Biodegradability of (micro)plastics: how does it work and how to communicate

Bachelor Integration Project

Industrial Engineering and Management, Faculty of Science and Engineering, Rijksuniversiteit Groningen

Supervisors:
Drs. C.M. (Karin) Ree
M. (Mehran) Mohebbi
Ir. T.M. (Tim) Kousemaker

June 17th, 2022

Zoé den Bieman Maturana S3444473

Abstract

Plastics are found everywhere in our daily lives. However, their particular durability threatens to affect the natural balance of many ecosystems. Plastics tend to accumulate in the environment, where the fragmentation of plastic debris can lead to microplastic pollution. Biodegradable plastics pose as an alternative to conventional plastics in many applications. Ideally, such plastics are mineralized by microorganisms and eliminated from our environment, causing no microplastic pollution. Evaluating their characteristic property – biodegradability, including complete mineralization, is a crucial and complex issue that has previously led to conflicting interpretations. In order to make test methods reproducible, a series of standards were formulated, which also serve as a basis for certification schemes. However, biodegradable plastics require further efforts in research and communication. This paper aims to inform on the several parameters involved in the biodegradation process and why not all plastics are biodegradable. In addition, it aims to emphasize why this is a complex matter and how current testing and labeling for biodegradability needs careful reconsideration to avoid unintended consequences.

Table of Contents

Abbreviations

ABA	Australasian Bioplastics Association
ASTM	American Society for Testing and Materials
BDPs	Biodegradable plastics
BMPs	Biodegradable microplastics
BOD	Biochemical Oxygen Demand
BPI	Biodegradable Products Institute
$CaCl_2$	Calcium chloride
CEN	European Committee for Standardization
CH_4	Methane
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
$C_6H_{12}O_6$	Glucose
DIN	German Institute for Standardization
DOC	Dissolved Organic Carbon
ELTs	End-of-Life Tires
EPAs	Environmental Protection Agencies
HV	3-hydroxyvalerate
H_2O	Water
ISO	International Organization for Standardization
JBPA	Japan BioPlastics
K_2HPO_4	Dipotassium phosphate
mcl-PHAs	Medium Chain Length PHAs
$MgCl_2$	Magnesium chloride
$\bar{M}_{\text{GreenFill}}$	Average weight of 10 GreenFill granules
$\bar{M}_{\text{PHA}}$	Average weight of 10 PHA granules
MPs	Microplastics
NaH_2PO_4	Monosodium phosphate
$(NH_4)_2SO_4$	Ammonium sulfate
O_2	Oxygen
PAHs	Polycyclic aromatic hydrocarbons
PCM	Phase-Contrast Microscope
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxy butyrate
PHBV	Poly (3-hydroxybutyrate-co-3-hydroxyvalerate)
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinylchloride
REACH	Registration Evaluation Authorization and Restriction of Chemicals

SAPEA	Science Advice for Policy by European Academies
SBR	Styrene Butadiene Rubber
scl-PHAs	Short Chain Length PHA
SUPD	Single Use Plastics Directive

1. Introduction

Plastics are among the most widely used materials in modern society and play an inevitable role in our day-to-day life. Most of these plastics are made from nonrenewable petrochemicals, as they are extracted from fossil oil, natural gas, and coal. These materials are inexpensive and highly engineered to achieve specific material properties. Their particular durability makes them ideal for many purposes, such as food packaging, sterile medical use, and construction, but also gives them a significantly longer lifespan when discarded. The durability of plastics arises from their biological inertness, which results from the absence of functional groups vulnerable to attack by microbial enzymes, light, and water. Thus, the properties that make plastics so versatile for people also pose an imminent threat to the environment (Chamas et al., 2020).

Plastic waste treatments attempt to alleviate the impact of microplastic (MP) pollution. Each year, 400 megatons of plastic waste are generated. Only 18% of plastic waste is recycled, and 24% is incinerated. The remaining 58% is either landfilled or enters the natural environment, where plastics accumulate and persist for an extended period (Chamas et al., 2020). Although these current clean-up strategies are not without any results, they are insufficient to manage the prevailing issue. MP particles are arbitrarily defined as particles smaller than 5 mm (Koelmans et al., 2022). They can be classified as "primary" or "secondary," depending on their origins. Primary MPs are tiny particles designed for commercial use, such as cosmetics. Most of the MP pollution follows from secondary MPs entering the environment. These arise from the breakdown of larger plastic fragments as they begin to degrade by exposure to environmental factors (Koelmans et al., 2022).

With the increasing severity of plastic pollution, biodegradable plastics (BDPs) become an alternative material to conventional plastics in various applications. The biodegradability of BDPs requires the right circumstances, which are often challenging to meet in the natural environment. If degradation conditions are not met, BDPs and conventional plastics are equivalent in terms of their lifespan. The biodegradable microplastics (BMPs) can also be formed by BDPs entering the environment (Wang et al., 2021). A recent study by Sun et al. (2022) examined the changes in the intestinal microbial population of the so-called "superworms" (*Zophobas morio*) grown on polystyrene (PS), one of the most widely produced plastics in the world, over three weeks. Their results provide the first insights into how these superworms' intestinal bacteria degrade PS.

Innovative companies that have developed biodegradable alternatives for products that result in environmental pollution via MPs cannot communicate this unique characteristic of their product. Moreover, in an attempt to communicate about the biodegradable property of their product, many companies end up greenwashing. Greenwashing is the act of providing misleading or incorrect information on how a company's operations are environmentally friendly rather than actually implementing operational practices that minimize environmental impact (de Freitas Netto et al., 2020). This paper aims to design a communication framework for these companies to convey this specific property in an understandable and transparent manner to business clients and policy advisors.

The problem owner Ecoras is a company that advises industrial organizations to lower the environmental impact of their operations. One of these organizations is Senbis, a Dutch company that produces sustainable polymeric products. One of its products is GreenFill, a fully in-soil biodegradable grass infill for artificial grass fields as an alternative to the currently used rubber granules. Ecoras is looking for an alternative way to communicate this particular property, as Senbis is currently unable to do so without greenwashing. In order to propose an alternative communication framework, this paper elaborates on why companies are actually unable to convey this unique property.

The remainder of this paper is organized into three different sections. The first section covers the Problem Analysis, where the stakeholders involved, the scope of the research, and the case study used are identified. The following section provides the Body of Knowledge of the paper, focusing on all aspects involved in the biodegradation process and the certification scheme. The third section elaborates on the biodegradable grass infill case study, where the assumption that bacteria found in environments surrounding sporting facilities will break down the GreenFill granules.

2. Problem Analysis

2.1 Problem Context

Humanity's enduring affinity for plastics seems to be diminishing due to their adverse effects on human health and the environment. The growing emphasis on sustainability has stimulated the search for developing plastics with new properties or plastics derived from alternative raw materials. However, terms such as 'bio-based,' 'degradable,' and 'biodegradable' are often misinterpreted and used inaccurately. Bio-based polymers originate from renewable raw materials unrelated to their biodegradability. Degradable polymers use additives broken down by composting, and biodegradable polymers degrade when left in the right environment, regardless of their origin. Biodegradable polymers seem to provide solutions for the increasing MP pollution. However, many uncertainties exist concerning the extent to which their benefits are trustworthy and of significance (Kawashima et al., 2019).

The exact definition of plastic products labeled as ‘bio-based’ and ‘biodegradable’ is unclear, and adjectives such as ‘green,’ ‘circular,’ or ‘eco-friendly are even vaguer. Producers, customers, and policy advisors are confronted with many options and approaches, yet meaningful information is scarce. A clear definition of 'plastic,' ‘biodegradable,’ and the biodegradation process are required to address this misconception. Clear definitions will be the basis for a differentiation between the many forms of plastics and their biodegradability in the natural environment. The Single Use Plastics Directive (SUPD) defines plastics as “*a material consisting of a polymer (...), to which additives or other substances may have been added, and which can function as a main structural component of final products, with the exception of natural polymers that have not been chemically modified*”. A comprehensive definition like this, including all elements that form the material, is necessary to avoid misunderstandings about the material and specify how biodegradability should be tested, certified, and communicated. As mentioned above, bio-based does not necessarily imply biodegradability, and both bio-based and fossil-based polymers can either be biodegradable or not. However, the origin of plastic is also a critical component and should be considered when comparing the environmental impact of plastics to that of other materials. Figure 1 provides a systematic overview of plastic materials and their interrelatedness (SAPEA, 2020).

