation and enhancing the kinetic of bioplastics degradation during composting.

Values reported in Table 3 for bioplastics degradation under composting conditions showed that bioplastics can effectively degrade during a conventional composting process of OFMSW. Indeed, composting is a longer process than AD and usually lasts about 90 days (Ayilara et al., 2020), and most of the bioplastics studied were found to degrade in less than 90 days. Interestingly, a few papers investigated the behaviour of starch-based blends during mesophilic composting (23 – 25 °C) and reported that under aerobic conditions, temperature also played a key role in bioplastics degradation (Accinelli et al., 2012, Mohee et al., 2008). Indeed, starch-based blends degraded with a reduced kinetic under mesophilic conditions (-46 %) if compared to thermophilic temperatures. These results were in accordance with Rudnik and Briassoulis (2011) who observed a very slow biodegradation of PLA bioplastic under mesophilic composting. Certainly, composting of OFMSW is carried out at industrial facilities operating under thermophilic conditions (maximum temperature 55-65 °C), but home composting is becoming more and more popular in recent years, especially in rural areas (Vázquez and Soto, 2017). Differently from industrial composting, during home composting temperature peaks do not usually exceed 35 – 40 °C (Guidoni et al., 2018) and this could lead to issues of bioplastics accumulation in compost produced in this way.

In recent years, the use of composite bioplastics to improve their degradation under composting conditions has been investigated (Ahn et al., 2011, Anstey et al., 2014, Sarasa et al., 2009). Blending of biofuel by-products with polybutylene succinate proved to enhance biodegradation of the composites during composting due to the increased content of soluble sugars in the composite itself (Anstey et al., 2014). Similarly, Ahn et al. (2011) and Sarasa et al. (2009) promoted PLA biodegradation under composting conditions by blending it with poultry feather fibres and corn, respectively.

Although composting represents a valuable strategy to treat OFMSW and degrade bioplastics, it should be highlighted that composting is an energy-requiring process (Lin et al., 2018). As already discussed, bioplastics' environmental profile is strongly dependent on their end-of-life strategy. For instance, bioplastics have been proved to have a higher global warming potential if industrial composting and disposal transportation are considered as their end-of-life strategy during LCA analysis (Zhao et al., 2020). Taking this into consideration, AD or AD coupled to digestate composting should represent preferred treatments for OFMSW and bioplastics treatment (Edwards et al., 2018, Wainaina et al., 2020) and, thus, strategies to improve bioplastics degradation during anaerobic processes should be further investigated.

3. Bioplastics in the environment

The transfer or leakage of bioplastics from the *technosphere* to the environment can occur both accidentally (e.g. littering) and voluntarily (e.g. agronomic use of digestate or compost containing residues of bioplastics). In both case, bioplastics can reach soil and aquatic (freshwater and marine water) environments, posing a serious concern for their ability to degrade in these natural systems.

3.1 Soil environment

Since soil contamination by petroleum-based plastics disposal has emerged as a major issue in the last decades, several papers dealing with bioplastics degradation in soil can already be found. In this review, soil contamination due to bioplastic leakage from waste management because of the use of compost and digestate was considered. Nevertheless, it is important to keep in mind that soil can be polluted directly by using agricultural wastes containing bioplastics (e.g. mulching).

Within the natural environments (soil, aquatic and air), soil is usually recognized as the one which can provide the fastest degradation of bioplastics, mainly due to the wide diversity of microorganisms that live in the soil (Emadian et al., 2017). Nonetheless, bioplastics degradation rate is strictly related to the chemical composition of the polymer, as well as to the soil characteristics (e.g. pH, clay and organic matter contents) (Elsawy et al., 2017, Folino et al., 2020). Siracusa (2019) reported that ageing factors such as sunlight and temperature can also promote or slow down biodegradation rates of bioplastics in soil. Consequently, biodegradation in soil can differ *from place to place*, *from season to season* (Siracusa, 2019). These considerations can be the reason behind the high variability of results found in literature concerning bioplastics degradation in soil, which are summarized in Table 4. Assuming a pseudo-zero order kinetic model for bioplastics degradation in soil (Chinaglia et al., 2018), kinetic constants and times for complete degradation in soil were also estimated (Table 4).