All plastics degrade to some degree, either physiochemically or biologically. Weathering (degradation by sunlight, wind, waves, or rain) and hydrolysis/oxidation are typical physio-chemical processes. These processes affect all plastics, and MPs result from them (Chamas et al., 2020). Plastic biodegradation is a complex process that requires microorganisms to rearrange the carbon-containing compounds in plastic. The Science Advice for Policy by European Academies (SAPEA) defines biodegradation as “*the* *microbial conversion of all its organic constituents to carbon dioxide (CO_2), new microbial mass and mineral salts under oxic conditions or to carbon dioxide (CO_2), methane (CH_4), new microbial biomass and mineral salts under anoxic conditions*". Therefore, the biodegradability of plastics applies only to the organic part (compounds carrying carbon-hydrogen bonds) of a plastic product. Accordingly, plastic made solely out of inorganic polymers is not considered biodegradable. Inorganic additives can affect the biodegradation of a product and need careful evaluation. Additionally, the definition of the biodegradation process of plastics needs to be complemented by the required rate of degradation within a predefined timeframe, as well as the specific environmental conditions in which biodegradation is perceived. The biodegradation process must be sufficiently fast not to be as harmful to the environment as conventional plastics and not to lead to long-term accumulation in the environment. As the biodegradability of plastic products is not perceived immediately, the exact end-of-life assumed by a company cannot be instantly verified. Moreover, the environmental safety of their product's end-of-life is also unknown (SAPEA, 2020) (Filiciotto & Rothenberg, 2020).

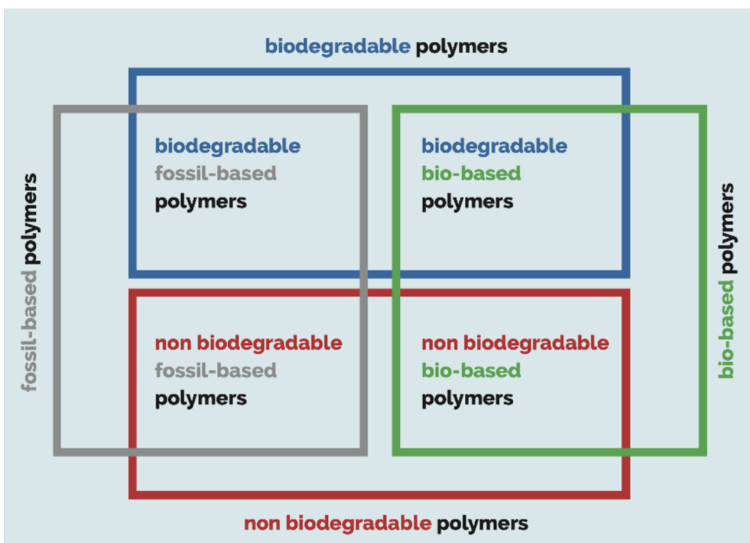


Figure 1: Overview of plastic materials, including biodegradable and bio-based polymers, and how they are related (SAPEA, 2020).

2.2 Stakeholder Analysis

Three different players form the whole system. These include Ecoras, clients of Ecoras (Senbis), and TÜV Austria Holding. Their corresponding interest in and power over the research can be found in Medelow's Diagram provided in Figure 2 and will be elaborated on in this section.

The key player and problem owner is Ecoras, a company that provides advice to industrial organizations to lower their operations' environmental impact. Ecoras emphasizes dealing with raw materials more carefully and consciously. By exploring technical and economic opportunities for the environment, they intend to realize circular value chains. The company has a high interest because it desires to solve the main problem and possibly provide a communication form underlining the benefits biodegradable materials have to their clients. Because Ecoras orders and supervises the research, they also show high power, as they could decide whether to use and distribute the alternative design.

Senbis, as well as other clients of Ecoras, shows high interest, as they are currently unable to communicate the biodegradable property of their product without greenwashing. The outcome of this research could impact their business-2-business communication and sales. However, the power of Ecoras' clients is limited because of their more distant relation to the research. Senbis' clients have significant indirect influence by acknowledging the material properties of the products and therefore influence the interest of Senbis in this research.

Finally, TÜV Austria Holding is also a stakeholder, as this company readily provides some biodegradability certifications for companies. They show low interest since the outcome of this research will not impact the certifications provided by them. Moreover, as they do not have a say in the decision-making process of Ecoras and its clients, whether they should implement the design or not, they have low power.

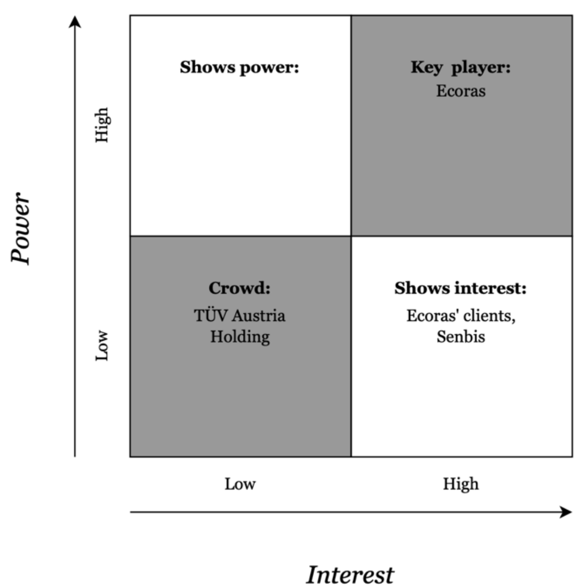


Figure 2: Stakeholder analysis of the players in the research.

2.3 System Analysis

Plastics may end up in the natural environment for various reasons. The intended end-of-life scenario for most plastic products is disposal in a managed waste stream, where they can be recycled or composted. Nevertheless, plastic products intended for managed waste streams may escape the material flow before reaching their end-of-life, resulting in MP pollution. This is the consequence of plastic products' inappropriate disposal and use (SAPEA, 2020). BDPs can be biodegraded, but the degradation process depends on several factors and requires specific conditions. These conditions are not always found in the natural environment. The moment BDPs do not (fully) biodegrade in the natural environment, they may decompose into smaller particles, forming BMPs (Wang et al., 2021).

The material flow of both conventional plastic products and BDP products will form the system and, at the same time, the scope of the research, which is illustrated in Figure 3. The inputs are raw materials, and the output is the degradation rate. The managed waste streams such as composting, recycling, and incineration are outside of the scope, as losses to the environment during the use phase of a product are assumed to be the main cause of microplastic pollution. In order to analyze the degradation process and end-of-life assumptions involved with both products, a case study available at Ecoras is used. Senbis produces a biodegradable product named Greenfill, providing a fully in-soil biodegradable grass infill for artificial grass fields as an alternative for the current rubber granules. There are various ways to measure the rate of degradation; at this point in the research, it is still unknown what methodologies TÜV has used to certify GreenFill to be biodegradable. However, a combination of methodologies is preferred for measuring mass loss and does not incorporate microplastics being released into the environment (Filiciotto & Rothenberg, 2020).

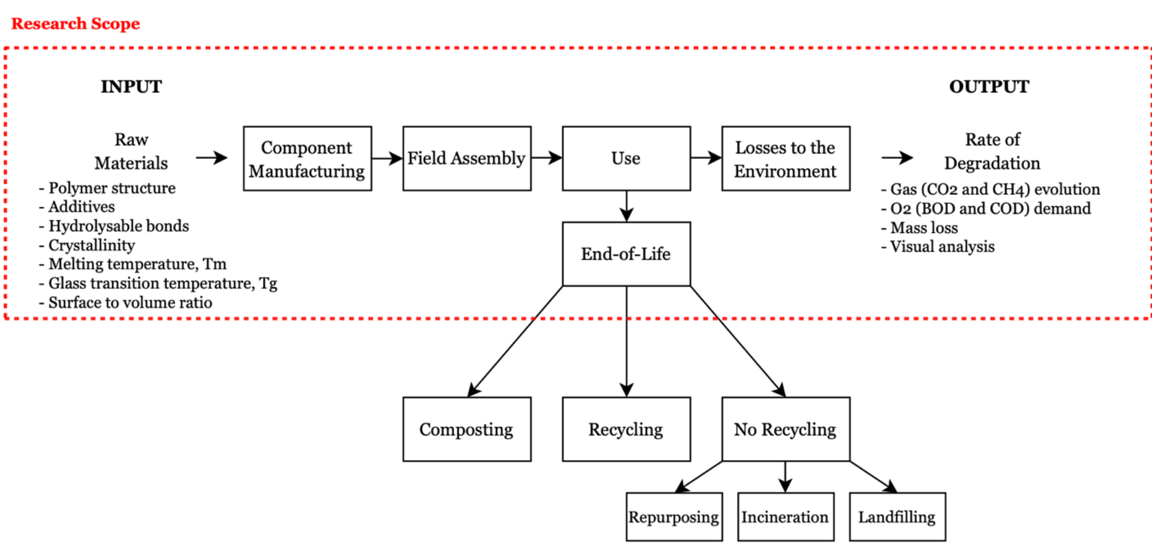


Figure 3: System description of case study on artificial grass infill material.

2.4 Case Study

Ecoras' client Senbis has developed an in-soil biodegradable alternative to used rubber granules. GreenFill appears to be a perfect substitute to the currently used products, as Senbis has demonstrated that the GreenFill granules preserve good sport performance and low abrasion, e.g., long life on the field. To scope the research to make it more attainable, Ecoras suggests applying the research to one of their clients as a case study. The degradation rate can be studied by analyzing the material flow of the currently used conventional plastic product and the biodegradable alternative developed by Senbis. Moreover, the case study will investigate when the product is defined to be fully degraded, what circumstances the product requires to biodegrade, and to which extent the product causes MP pollution. The obtained results may cause discussions with Ecoras and Senbis.

2.5 Problem Statement

Biodegradable materials are a possible alternative to alleviate the environmental impact of microplastic pollution. However, biodegradable materials require certain degradation conditions. If these are not met, they may not differ from conventional plastic materials in terms of longevity and may still result in MPs entering the environment. The formation of microplastics during the life cycle of plastics has only been considered to a minimal extent. However, it is crucial to determine the environmental impact of plastics. After analyzing all components and their context, the following two problem statements can be formulated:

(1) It is not possible to have one universal definition of biodegradability.

(2) In an attempt to communicate the biodegradable property of their product, many companies end up greenwashing.

2.6 Research Objective

The problem that is proposed to be solved during this research can be converted into a research objective. This provides the overall goal of the research and shows how the results will be delivered. The research goal can be subdivided into a knowledge goal followed by a design goal. To achieve the design goal, we must first establish the knowledge goal. The design goal of the research project is to provide a communication framework for companies that develop biodegradable alternatives for products that result in environmental pollution via MPs without greenwashing. In contrast, the knowledge goal is to have a broad understanding of the biodegradability of (micro)plastics. The goal statements provide the backbone to the research objective, which reads as follows:

To propose a communication framework that provides clear and unambiguous information for business clients and policy advisors by specifying when a product is *defined to be fully degraded, what circumstances the biodegradation of a product requires, and to which extent the product causes MP pollution. The project will be finalized within 12 weeks.*

2.7 Research Questions

In order to establish the knowledge necessary to achieve both the research objectives, a set of research questions is formulated. When beginning with gathering knowledge and data, these questions will be answered. Hereafter, the core question can be answered by combining all the information of all these answers (Verschuren et al., 2010). The core question is described as follows:

Why are companies unable to communicate the fact that their developed product is biodegradable and, therefore, an environmentally safe alternative for the existing product that causes environmental pollution via microplastics?

Subsequently, a research framework is drawn up in order to schematically represent the research objective, including the appropriate steps that should be taken to achieve it. The research framework establishes the theoretical background, including key concepts (Verschuren et al., 2010).

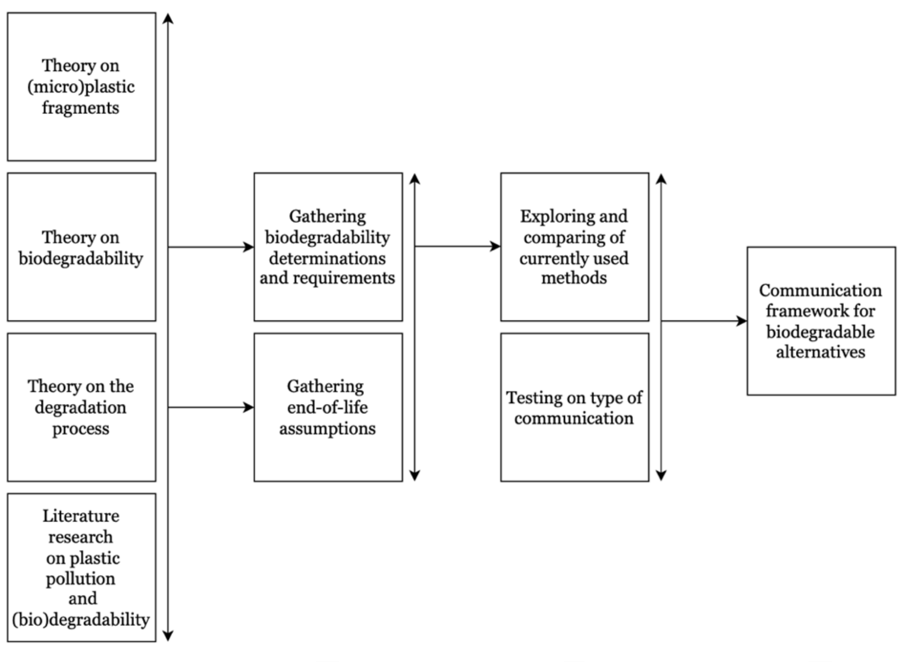


Figure 4: Research framework used to create the sub-research questions.

By reading the research framework backward, approaching point (a) starting at point (d), the prerequisites for each domain are traced. That is, to reach point (d), the domains in point (c) must be obtained beforehand and so on. Along these lines, a set of sub-research questions is generated. The sub-questions are described as follows:

(1) *How does the biodegradation process of (micro)plastics take place in the environment?*

(2) *Does the biodegradation of (micro)plastics indeed lead to zero environmental impact?*

(3) *How does it translate to transparent information regarding biodegradation?*

(4) *Which tools/methods are currently being used by companies and scientific literature to communicate biodegradability?*

(5) *Which methods are understandable by the target audience?*

3. Body of Knowledge

There have been many attempts to universally define the terms ‘degradation’, ‘biodegradation,’ and ‘biodegradability.’ However, there are several reasons why the establishment of an internationally accepted definition for these terms is not so straightforward, including:

1) The unpredictability of plastics ending up in the intended environment, considering the various environments into which plastic can be introduced and the related impact on those environments.
2) The misalignment between lab test protocol conditions and the actual environment where plastics may end up due to improper disposal or leakage of plastics.
3) The disagreement concerning whether the scientific approach or extrapolation method used to determine biodegradability ensures zero environmental impact.

As a result, various definitions have been adopted, depending on the defining organization's background and particular interests. However, of more relevance are the criteria to label a plastic product as 'biodegradable' since a plastic product's demonstrated ability to biodegrade does not incorporate any information on the time frame in which complete biodegradation occurs nor the specifications of complete biodegradation.

3.1 (Bio)degradation Process of Plastics in the Environment

The term biodegradation is frequently confused with the term degradation. The latter refers to the fragmentation of a plastic product into smaller pieces, while biodegradation involves biological activity (van der Zee, 2014). The difference between both terms is illustrated in Figure 5. As illustrated here, fragmentation generally takes place prior to biodegradation. The degradation process of plastics in the environment can be categorized into (1) physical or (2) chemical degradation. Physical degradation is generally caused by weathering and results in changes in the bulk or surface structure, such as cracks and ruptures. Chemical degradation typically involves either hydrolysis (requiring water (H2O)) or oxidation (requiring oxygen (O2)), resulting in changes at the molecular level of a plastic, such as bond cleavages. Both of these processes are non-selective, meaning they affect all plastics and are the primary cause of the generation of MPs (Chamas et al., 2020) (Filiciotto & Rothenberg, 2020).

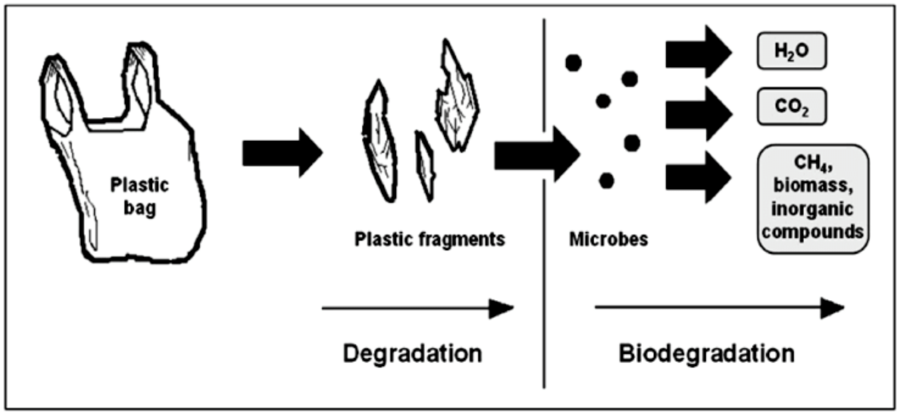


Figure 5: Schematic representation of the degradation and biodegradation of plastics (Islam et al., 2016).