In soil, bioplastics showed a slow degradation if compared to both AD and composting. This fact could probably be due to the lower concentration of microorganisms in soil in comparison with digestate and compost mixtures. Among the three blends studied, PHAs' blends showed the highest kinetic constants of degradation in soil, followed by starch-based blends and PLA blends. PLA blends showed the longest estimated time for complete degradation, i.e. about 4 – 5 years, and this was probably due to the low temperatures that characterize the soil environment in the experiments reviewed in the present paper, i.e. 20 – 30 °C (Kalita et al., 2021, Palsikowski et al., 2018). These temperatures were far below the glass transition temperature of PLA blends, leading to such a slow degradation. PHAs blends and starch-based blends shared similar estimated times for complete degradation (1.2 and 1.6 years, respectively).

The possible blending of bioplastics with other biodegradable materials was investigated in recent years in order to accelerate the biodegradation of bioplastics in soil. For instance, blending potato peel waste fermentation residues with PHBs led to a reduced crystallinity of the blend and to a faster degradation in soil compared to the pure PHBs (Wei et al., 2015). PLA degradation in soil has also been proved to be promoted by production of composites made of PLA and oil palm fibres (Harmaen et al., 2015). Although years are required for biodegradation of bioplastics in soil, this time is significantly shorter than that of the petroleum-derived plastics that require hundreds or thousands of years to degrade in soil (Chamas et al., 2020). These plastics (e.g. polypropylene, polyethylene, polyvinylchloride) are highly stable and cannot enter the degradation cycle of the biosphere, or show slow degradation rates that do not allow for a complete disintegration (Ahmed et al., 2018, Briassoulis et al., 2020). As a consequence of that, Chamas et al. (2020) reported that high-density polyethylene, polyvinylchloride and polystyrene buried in soil had half-life times of about 2,500 – 5,000 years that are much more than the times required to degrade bioplastics (Table 4).

3.2 Aquatic environment

Although the aquatic environment was recognized as the most susceptible to plastics contamination (Calabrò and Grosso, 2018), until now only a few papers dealing with the fate of bioplastics in fresh and seawater can be found. Results of literature study which are summarized in Table 5 including kinetic parameters of bioplastics degradation in the

aquatic environments, estimated assuming a pseudo-zero order model (Chinaglia et al., 2018). A large variability in bioplastics degradation in aquatic conditions was found but generally, degradation of bioplastics in fresh and seawater appeared to be slower than degradation in soil or under active waste management (AD and composting). This was mainly related to the characteristics of the aquatic environment that play a central role in bioplastics degradation. Besides bioplastics' characteristics, temperature, pH, nutrients content and microbial population density and diversity are the most important factors that affect bioplastics degradation in the aquatic environment (Harrison et al., 2018, Rana, 2019, Urbanek et al., 2018). Low temperature, nutrients and microbial population density might be responsible for the slow degradation of bioplastics in the aquatic environment. The role of temperature was highlighted by Volova et al. (2007) who studied the rate of PHAs degradation in seawater. The authors concluded that seasonal changes in water temperature were responsible for different rates of degradation.
Sekiguchi et al. (2011) studied the degradation of PHBs bioplastics under three different seawater typologies, concluding that microbial community composition of the aquatic system can also influence significantly the degradation rate of bioplastics. The aquatic environment is really heterogeneous, i.e. it is possible to classify at least eight different liquid environments (Folino et al., 2020). Different aquatic environments host different microbial communities, and this could explain the differences observed in the degradation of the same bioplastics under different liquid environments (Emadian et al., 2017, Sekiguchi et al., 2011, Tosin et al., 2012).
Due to all the described factors, PHAs blends showed a wide range of degradability in aquatic systems, and the estimated time for their complete degradation ranged from 50 days in seawater at 21 °C to 4,348 days in fresh and seawater at 25 °C (Bagheri et al.,

2017, Thellen et al., 2008). PLA blends presented the slowest degradation rate in aquatic environments (the average estimated time for complete degradation was over 10 years). Concerning starch-based blends, degradation in fresh and seawater, a high variability was reported. Whilst Accinelli et al. (2012) obtained only a 1.5 % degradation (weight basis) of starch-based bioplastics under both fresh and seawater systems (25 °C, 90 days), other studies reported a significant degradation of these bioplastics. For instance, Tosin et al. (2012) obtained a 69 % degradation (weight basis) of starch-based shoppers after 236 days and this quick degradation was probably related to both characteristics of the tested materials and the environmental conditions (sea water + sediment).