The biodegradation process involves the breakdown or assimilation of organic compounds by enzymes generated by microorganisms. These living microbes use these organic molecules as a carbon and food/energy source. This process can be categorized into three sequential steps: (1) biodeterioration, (2) biofragmentation, and (3) assimilation. A schematic representation of these steps is illustrated in Figure 6. The physical and chemical change of a polymer caused by the accumulation of microorganisms in or on a polymer's surface is known as biodeterioration. Subsequently, biofragmentation is the process of microorganisms breaking down polymers into oligomers, dimers, and monomers. The last step is assimilation, which involves providing microorganisms with carbon, nutrients, and energy from the resulting oligomers, dimers, and monomers and converting the carbon acquired into H2O, CO2, biomass in the presence of oxygen (aerobic biodegradation) or in the absence of oxygen (anaerobic biodegradation) CH4 is formed as an additional byproduct (Lucas et al., 2008). Equation (1) illustrates the general chemistry of the aerobic biodegradation process, and equation (2) illustrates the general chemistry of the anaerobic biodegradation process, and $C_{polymer}$ represents any polymer considered for degradation. For generalization purposes, the polymer, in this case, is assumed to consist exclusively of carbon, hydrogen, and oxygen (van der Zee, 2014).

$$C_{polymer} + O_2 \longrightarrow CO_2 + H_2O + C_{residue} + C_{biomass} \quad (1)$$

$$C_{polymer} \longrightarrow CO_2 + CH_4 + H_2O + C_{residue} + C_{biomass} \quad (2)$$

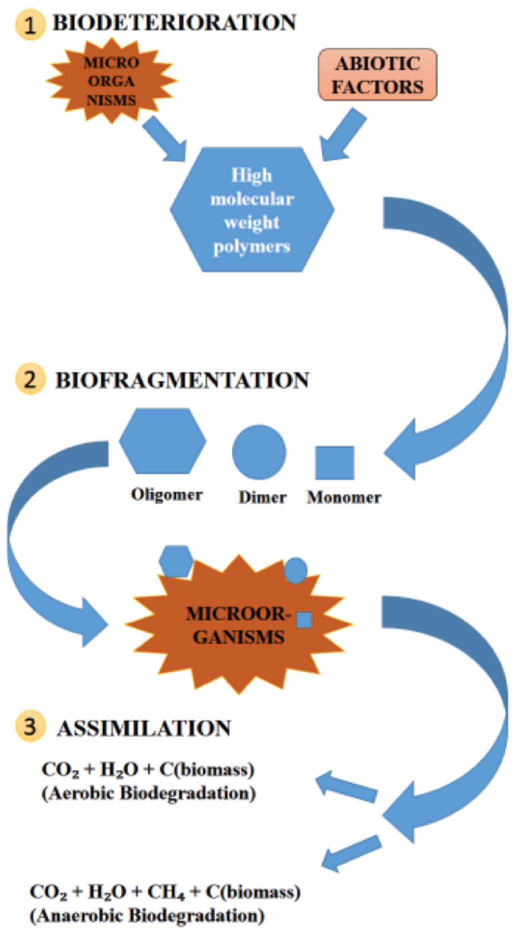


Figure 6: Schematic representation of the biodegradation process, including biodeterioration, biofragmentation, and assimilation (Rana, 2019).

Environmental conditions have an impact on the degradation of a polymer. They play a vital role in the microbial population as well as the activity of the various microorganisms. Humidity, temperature, pH, salinity, the presence or lack of oxygen, and the presence of several nutrients all impact the biodegradation of polymers, and these factors must therefore be taken into account when assessing the biodegradability of a plastic (Mishra, 2015).

3.2 Influence of the Plastic Structure on Biodegradation

The International Organization for Standardization (ISO) defines terms used in the plastic industry, where plastics are defined as "*material which contains as an essential ingredient a high polymer and which, at some stage in its processing into finished products, can be shaped by flow.*" All plastics are polymers, yet not all polymers are plastics. Polymers can be organic or synthetically made and are composed of three or more repeated individual molecules, called monomers. Plastics, on the other hand, are a type of polymer formed from chains of polymers that can be partially organic or fully synthetic (Filiciotto & Rothenberg, 2020).

As recognized here, plastics do not consist of polymers alone; additives such as stabilizers or plasticizers may be used to enrich the material with desired properties. A plasticizer can be dissolved into a polymer to increase its flexibility; the plasticizer decreases the attraction between the polymer chains, allowing them to slide past one another, as illustrated in Figure 7 (Bruice, 2015). Since these additives alter the physical and chemical properties of plastics, they must be taken into account when evaluating their degradation. Additives may negatively but also positively affect the rate of degradation of a plastic product; this differs from case to case and must be investigated closely. Photo-stabilizers are examples of the complexity of additives' effects on biodegradation. A study by de Hoe et al. (2019) illustrates how these additives can oppositely affect the biodegradation of plastics. Photo-stabilizers are used to protect the plastic from oxidations induced by the combined action of UV-light and oxygen. From one point of view, these additives inhibit the fragmentation of the polymer, decreasing the rate at which smaller plastic fragments are formed of sufficiently low molecular weights to be susceptible to microbial attack. At the same time photo-stabilizers may inhibit the formation of UV-light-induced cross-linking reactions between the individual polymer chains, which can adversely affect the enzymatic hydrolysability of these plastics (de Hoe et al., 2019).

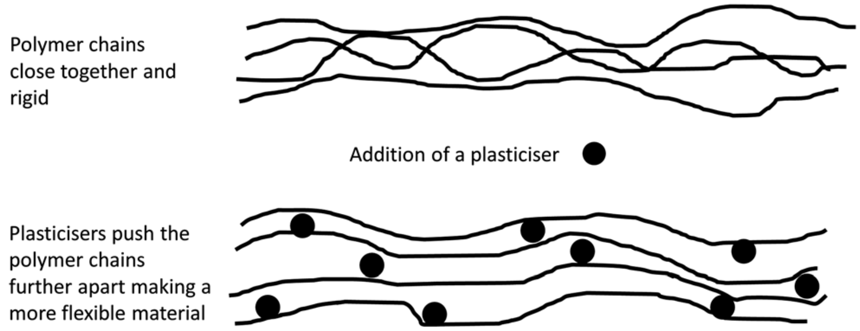


Figure 7: Plasticizers within a polymer chain (Lambert & Wagner, 2017).

Plastics may consist of one single type of monomer, homopolymers. However, often two or more distinct types of monomers are used to generate copolymers. The number of distinct monomers used to form a copolymer drastically increases the number of distinct copolymers that can potentially be formed. By altering the amounts of each monomer, copolymers with a wide range of properties can be produced. The structural differences in the distribution of the individual polymer chains extend the range of physical properties a plastic can possess (Bruice, 2015). As mentioned before, the biodegradation process initiates once the polymer(s) composing the plastic break(s) down into fragments of sufficiently low molecular weights to potentially be microbially accessible. A key factor influencing the tendency of a polymer to undergo sufficient fragmentation is the molecular structure of its backbone. More precisely, the chemical bonds present in the backbone chain need to be able to undergo a reaction resulting in bond breakage.

These chemical bonds typically include hydrolyzable bonds, including esters, amides, and glycosidic bonds, where H2O molecules react with these bonds (Chen et al., 2020) (Haider et al., 2018). However, it must be stressed that not all polymers containing hydrolyzable bonds actually undergo hydrolysis as they end up in the open environment. Polyethylene terephthalate (PET) is an example of a polymer containing hydrolyzable bonds that do not necessarily undergo hydrolysis in the environment. The ester bonds in PET linking terephthalic acid and ethylene glycol cannot be cleaved easily, neither enzymatically nor abiotically. Nevertheless, there do exist some microorganisms in nature that can hydrolyze the ester bonds present in PET. This example highlights the necessity for specific polymer and receiving environment evaluation and testing to determine whether hydrolyzable bonds will actually undergo bond cleavage (Tournier et al., 2020) (Kawai et al., 2020). Because of the highly stable carbon-carbon bonds, it can be stated that polymers that lack chemical bonds that can easily be broken do not biodegrade. Polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), and polystyrene (PS) are, among others, polymers that solely contain carbon-carbon bonds in their backbone (SAPEA, 2020).

A polymer's backbone chemistry is critical in determining its biodegrade capability. Even if the polymer's backbone in question contains chemical bonds that can be broken, the tendency of these bonds to react and actually break is significantly influenced by the strength of the interactions between the individual polymer chains. Most plastics are semi-crystalline polymers, containing both crystalline and amorphous regions. The amorphous regions have their individual chains packed together loosely, where the molecules are randomly arranged. Here, the polymer chains have a high degree of freedom compared to the crystalline regions. This is especially the case at temperatures over the glass transition temperature T_g, which refers to the temperature at which a transition from a glassy to a rubbery state occurs and chain mobility increases (SAPEA, 2020).

On the contrary, in crystalline regions the individual chains are folded to form well-ordered stacks, also known as lamellae, as presented in Figure 8. Here, the individual chains strongly interact and have little degree of freedom, resulting in restricted chain mobility. As the polymer chains in the amorphous regions have higher flexibility, the chemical bonds tend to be more vulnerable to enzymatic and microbial attack (Wei & Zimmermann, 2017). The melting temperature T_m refers to the temperature at which the crystalline structures in a polymer transform into amorphous ones. The hydrolysability of the ester bonds present in a polymer decreases as both the T_m and the T_g of the polymer increase. Therefore, the degree of crystallinity of plastics has a significant impact on their biodegradability (Tokiwa et al., 2009). While increasing the degree of crystallinity increases the hardness and density of a product, the overall biodegradation is inhibited. However, a polymer with too few crystalline regions risks being too ductile for its intended application. In terms of crystallinity, the desired material properties of plastics may not be in accordance with their intended biodegradability and need proper examination during design (Chamas et al., 2020).