Blending bioplastics with biodegradable materials has been studied recently to enhance their degradation in aquatic systems. Beltrán-Sanahuja et al.(2020) obtained a significant increase of the degradation kinetic in seawater (16 °C) by blending PLA with cellulose (kinetic constant of degradation increased from 0.15 mg g^{-1} d^{-1}, pure PLA, to 0.80 mg g^{-1} d^{-1}, PLA and cellulose blend).

Summarising, times needed for complete degradation of bioplastics in aquatic environments ranged from about 4 years (PHAs blends) to 12 years (PLA), but it must be highlighted that, since the biodegradation of bioplastics in aquatic environments is dependent upon several factors, this makes it very difficult to define reliable conditions. Nevertheless, the values found are much lower than the values estimated by Chamas et al. (2020) for the degradation of petroleum-derived plastics in marine environments. Indeed, they reported that half-lives of high-density polyethylene, low-density polyethylene and polypropylene varied from few decades to more than 2,500 years.

4. Assessment of potential bioplastics' leakage into the environment

Plastic pollution of natural environments has been thoroughly studied in the last decades with particular emphasis on microplastics accumulation and their toxic effects (He et al., 2018, Jung et al., 2021). In the last few years, concerns emerged regarding the partial degradation of bioplastics in natural and industrial environments, as well as the fate in the environment of bioplastics residues coming from waste management (Abraham et al., 2021, Emadian et al., 2017, Folino et al., 2020). The major concern regarded the possible leakage of bioplastics from the *technosphere* to the biosphere, both following accidental and voluntary pathways (e.g. littering and agronomic use of compost or digestate rich in bioplastics residues). The possible accumulation of bioplastics and their smallest fragments, as well as their eco-toxicological effects were recently reviewed by Shruti and Kutralam-Muniasamy (2019). They described the generation of microplastics from biobased biodegradable bioplastics (e.g. PHBs) and reported that several studies have identified that some biodegradable microplastics showed the same effects as those of petroleum-derived microplastics (e.g. transfer of chemical contaminants, increased stress in benthic communities) (Green, 2016, Hartmann et al., 2017). Nevertheless, the same authors identified different knowledge gaps in biodegradable microplastics effects, i.e. understanding the timeframe of disintegration and degradation of bioplastics and ensuring biodegradability and less persistence (Shruti and Kutralam-Muniasamy, 2019). Recently, Degli Innocenti and Breton (2020) defined bioplastics as intrinsically biodegradable materials due to their tendency to biodegrade similarly to natural polymers under different industrial and environmental conditions. The present paper confirms that intrinsic biodegradability can be ascribed to bioplastics since they were shown to be degradable in all the studied environments, even though with different kinetics (Tables 2, 3, 4 and 5). In the contexts described, intrinsic biodegradability of bioplastics makes them always more sustainable than petroleum-derived plastics from an environmental point of view. Accumulation of bioplastics and their fragments in soil and aquatic environments after leakage appears to be unlikely in high amounts, because of the dynamic equilibrium that becomes established between bioplastics' leakage and biodegradation in the environment that, as discussed, requires years. This is in contrast with what happens with petroleum-derived non-degradable plastics that tend to accumulate in natural environments due to their long degradation time (centuries) (Chamas et al., 2020).

Based on the data reviewed in the present paper, an attempt to estimate the potential bioplastics' leakage into the environment was carried out. Indeed, defining the *potential bioplastics' leakage* can be useful since any time a plastic or bioplastic item enters the biosphere from the *technosphere*, it can accumulate and, depending on their potential hazard for living organisms (Barbale et al., 2021), the result can be toxic. The potential bioplastic accumulation in the environment depends mainly on the concentration of the bioplastic leakage and on its residence time (biodegradability in the environment). This can be described by the following linear proportionality previously used by Degli Innocenti and Breton (2020) to describe the ecological risk of bioplastic, then adapted to describe plastic/bioplastics' leakage into the environment:

Potential leakage = Residence time x Concentration (Equation 1)

It appears evident that the potential leakage derived from plastics and bioplastics can be reduced by decreasing one or both of the factors of Equation 1.