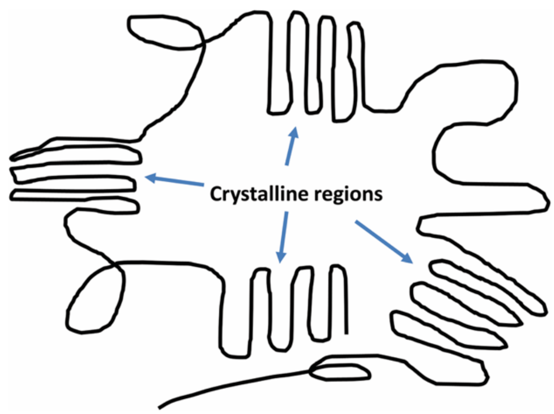


Figure 8: Crystalline regions within a polymer chain (Lambert & Wagner, 2017).

The biodegradation process of a plastic product is initiated by physicochemical degradation into smaller plastic fragments. Once oligomeric or monomeric fragments of sufficiently low molecular weight are generated through abiotic as well as biotic pathways, assimilation begins (van der Zee, 2014). These reactions can take place both through bulk erosion as well as surface erosion. In the case of bulk erosion, the degradation is uniform throughout the material. In surface erosion, the polymer breaks down on the external surface, and the inner part only starts breaking down when all the surrounding material has degraded. Bulk and surface erosion are not mutually exclusive; most materials experience a combination of both processes (Manavitehrani et al., 2016). Due to their size, enzymes cannot penetrate a polymer's interior; this results in an enzyme-mediated mechanism for surface erosion. Consequently, the rate of degradation of a BDP is proportional to its surface-to-volume ratio; plastics are, for instance, more susceptible to surface erosion in the form of thin or small fragments (Abe & Doi, 1999).

Certain implications arise with the significant influence of the specific surface area on the biodegradation of plastic products. First, product biodegradation tests and certifications are frequently conducted on plastic powders. For example, a study by Farzi et al. (2019) isolated bacteria from soil and incubated them with PET powders originating from drinking bottles. Observed biodegradation rates may be higher than for the actual product when leaked into the environment, as these fragments have significantly smaller surface-to-volume ratios. This is a serious cause for concern. Moreover, the physicochemical degradation of BDPs in the open environment due to weathering is expected to increase the product's overall biodegradation rate due to its increased specific surface area. The notion that BDPs, compared to conventional plastics, are more likely to produce MPs is unjustified if biodegradation rates increase with decreasing particle sizes (SAPEA, 2020).

3.3 Environmental Impact of the Biodegradation of Plastics

BDPs are materials that can be broken down by microorganisms (including bacteria, fungi, and algae) and converted into H2O, naturally occurring gasses such as CO2 and CH4, and biomass (van den Oever et al., 2017). The biodegradability of plastics is determined by their raw materials, chemical structure, product shape, and the environmental conditions under which the product is expected to biodegrade, which is often neglected (Letcher, 2020). Temperature, UV radiation, salinity, and the presence of oxygen, water, and microorganisms are all critical environmental factors affecting biodegradability. Scientific literature has made an effort to address all different aspects affecting the biodegradability of plastics. However, in the open environment, all these factors simultaneously affect BDPs in a complex and dynamic interaction of processes (Ghosh & Jones, 2021). A schematic representation of the multivariable factors involved in the biodegradation process is given in Figure 9.

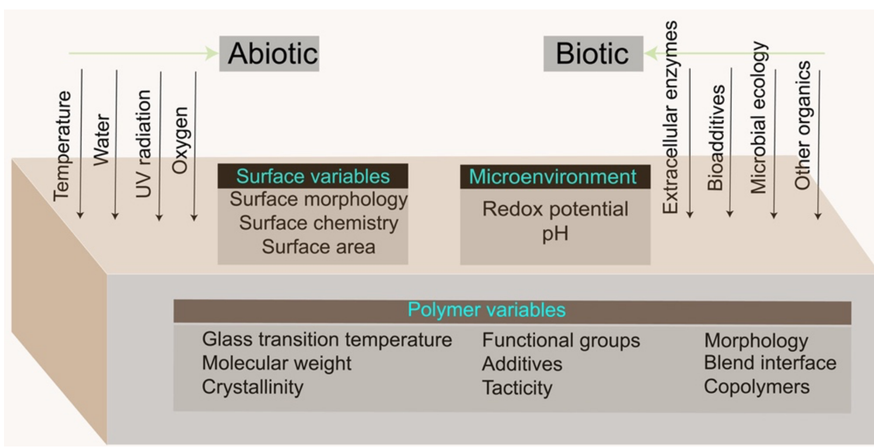


Figure 9: Schematic representation of the multivariable factors involved in the biodegradation process (Ghosh & Jones, 2021).

Comparing the potential environmental consequences of BDP debris with conventional plastics, it is worth considering the ecological risks following conventional plastic debris. The principal difference between conventional plastics and BDPs is their ability to biodegrade. Despite the evidence that some microorganisms can biodegrade conventional plastics, their corresponding degradation rates in the open environment are so slow that they are considered non-biodegradable (Ahmed et al., 2018). The exposure time of BDPs to the environment depends on their degradation rate in the receiving environment. Some of the risks associated with BDPs are expected to have similar effects to those associated with conventional plastics if they accumulate in the environment for an extended period before biodegrading (Haider et al., 2018) (Napper & Thompson, 2019).

BDPs have the potential to be an added source of carbon in the environment. Suppose BDPs are released into the environment in the same manner and quantities as conventional plastics. In that case, their potentially shorter lifespan allows for complete biodegradation and mineralization, which in turn could result in an increased organic carbon load. Although BDPs are a minimal source of carbon, taking the receiving environment into account, microorganisms demonstrate responses even to these small inputs. Increased enzyme activity, microbial degradation, and microbial biomass suggest enhanced carbon cycling under BDPs, which raises the possibility of a local imbalance of nutrient ratios, resulting in long-term implications. This potential risk is dosage-dependent as it differs between regular and irregular exposure. However, since even small carbon inputs affect the element cycles in the natural environment, unnecessary disposal of BDPs must be avoided (Bandopadhyay et al., 2018).

The biodegradation of BDPs is not guaranteed. Biodegradation of BDPs is possible, although the process necessitates precise circumstances which do not always exist under environmental conditions. Due to mechanical fragmentation, photooxidation, thermooxidation, and biodegradation, biodegradable plastic debris will eventually decompose into smaller pieces producing BMPs (Yu et al., 2021). The formation of MPs out of large plastic fragments is a relatively fast process compared to the mineralization of MPs. Until they are entirely mineralized, BMPs possess similar characteristics to MP particles from conventional plastics (Wang et al., 2021). However, due to their higher surface-to-volume ratios, BMPs are expected to biodegrade faster than larger BDP items (Chinaglia et al., 2018). Their biodegradability also suggests that, in comparison to MPs originating from conventional plastics, their negative impact after ingestion may be reduced in species with intestinal bacteria capable of biodegrading the polymer. MPs are the most abundant form of plastic debris and, as a result, are ingested by species at all trophic levels. However, the belief that BMPs may be less harmful after ingestion cannot be universally accepted as it varies by species (SAPEA, 2020). On the contrary, a study by Zuo et al. (2019) found that MPs derived from BDPs have a higher adsorption and desorption capability than conventional MPs, implying that BMPs are a better carrier of pollutants and microbial contamination than non-degradable MPs. Finally, large BDP fragments with low biodegradation rates also give rise to the risk of entanglement by several species.


Figure 10: Mortality of birds due to the ingestion of plastic fragments (Devlin, 2021).

Plastic products do generally not consist of polymers alone; additives may be used to enrich the material with desired properties. BDPs could release these additives and other pollutants upon complete biodegradation in the open environment. Moreover, how long they will remain in the open environment after complete biodegradation of the polymer is also unknown. A study by Zimmermann et al. (2020) observed that toxicity was less prominent and severe in the raw materials than in the final products. In addition, they exhibit similar toxicity when comparing conventional plastics with their BDP alternatives.

Innovative companies claim to be able to produce BDP products specifically engineered to degrade in a particular environment, such as marine or soil conditions. These plastics merely require the presence of certain microorganisms in these specific environments that can break down and mineralize the polymer in question. Nevertheless, their actual presence in the open environment and their tendency to acquire the BDP product as carbon or energy source cannot be ascertained. Therefore, they should not be released into the environment and should not be assumed as a solution to the littering problem. Instead, a plastic product should be designed with an effective recovery solution. A product's ability to biodegrade merely suggests that, in addition to its intended end-of-life option, a BDP product may biodegrade in the open environment (van den Oever et al., 2017). Nonetheless, our understanding of all interdependent variables influencing degradation in natural environments is not yet sufficiently advanced to estimate the precise persistence of BDPs.

3.4 Standards, Testing, and Labels

At present, BDP products are marketed by means of certification and labeling. Certification of these products establishes the overall credibility of sustainability claims; it translates complex data obtained from test results into digestible communication about a product's intended end-of-life. Every product requires separate certification as its degradation rate may differ based on several aforementioned factors. In general, the certification procedure takes place in three sequential steps:

1) The company determines which certifying body and which certification to acquire based on their product and customer requirements.
2) The test is carried out by a third-party testing laboratory (OWS, AIMPLAS, Innovhub SSI) according to the test protocols established by the International Organization for Standardization (ISO), the American Society for Testing and Materials (ASTM), the European Committee for Standardization (CEN), the German Institute for Standardization (DIN), and others.
3) The certifying body (TÜV Austria, DIN CERTO, Biodegradable Products Institute (BPI), Japan BioPlastics Association (JBPA), and Australasian Bioplastics Association (ABA)) evaluates the obtained results from the third-party testing laboratory and decides upon certification.

The block diagram in Figure 11 illustrates the interplay between the different institutes involved in the certification procedure.

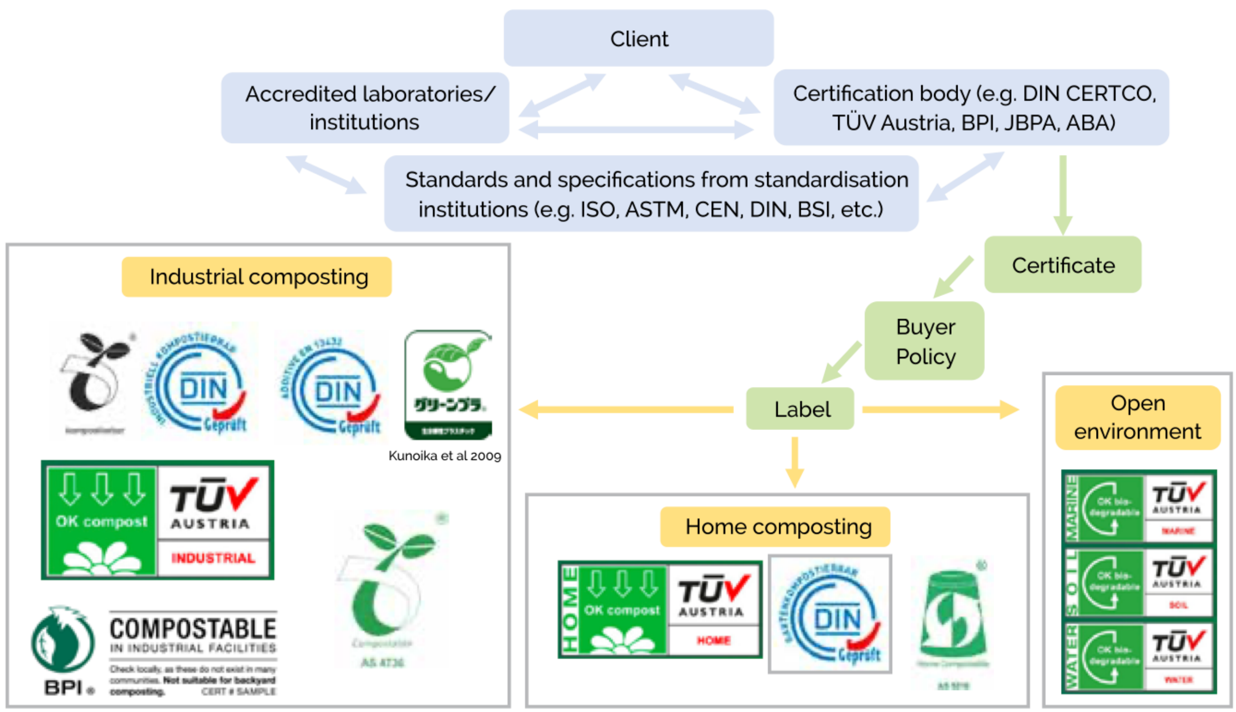


Figure 11: Certification procedure and examples of currently available labels for industrial, home composting, and biodegradable in soil, freshwater (water), and seawater (marine) (SAPEA, 2020).

3.4.1 Standards

The following organizations are the four key players contributing to the development and publication of standards on BDPs:

1) The International Organization for Standardization (ISO)

2) The American Society for Testing and Materials (ASTM)
3) The European Committee for Standardization (CEN)
4) The German Institute for Standardization (DIN)

42 of the 66 standards published by these four organizations are related to biodegradability test protocols; this emphasizes the significance of biodegradation as the only mechanism enabling ultimate degradation. In all of these standards, the degradation process is determined by measuring one of the following three parameters: CO_2 evolution, biochemical and chemical O_2 demand (BOD and COD), or dissolved organic carbon (DOC) reduction. These standards differentiate between three types of biodegradability, "ready" biodegradability, "inherent" biodegradability, and "ultimate" biodegradability. The test conditions and analyses differ for each type of biodegradability determination. Therefore, recognizing their distinctions is essential for selecting relevant testing standards and properly interpreting the results.

Further clarification for the distinction between these different types of biodegradability is given by categorizing tests in three levels: preliminary, simulated, and complementary. The preliminary tests are generally used to determine the "ready" biodegradability and are intended as the first screening step. They are considered less conclusive for certification as they are often performed in a simplified environment. Positive results from these preliminary tests indicate that the material in question is presumed to break down in most natural environments.

Complementary tests are often carried out to obtain additional information about the materials and determine the "inherent" biodegradability. These tests typically employ optimal test conditions to obtain the highest feasible degradation rates. Consequently, proper interpretation is essential, in particular when an estimation of the open environment is to be derived.

Simulated tests provide a more thorough assessment of the degradation process, including determinations of degradation rates or the generation of possible byproducts. These tests are generally conducted in a controlled environment at lower concentrations, requiring precise measurements and specific preparations. Accordingly, these tests are used as a basis for the certification of BDPs. The degradation process is examined in specific environments and is used to determine the "ultimate" biodegradability of a plastic product for that specific environment (Krzan et al., 2006).

However, the use of terms such as "ready," "inherent," and "ultimate" in relation to biodegradation rates in the open environment can be problematic and cause confusion. To understand the differences between these terminologies, one has to be particularly well-informed as well as be aware of the fact that these terms are limited to optimized laboratory tests on biodegradability. In terms of communication, this type of terminology should either be avoided or described thoroughly.

3.4.2 Testing

Biodegradation conditions are, in some situations, harsh (high temperatures and pH values) or not environmentally realistic (isolated or enhanced microorganisms) (Ghosh & Jones, 2021). The biodegradation process must closely follow the test standards to avoid misinterpretation and false claims. Standard test methods provide thorough instructions on how to complete tests according to the standard in question. As a result, the obtained test results from different institutions are more comparable, ensuring a certain level of quality, which helps stakeholders such as clients and certifying bodies (SAPEA, 2020). However, standards are not without their faults and should be questioned.

Tests performed under optimized laboratory conditions are criticized with respect to their environmental relevancy, more precisely: "*they are not designed to predict biodegradation kinetics in environmental compartments, due to their unrealistic high-test concentrations, inoculum concentrations and higher temperatures, compared to nature*" (Gartiser et al., 2017). The clear gap between the laboratory and environmental circumstances is self-evident. Laboratory conditions are well-defined, controlled, and reproducible, while when plastics end up in the environment, they are exposed to the interplay of multivariable factors. Moreover, the presence of microorganisms is the fundamental component of the process, where replication of the microbial population, diversity, and dynamics from the field to the lab is an unfeasible task (Ghosh & Jones, 2021). Another concern arises when it is recognized that, in the absence of alternative nutrients, the polymer may not be the preferred feedstock in a natural environment. Another concern arises when it is recognized that plastic may not be the preferred feedstock in the environment due to the availability of alternative nutrients. Although laboratory inoculum has the potential to biodegrade plastics, these tests were limited to the incubated microorganisms where the plastic product was the microorganism's sole carbon source (Ru et al., 2020). This misalignment between laboratory and field conditions can be illustrated by the example of the industrial compost environment in Figure 12.

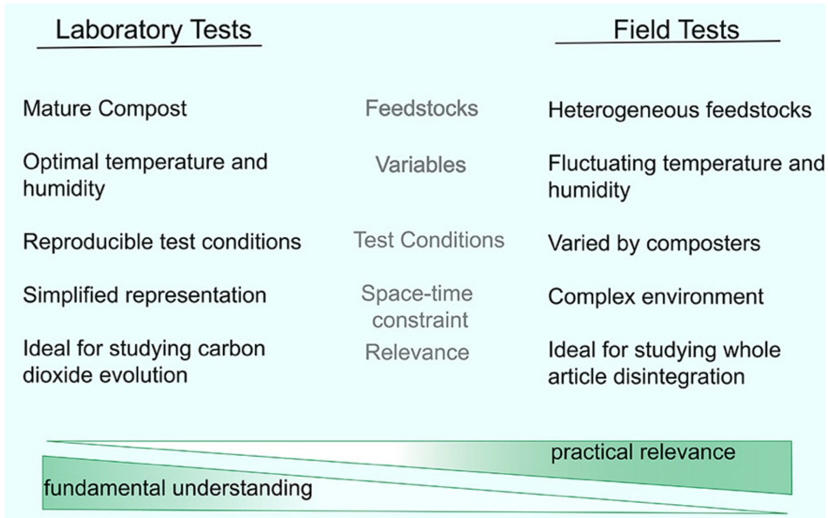


Figure 12: Gap between the laboratory and field tests relevant to the composting environment (Ghosh & Jones, 2021).