Residence time factor depends mainly on the type of materials and environment. As reviewed in this work, traditional plastics are not biodegradable in industrial and natural environments and the first factor of Equation 1 can almost be assumed to be infinite. This makes it clear why potential leakage of plastics is always higher than the potential leakage of bioplastics, which are intrinsically biodegradable in years. Therefore, the only way to reduce petroleum-derived plastics' leakage is to reduce the *concentration* factor, i.e. by substituting plastic items with bioplastic ones and increasing the separate collection and recycling of petroleum-derived plastics. As reviewed in sections 4.1 and 4.2, *residence time* of bioplastics in natural environments (soil, water) varies according to the type of bioplastics and the environmental conditions, but it can be assumed to range between 1 and 10 years. Assuming 1,000 years *residence time* for petroleum-derived plastics, it is possible to estimate that bioplastics reduce the potential leakage with respect to traditional plastics by a 1/100 – 1/1000 factor (considering the same concentration of material).

In this context, waste management can play a role in reducing the potential leakage of bioplastics since it can enhance bioplastics' degradation under industrial controlled conditions, decreasing the *concentration* factor in Equation 1. The potential role of waste management in decreasing the potential bioplastics' leakage following their usage and disposal was assessed by simulating different scenarios described in Table 6.

The other assumptions made for the potential leakage assessment were that bioplastics that were not treated in waste management directly leaked into natural environment, bioplastics residues in digestate and compost reached the natural environment after waste management, and that all bioplastics divided equally between soil and aquatic environments. The AD process was assumed to have 25 days HRT, whereas 90 days treatment were considered for thermophilic composting (Cerda et al., 2018, Panigrahi and Dubey, 2019). For the integrated AD and composting process, the timing used in the assessment were 25 days HRT of AD and 65 days of thermophilic composting of the digestate. Based on these considerations and on the degradation rates reviewed in this paper (Tables 2, 3, 4 and 5), the potential leakage derived by the disposal of 100 kg of bioplastics was calculated following Equation 2:

$$Potential\ leakage = (C \times RT)_{soil} + (C \times RT)_{aquatic\ env.} \quad \text{(Equation 2)}$$

where C is the concentration of bioplastic and RT is the residence time of bioplastic. The potential leakage of each scenario was estimated in a range from 0 (minimum leakage) to 1 (maximum leakage, absence of waste management) by dividing the result for the potential leakage calculated for the worst scenario (Scenario 0, absence of waste management and leakage of all the bioplastics into the environment). The results of potential leakage assessment for the three bioplastics considered in the present review (PHAs, PLA and starch-based blends) are reported in Table 6.

PHAs blends showed a high reduction of potential leakage as a consequence of waste management and the leakage was reduced to zero in two scenarios (100 % bioplastics treated through AD and digestate composting). Interestingly, no differences were observed between mesophilic and thermophilic ADs, as expected from these kinds of bioplastics that were easily biodegradable in anaerobic conditions. PLA blends showed a small reduction of potential leakage after AD processes due to the slow degradation of these materials under anaerobic conditions. Conversely, PLA blends showed the highest benefits from composting and the potential leakage was reduced to 0.5 and 0 when 50 % and 100 % (weight basis) of PLA blends were managed through thermophilic composting. The integration of AD and digestate composting also led to strong reduction of the potential leakage associated with PLA blends (90 % and 100 % reduction for mesophilic and thermophilic AD coupled to composting, respectively).

The key role of temperature in degradation of PLA blends was confirmed in the present potential leakage assessment, and it appeared evident that a stage of thermophilic composting is mandatory to degrade PLA bioplastics quickly. Waste management also reduced the potential leakage associated with starch-based blends, even if not one of the studied scenarios allowed reducing the leakage to zero. The best results were obtained from scenarios 6 (100 % bioplastics in composting), scenario 8 (100 % bioplastics in mesophilic AD + composting) and scenario 10 (100 % bioplastics in thermophilic AD + composting).

Summarising, the proposed potential leakage assessment highlighted the potential role of waste management in reducing the concentration of bioplastics that can reach the environment. Indeed, the best results were obtained when 100 % (weight basis) of the bioplastics were supposed to be treated in waste management. Separate collection of bioplastics within OFMSW appears as the most suitable solution to avoid leakage of bioplastics into the environment and to reduce their concentration in soil and water. The integration of AD and digestate composting appeared as the most promising treatment to degrade bioplastics, and this was an interesting result since coupled AD and composting allows recovering energy and nutrients from organic waste making the whole process sustainable from an energetic point of view (Ma et al., 2018).

5. Future challenges

The present review highlighted how waste management can reduce the presence of bioplastics in the environment, minimizing the potential leakage of these materials, because of their biodegradation under controlled conditions. Therefore, research dealing with bioplastics biodegradation during waste management with particular attention on how to enhance bioplastics degradation under AD and/or composting conditions is becoming necessary and mandatory in the near future. Reaching a temperature higher than 55 °C is mandatory to improve the degradation kinetic of most of the bioplastics commonly used (e.g. PLA and starch-based bioplastics) due to the chemical and mechanical transformations that occur after reaching the glass transition temperatures. Nowadays, mesophilic AD is more widespread than thermophilic AD for OFMSW treatment, mainly due to higher stability and lower investments and energy requirements (Kumar and Samadder, 2020). Moving to thermophilic AD facilities may improve bioplastics degradation (Cazaudehore et al., 2021). On the other hand, mesophilic AD can be considered if it is coupled with digestate composting, since the thermophilic conditions of the active phase of composting can enhance bioplastics degradation. Nevertheless, sometimes composting after mesophilic AD is not capable of achieving high process temperatures because the major part of the readily degradable organic matter has been degraded during the AD (Tambone et al., 2015). In this case, AD-HRT plays an important role in determining residual organic matter to be degraded during composting.

Other strategies to enhance bioplastics degradation under anaerobic conditions are the material pre-treatments before biological processes. Actually, this opportunity is still almost unexplored and the few papers dealing with this topic have reported controversial results. Acidic and basic chemical pre-treatments of starch-based and PLA bioplastics carried out at room temperature did not affect bioplastics degradation under AD (Battista et al., 2021). Conversely, Calabro' et al. (2020) reported that basic pre-treatment of starch-based bags using NaOH 5 % w/v for 24 h, increased by 344 % and 283 % the degradation under mesophilic and thermophilic AD, respectively. In the same paper, mechanical pre-treatment of starch-based bags did not produce significant results. These data agreed with those of Benn and Zitomer (2018) who reported that basic and thermal pre-treatment of PHBs and PLA increased the bioplastics conversion to biogas up to over 100 %. Since these are the first reported results of bioplastics pre-treatments enhancing degradation under anaerobic conditions, the need for more investigation has emerged. In fact, improving the degradation of bioplastics in AD can act positively in reducing the potential leakage of bioplastics but can also affect positively the biomethane production of the digester. Bioplastics have the potential to increase significantly the biomethane potential of OFMSW, and it is reasonable to suppose that in 2030, because bioplastic content in the OFMSW could reach 10 % (w/w), the contribution of bioplastics to total biomethane production of OFMSW could reach about 40 %. Unmixed AD may represent an interesting treatment for bioplastics' disposal because in this particular case, the solid retention time (SRT) is much longer than HRT allowing for a significant biomethane recovery from bioplastics even under mesophilic conditions. Surely, this research field need to be further explored and better addressed. Another research field that needs to be further investigated in order to improve degradation of bioplastics under industrial and natural environments is the use of bioplastics composites blended with easily biodegradable materials. The present paper already reported some examples of how the presence of soluble sugars, proteins and/or cellulose in the bioplastics structure may promote their degradation under composting, soil and aquatic environments (Beltrán-Sanahuja et al., 2020, Harmaen et al., 2015, Sarasa et al., 2009). In this context, future research should consider the findings indicated above on enhancing bioplastic biodegradability (Kalita et al., 2020). Plant residues and organic wastes may represent low-cost suitable sources of easily biodegradable molecules to be blended with bioplastics (Ncube et al., 2020). Recycling bioplastics to recover valuable monomers is actually an unexplored field. Only PLA has been recently studied to recover lactic acid or lactate esters through chemical recycling (hydrolysis and alcoholysis processes, respectively), showing the need for more research on this topic (Lamberti et al., 2020). Conversely, the recovery of functional chemicals (e.g. sugars, volatile fatty acids, biofuels) from petroleum-derived plastics has also been investigated in recent years (Al Rayaan, 2021, Bäckström et al., 2017). Although bioplastics were introduced as eco-friendly substitutes for single-use plastic items and they were always intended to be collected within the bio-waste, the possible separate collection of bioplastics should be encouraged in a scenario of increased use of these products. Separate collection and subsequent conversion of bioplastics into valuable products through chemical processes would be possible in this way. Bioplastics management may move from the traditional *degradation paradigm* to a new one named *bioplastics as feedstock*, where bioplastics are no longer intended as single-use products but are projected to be recovered in a circular economy perspective. In a future perspective of separate collection of bioplastics' wastes, incineration coupled to energy recovery and bioreactor landfill with biomethane recovery could also be considered for the disposal of these materials. Although a preliminary study by Piemonte (2011) reported incineration to be lower performing than mechanical recycling, the *waste-to energy* strategy for bioplastics' waste might deserve more attention in future research due to energy recovery and the reduction of leakage's risk. The increasing use of bioplastics and their disposal within the OFMSW also challenges the existing regulations concerning compost quality. Actual regulations do not discriminate between petroleum-derived plastics and bioplastics and, consequently, it is reasonable to expect an increase in the quantity of composts that do not meet quality requirements, thereby increasing the costs and environmental impacts of OFMSW management. For instance, Italian legislation concerning high quality compost production prescribes a 0.5 % w/w limit for the presence of *inert materials* (e.g. plastics, metals and glass particles with particle size > 2 mm), without any distinction between petroleum-derived plastics and bioplastics (Decreto Legislativo 29 Aprile 2010, 2010). The same limits were proposed by the European Commission as end-of-waste criteria for biodegradable waste subjected to biological treatments (i.e. compost and digestate) (Saveyn and Eder, 2014). Bioplastics residues in compost should not be taken to count as *inert materials* (plastics, metals, glass) since they have been proved to degrade in natural environments (e.g. soil, water) (Emadian et al., 2017, Calabro' et al., 2020). Conversely, they might be considered together with the other biodegradable polymers constituting compost (e.g. cellulose, hemicellulose, lignin etc.) and thus regulations might be adapted to the new framework by excluding bioplastics from the fraction of *inert materials*. Nevertheless, the development of a standardized procedure to distinguish bioplastics and plastics residues in compost is needed before adapting the regulations dealing with compost quality.