The to-be-tested material requires specific preparations prior to performing the laboratory tests according to the specified biodegradability standards. For instance, ISO describes in ISO 10210 methods for the preparation of test samples used to determine the ultimate aerobic and anaerobic biodegradability of plastic materials in an aqueous medium, soil, controlled compost, or anaerobic digesting sludge. These standards include ISO 14851, ISO 14852, ISO 14853, ISO 14855-1, ISO 14855-2, ISO 15985, and ISO 17556. The indicated procedures are intended to ensure dimensional consistency of test samples across standards, which will improve the reproducibility of the test results in determining the ultimate biodegradability of the concerned product (*ISO 10210:2012*, 2012).

The test material is made into sheets, films, pellets, granules, or powder. A sheet is a planar product of a limited maximum thickness, typically ranging from 0,5 mm to 3 mm. A film is again a thin planar product of a limited maximum thickness, typically ranging from 0,01 mm to 0,3 mm. A pellet is a small mass having relatively uniform dimensions in any given batch, with an average diameter ranging from 1 mm to 5 mm. A granule is a relatively small particle with an average diameter ranging from 0,1 mm to 3 mm. Finally, the powder is defined as a very fine particulate material smaller than granules with an average diameter ranging from 0,01 mm to 0,1 mm. This way, test samples with a uniform surface area are obtained using the predefined preparation processes. Although comparison of biodegradability results is facilitated in this manner, products will never undergo such a uniform size reduction when left in the open environment (ISO 10210:2012, 2012).

As the biodegradation process of plastic products is slow and natural, the general time frame for evaluating biodegradability ranges from months to years. According to the ISO, ASTM, CEN, and DIN standards, the running time for ultimate biodegradation should not exceed six months but may be extended to 24 months, where the required percentage of biodegradation is 90%, absolute or relative (Pires et al., 2022). More specifically, for the test samples, the percentage of biodegradation shall be either 90% in total or 90% of the maximum degradation of a suitable reference substance. However, a lack of predictability exists whether the plastic product will eventually reach 100% biodegradation in the open environment within a specific time frame. If the percentage of biodegradation remains 90% in actual environmental conditions, MP pollution could still be the consequence. Moreover, the test sample may achieve 90% under, e.g., soil conditions; however, littering alters degradation rates and fate in different environments (Ghosh & Jones, 2021).

Because the general test methods entail incubating a plastic material with microorganisms, only limited extrapolation methods are possible: those related to the material, the microorganisms, or the reaction products (van der Zee, 2014). This results in four common approaches for measuring biodegradation processes. Before choosing one of the different approaches, one should consider the closeness of fit between the material and the biodegradability the measurement will provide.

1) Gas (CO_2 and CH_4) evolution
2) O_2 (BOD and COD) demand
3) Mass loss
4) Visual analysis

A direct measure of mineralization is the evolution of CO_2 and CH_4 from a material. As a result, gas evolution tests are considered valuable tools in determining the biodegradability of plastic.

Aerobic microbial activity is generally characterized by oxygen consumption. However, the amount of oxygen consumed (BOD or COD) during incubation is considered a nonspecific, indirect measure for biodegradation. Moreover, because the test materials must be the sole carbon/energy source for the microorganisms during incubation, using oxygen measurements in complex natural environments is redundant.

Mass loss is also an indicator of biodegradation and is measured by the decrease in molecular weight, the experimental mass loss, or the disintegration rate. However, these measurements are not suitable for determining mineralization rates. Mass loss methodologies are only used on plastic fragments retrieved from the sample and are generally not smaller than 2 mm, leaving the generation of MPs out of account.

Inspection of surface conditions in the tested material is not listed as mandatory analysis in standards for biodegradability. Visual assessment measures generally include the deterioration of the material and signs of microbial colonization on the material;

however, this merely indicates that microorganisms can grow on the plastic (Ruggero et al., 2019).

3.4.3 Labels

In order to identify the type of plastic material used in a product, labels can be used to distinguish between different types. In addition, labels help consumers distinguish between different types of plastic and understand how to dispose of it after use properly. Because bio-based and fossil-based plastics present similar visual features, it can be difficult for consumers to differentiate between them. However, since the biodegradable property is not universally defined, labels need to be tied to standards and certification systems to have a meaningful significance. Therefore, biodegradability does not ensure that the product will fully biodegrade in the natural environment (van den Oever et al., 2017).

There are currently five institutes that provide certification for the biodegradation of plastic products; however, there is no official reciprocal recognition of these certificates.

(1) TÜV Austria (Belgium) for biobased, home composting, industrial composting, soil, water, and marine
(2) DIN CERTO (Germany) for home composting, industrial composting, and soil
(3) Biodegradable Products Institute (BPI) (USA) for industrial composting
(4) Japan BioPlastics Association (JBPA) for industrial composting
(5) Australasian Bioplastics Association (ABA) for home composting and industrial composting

TÜV Austria is the only organization that offers a certification on biodegradability, distinguishing three different areas in the open environment. This certifier recognizes that biodegradation in the open environment is impossible to define as such and that soil, water, or marine environment must be specified instead (*OK Biodegradable*, n.d.). The distinguished environments and their appurtenant labels are described as follows:

The OK Biodegradable SOIL label indicates: "*The OK biodegradable SOIL is a guarantee that a product will completely biodegrade in the soil without adversely affecting the environment*" (*OK Biodegradable*, n.d.).

Figure 13: TÜV Austria OK biodegradable SOIL label (OK Biodegradable, n.d.).

Applicable standards for the OK Biodegradable SOIL label include all the standards in Table 1.

Table 1: Applicable standards for the OK Biodegradable SOIL label provided by TÜV Austria (OK Biodegradable, n.d.).

Standard	Description
EN 13432	Packaging – Requirements for packaging recoverable through composting and biodegradation – Test scheme and evaluation criteria for the final acceptance of packaging
EN 14995	Plastics — Evaluation of compostability — Test scheme and specifications
ISO 17556	Plastics — Determination of the ultimate aerobic biodegradability of plastic materials in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved
ISO 11266	Soil quality – Guidance on laboratory testing for biodegradation of organic chemicals in soil under aerobic conditions
ISO 14851	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium — Method by measuring the oxygen demand in a closed respirometer
ISO 14852	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium — Method by analysis of evolved carbon dioxide
EN 29408	Water quality – Evaluation in an aqueous medium of the "ultimate" aerobic biodegradability of organic compounds – Method of determining the oxygen demand in a closed respirometer
EN 29439	Water quality – Evaluation in an aqueous medium of the "ultimate" aerobic biodegradability of organic compounds – Method by analysis of released carbon dioxide
ISO 9408	Water Quality — Evaluation of ultimate aerobic biodegradability of organic

	compounds in an aqueous medium by determination of oxygen demand in a closed respirometer
ISO 9439	Water Quality — Evaluation of ultimate aerobic biodegradability of organic compounds in an aqueous medium — Carbon dioxide evolution test
ASTM D5271	Standard Test Method for Determining the Aerobic Biodegradation of Plastic Materials in an Activated-Sludge-Wastewater-Treatment System
ASTM D5988	Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in Soil
OECD 301 C	(MITI) Biodegradation Test – Aquatic respirometry
OECD 301 B	Biodegradation Test – CO_2 Evolution (Modified Sturm Test)
ASTM D6691	Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in the Marine Environment by a Defined Microbial Consortium or Natural Sea Water Inoculum
OECD 208	Terrestrial Plant Test - Seedling Emergence and Seedling Growth Test
EN 13193	Packaging – Packaging and the Environment – Terminology
EN 13137	Characterization of waste – Determination of total organic carbon (TOC) in waste, sludges, and sediments

The OK biodegradable WATER indicates: "*Products certified for OK biodegradable WATER guarantee biodegradation in a natural freshwater environment, and thus substantially contribute to the reduction of waste in rivers, lakes, or any natural fresh water*" (*OK Biodegradable*, n.d.).

Figure 14: TÜV Austria OK biodegradable WATER label (OK Biodegradable, n.d.).

Applicable standards for the OK Biodegradable WATER label include all the standards in Table 2.

Table 2: Applicable standards for the OK Biodegradable WATER label provided by TÜV Austria (OK Biodegradable, n.d.).