In summary, although more research to enhance bioplastic degradation under engineered environments is needed, the environmental benefits of bioplastics in comparison with petroleum-derived plastics are unequivocal because of their complete biodegradation in reasonable time.

6. Conclusions

The present review paper summarizes the current knowledge on bioplastics degradation under different environments (industrial and natural) and highlights the potential relationship between degradation of bioplastics during waste management and their potential leakage. Specifically, enhancing bioplastics degradation during anaerobic digestion and composting may reduce the concentration of bioplastics leaking to the soil and water environments, minimizing the potential environmental impact of these materials. Further investigation is needed to improve biodegradation of bioplastics in waste management through different strategies (e.g. thermophilic processes, pretreatments for anaerobic digestion, introduction of easily degradable blends).

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115. **Table 1**. Main characteristics of selected bio-based biodegradable bioplastics and their global production in 2020 and 2025.

Bioplastic	Source	Main applications	Global production[a] (10^3 tonnes year^{-1})	
			2020	*Forecast 2025*
Starch-based blends	Starch from dedicated crops (e.g. corn, rice, potato) processed with plasticizers	Films, rigid materials (dishes, cutlery, glasses), packaging, medical products, mulching films, carrier bags, waste-collection bags	390	400
PLA blends	Fermentation of carbohydrates from dedicated crops (e.g. corn, sugar cane, sugar beet, tapioca) to low MW[b] PLA and subsequent repolymerization to high MW PLA	Packaging, disposable goods, electronic applications, fibres, medical products, textiles and films, agricultural applications, building and constructions	390	560
PHAs blends	Microbial synthesis and intracellular accumulation from carbohydrates (e.g. sugars, starch)	Packaging, agricultural applications, medical products	50	330

116. [a]European bioplastic, 2020
117. [b]Molecular weight

118. **Table 2**. Degradation of bioplastics during anaerobic digestion and estimation of kinetic parameters.

119.

Bioplastic	Temperature	Time (d)	Degradation (%)	k[a] ($mg\ g^{-1}\ d^{-1}$)	Time for complete degradation[a] (d)	Average time for complete degradation ± SD[a] (d)	Reference
PHAs blends	Mesophilic	9	93	103.3	10	31 ± 20	Yagi et al., 2014
		42	86	20.4	49		Ryan et al., 2017
		30	90	30	33		Reischwitz et al., 1997
	Thermophilic	14	90	64.3	16	36 ± 28	Yagi et al., 2013
		50	90	18	56		Yagi et al., 2013
PLA blends	Mesophilic	60	12	2	500	423 ± 76	Yagi et al., 2009
		227	49	2.2	454		Yagi et al., 2014
		65	20	3.1	322		Zhang et al., 2018
		100	24	2.4	417		Cazaudehore et al., 2021
	Thermophilic	151	94	6.2	161	116 ± 48	Tseng et al., 2019
		60	90	15	67		Yagi et al., 2009
		65	80	12.3	81		Yagi et al., 2010
		75	75	10	100		Yagi et al., 2013
		100	58	5.8	172		Cazaudehore et al., 2021
		65	18	2.8	357		Zhang et al., 2018
Starch-based blends	Mesophilic	50	26	5.2	192	376 ± 319	Gómez and Michel, 2013
		30	24	8	125		Calabro' et al., 2020
		100	12	1.2	833		Cazaudehore et al., 2021
	Thermophilic	30	37	12	83	148 ± 92	Calabro' et al., 2020
		100	47	4.7	213		Cazaudehore et al., 2021

120. [a]Estimated in this work assuming a pseudo-zero order kinetic

Table 3. Degradation of bioplastics during composting and estimation of kinetic parameters.

121.

Bioplastic	Temperature (°C)	Time (d)	Degradation (%)	k[a] (mg g^{-1} d^{-1})	Time for complete degradation[a] (d)	Average time for complete degradation ± SD[a] (d)	Reference
	> 50	60	30	5	200		Sun et al., 2021
s blends	58	110	80	7.3	137	124 ± 83	Weng et al., 201
	55	28	80	28.6	35		Tabasi and Ajji, 2
	n.a.	98	90	9.2	109		Kalita et al., 202
	58	130	75	5.8	172		Balaguer et al., 2
	65	58	84	14.5	69		Kale et al., 200
blends	55	28	70	25	40	84 ± 47	Tabasi and Ajji, 2
	58	30	60	20	50		Mihai et al., 201
	58	28	100	35.7	28		Arrieta et al., 20
	58	90	80	8.9	112		Sarasa et al., 200
	62	90	100	11.1	90		Báreková et al., 2
	58	90	85	9.4	106		Javierre et al., 20
	55	85	50	5.9	169	119 ± 43 (thermophilic)	Gómez and Michel,
h-based blends	45 - 65	60	90	15	67		Cafiero et al., 20
	58	60	45	7.5	133		Ruggero et al., 20
	23	72	27	3.8	263		Mohee et al., 200
	25	90	43	4.8	208	220 ± 38 (mesophilic)	Accinelli et al., 2
	25 - 45	180	95	5.3	189		Cafiero et al., 20

122.[a]Estimated in this work assuming a pseudo-zero order kinetic

123.[b]Not available

124.

125. **Table 4**. Degradation of bioplastics in soil and estimation of kinetic parameters.

126.

Bioplastic	Temperature (°C)	Time (d)	Degradation (%)	k[a] ($mg\ g^{-1}\ d^{-1}$)	Time for complete degradation[a] (d)	Average time for complete degradation ± SD[a] (d)	Reference
	n.a.[b]	180	64.3	3.6	278		Jain and Tiwari
	Room temperature	60	35	5.8	172		Wu, 2014
ends	20	280	48.5	1.7	588	435 ± 241	Gómez and Mich
	Natural conditions	365	98	2.7	370		Boyandin et al.,
	Natural conditions	365	47	1.3	769		Boyandin et al.,
	23	180	20	1.1	909		Kalita et al., 2
	20	98	10	1.0	1,000		Wu, 2012
ds	25	180	16	0.9	1,111	1,604 ± 1,010	Palsikowski et al
	n.a.	600	20	0.3	3,333		Urayama et al.,
	25	90	5	0.6	1,667		Unpublished
	20	110	14.2	1.3	769		Gómez and Mich
	25	90	37	4.1	244		Accinelli et al.,
ased blends	20	40	5	1.3	769	591 ± 313	Alvarez et al.,
	30	70	8	1.1	909		Rapisarda et al.
	25	90	34.3	3.8	263		Unpublished

127. [a]Estimated in this work assuming a pseudo-zero order kinetic

128. [b]Not available

129.

130.

131. **Table 5**. Degradation of bioplastics in aquatic environment and estimation of kinetic parameters.

132.

Environment	Temperature (°C)	Time (d)	Degradation (%)	k[a] (mg g^{-1} d^{-1})	Time for complete degradation[a] (d)	Average time for complete degradation ± SD[a] (d)	Refer
Freshwater	25	365	8.5	0.23	4,348		Bagheri et
Sea water	25	365	8.5	0.23	4,348		Bagheri et
Freshwater	20	42	43.5	10.4	96	1,570 ± 2,154	Volova et
Sea water	29	160	58	3.60	278		Volova et
Sea water	21	49	99	20.2	50		Thellen et
Sea water	12-22	90	30	3.30	303		Thellen et
Sea water	30	365	5.7	0.16	6,250		Greene,
Sea water	30	365	8.4	0.23	4,348		Greene,
Freshwater	25	365	< 2	-	-	4,629 ± 2,468	Bagheri et
Sea water	25	365	< 2	-	-		Bagheri et
Sea water	16	365	29.2	0.80	1,250		Beltrán-Sanahu
Sea water	16	365	5.6	0.15	6,667		Beltrán-Sanahu
Freshwater	25	90	1.5	0.17	5,882		Accinelli et
Sea water	25	90	1.5	0.17	5,882	3,068 ± 3,249	Accinelli et
Sea water + Sediment	Room temperature	236	69	2.92	342		Tosin et a
Sea water	n.a.[b]	168	100	5.95	168		O'Brine and Th

133.[a]Estimated in this work assuming a pseudo-zero order kinetic

134.[b]Not available

135.

136. **Table 6**. Ecological risk assessment for 100 kg of bioplastics under different waste management scenarios.

137.

	PHAs blends				PLA blends				Starch-based blends			
Scenario[a]	Degradation in WM[b] (%)	BP[c] soil (kg)	BP aquatic environment (kg)	**Risk**	Degradation in WM (%)	BP soil (kg)	BP aquatic environment (kg)	**Risk**	Degradation in WM (%)	BP soil (kg)	BP aquatic environment (kg)	**Risk**
0	-	50	50	**1.00**	-	50	50	**1.00**	-	50	50	**1.00**
1	75	31.2	31.2	**0.63**	6	48.5	48.5	**0.97**	7	48.2	48.2	**0.97**
2	75	31.2	31.2	**0.25**	6	44.8	44.8	**0.94**	7	46.5	46.5	**0.93**
3	75	12.5	12.5	**0.63**	21	47	47	**0.90**	17	45.8	45.8	**0.92**
4	75	12.5	12.5	**0.25**	21	39.5	39.5	**0.79**	17	41.5	41.5	**0.83**
5	75	31.2	31.2	**0.63**	100	25	25	**0.50**	65	33.8	33.8	**0.68**
6	75	12.5	12.5	**0.25**	100	0	0	**0.00**	65	17.5	17.5	**0.35**
7	100	25	25	**0.50**	91	27.2	27.2	**0.55**	62	34.5	34.5	**0.69**
8	100	0	0	**0.00**	91	4.5	4.5	**0.09**	62	19	19	**0.38**
9	100	25	25	**0.50**	100	25	25	**0.50**	72	32	32	**0.64**
10	100	0	0	**0.00**	100	0	0	**0.00**	72	14	14	**0.28**

138. [a]Scenario description:
139. Scenario 0: no waste management foreseen. All the bioplastics leak into natural environments
140. Scenario 1: 50 % (weight basis) of bioplastics treated by AD under mesophilic conditions
141. Scenario 2: 100 % (weight basis) of bioplastics treated by AD under mesophilic conditions
142. Scenario 3: 50 % (weight basis) of bioplastics treated by AD under thermophilic conditions
143. Scenario 4: 100 % (weight basis) of bioplastics treated by AD under thermophilic conditions
144. Scenario 5: 50 % (weight basis) of bioplastics treated by thermophilic composting
145. Scenario 6: 100 % (weight basis) of bioplastics treated by thermophilic composting
146. Scenario 7: 50 % (weight basis) of bioplastics treated by mesophilic AD and digestate thermophilic composting
147. Scenario 8: 100 % (weight basis) of bioplastics treated by mesophilic AD and digestate thermophilic composting
148. Scenario 9: 50 % (weight basis) of bioplastics treated by thermophilic AD and digestate thermophilic composting
149. Scenario 10: 100 % (weight basis) of bioplastics treated by thermophilic AD and digestate thermophilic composting
150. [b]Waste management
151. [c]Bioplastic