Standard	**Description**
EN 13432	Packaging – Requirements for packaging recoverable through composting and biodegradation – Test scheme and evaluation criteria for the final acceptance of packaging
EN 14995	Plastics — Evaluation of compostability — Test scheme and specifications
ISO 14851	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium — Method by measuring the oxygen demand in a closed respirometer
ISO 14852	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium — Method by analysis of evolved carbon dioxide
EN 29408	Water quality – Evaluation in an aqueous medium of the "ultimate" aerobic biodegradability of organic compounds – Method of determining the oxygen demand in a closed respirometer
EN 29439	Water quality – Evaluation in an aqueous medium of the "ultimate" aerobic biodegradability of organic compounds – Method by analysis of released carbon dioxide
ISO 9408	Water Quality — Evaluation of ultimate aerobic biodegradability of organic compounds in an aqueous medium by determination of oxygen demand in a closed respirometer
ISO 9439	Water Quality — Evaluation of ultimate aerobic biodegradability of organic compounds in an aqueous medium — Carbon dioxide evolution test
ASTM D5271	Standard Test Method for Determining the Aerobic Biodegradation of Plastic Materials in an Activated-Sludge-Wastewater-Treatment System
OECD 301 C	(MITI) Biodegradation Test – Aquatic respirometry
OECD 301 B	Biodegradation Test – CO2 Evolution (Modified Sturm Test)
ASTM D6691	Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in the Marine Environment by a Defined Microbial Consortium or Natural Sea Water Inoculum

EN 14987	Plastics - Evaluation of disposability in wastewater treatment plants - Test scheme for final acceptance and specifications
EN 13193	Packaging – Packaging and the Environment – Terminology
EN 13137	Characterization of waste – Determination of total organic carbon (TOC) in waste, sludges, and sediments

The OK biodegradable MARINE label indicates: "*Considering the fact that most of the marine debris is land-based, marine biodegradability is an added value to any product, regardless of where it is consumed*" (*OK Biodegradable*, n.d.).

Figure 15: TÜV Austria OK biodegradable MARINE label (OK Biodegradable, n.d.).

Applicable standards for the OK Biodegradable MARINE label include all the standards in Table 3.

Table 3: Applicable standards for the OK Biodegradable MARINE label provided by TÜV Austria (OK Biodegradable, n.d.).

Standard	**Description**
ASTM D6691	Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in the Marine Environment by a Defined Microbial Consortium or Natural Sea Water Inoculum
OECD 202	*Daphnia sp.*, Acute Immobilization Test
ASTM D6400	Standard Specification for Labeling of Plastics Designed to be Aerobically Composted in Municipal or Industrial Facilities
EN 13193	Packaging – Packaging and the Environment – Terminology
EN 13137	Characterization of waste – Determination of total organic carbon (TOC) in waste, sludges, and sediments
EN 13432	Packaging – Requirements for packaging recoverable through composting and biodegradation – Test scheme and evaluation criteria for the final acceptance of packaging

OPPTS 850.1010	Aquatic Invertebrate Acute Toxicity Test, Freshwater Daphnids
OPPTS 850.1075	Fish Acute Toxicity Test, Freshwater, and Marine
OECD 203	Fish, Acute Toxicity Test
OPPTS 850.5400	Algal Toxicity, Tiers I and II
OECD 201	Freshwater Alga and Cyanobacteria, Growth Inhibition Test
OECD 306	Biodegradability in Seawater
ISO 16221	Water quality — Guidance for the determination of biodegradability in the marine environment
ISO 18830	Plastics — Determination of aerobic biodegradation of non-floating plastic materials in a seawater/sandy sediment interface — Method by measuring the oxygen demand in a closed respirometer

Labels are an essential tool allowing communication towards consumers and business clients about a particular fact. Because the communication about the biodegradability of plastics is of a complex nature, labels attempt to simplify it, which can be regarded as greenwashing as it can lead to misleading information. For instance, the EN 13432 standard is applicable for all three labels certifying biodegradability in distinct environments. However, this standard implies the plastic product in question is compostable in an industrial facility; it does not mean the plastic product is biodegradable in the open environment. A consumer may misinterpret the claim, which is an undesirable outcome. Therefore, a clear distinction must be made between biodegradable products destined for biodegradation in the open environment and biodegradable products destined for industrial composting. Industrial composting provides ideal and steady conditions rather than uncertain circumstances in the open environment (SAPEA, 2020).

BDP products destined for biodegradation in the open environment may be certified for one specific environment but could end up in a different environment, as products may pass through multiple environments. On such occasions, the obtained certification is not applicable to the receiving environment, resulting in deviations from the expected biodegradation rate. This uncertainty arises from the wide range and complex interplay of environmental factors influencing the biodegradation rate.

There are several strategies to prevent such misinterpretations. According to a survey conducted by Environmental Protection Agencies (EPAs), BDP product labels should provide clear instructions on how to dispose of the product after use (EPA Network, 2018). Another option is prohibition. For instance, the State of California acknowledges the complex nature of the biodegradation process and that most plastic products will pass through multiple environments. Given these and other constraints and the environmental impact induced by plastic litter, the use of terms such as 'biodegradable' is prohibited until the ASTM provides a standard approved by legislation (*California Law - CHAPTER 5.7. Products [42355 - 42358.5],* 2022). Standards offer another means of improvement. As an international guideline, ISO established a sequence of "Environmental Labels and Declarations." These include self-asserted claims (ISO 14021), environmental labeling (ISO 14024), and declarations (ISO 14024) (SAPEA, 2020).

4. Artificial Grass Infill Material

Due to the emergence of third-generation (3G) synthetic grass fields, consisting of three elements: synthetic turf, sand infill, and rubber infill, artificial grass fields have become an appropriate alternative to natural grass fields to preserve good sport performance. Artificial grass fields must possess the playing characteristics required by the players to ensure comfort and protection during walking, running, falling, and sliding on the surface. The artificial grass usually has a length of 40 to 65 mm, where the gaps between the sprays are filled with the infill material to maintain the sprays in an upright position (*Synthetic Turf FAQs*, 2019). Figure 16 provides a schematic representation of the aforementioned 3G synthetic turf system.

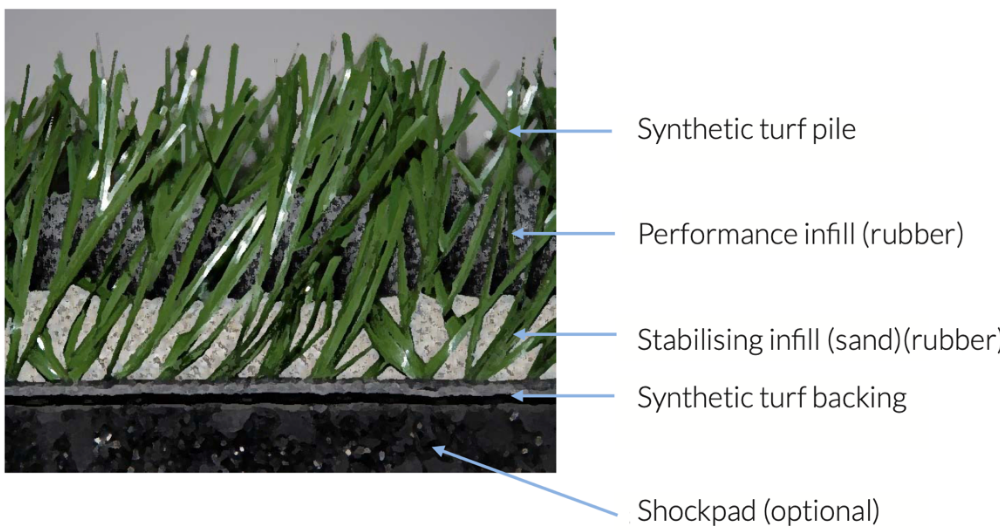


Figure 16: Schematic representation of 3G synthetic turf system (Synthetic Turf FAQs, 2019).

As well as other conventional plastics, rubber tends to accumulate in the environment for an extended period. Rubber is a waterproof material because its entangled hydrocarbon chains exhibit no affinity to water. Scientists have produced synthetic rubbers to meet specific requirements by resembling nature. Like natural rubber, these materials possess similar properties, such as being elastic and waterproof. However, they also contain improved properties: they are tougher, more flexible, and more durable than natural rubber. As most rubbers are soft and sticky, they are hardened by vulcanization, which is the process of heating rubber with sulfur. The disulfide bonds between the polymer chains are cross-linked when rubber is heated with sulfur. As a result, the vulcanized chains form one large molecule that is linked by covalent bonds. Due to double bonds, the chains have bends and kinks, allowing them to stretch. When rubber is stretched, the cross-linking keeps it from tearing; the cross-linking also ensures that the material returns to its original shape when the stretching force is removed. The amount of sulfur used during vulcanization is adjusted to alter the physical properties of rubber (Bruice, 2015).

Generally, the rubber granules used as artificial grass infill material are obtained from discarded end-of-life tires (ELTs) cut into smaller pieces. One of the most common synthetic rubber polymers used in tire manufacturing is Styrene-Butadiene-Rubber (SBR), which refers to the chemical composition of the copolymer, consisting of styrene and butadiene. Among vulcanization of sulfur and several other additives used in SBR today, some of the key additives include the following: fillers such as carbon black, China clays, silicas, calcium carbonates, and stabilizers such as antioxidants and antiozonants. Moreover, the granules obtained from ELTs also contain substances such as Polycyclic aromatic hydrocarbons (PAHs), phthalates, and certain heavy metals that adversely affect the environment and human health (*Rubberkorrels en -strooisel op sport- en speelvelden - ECHA*, n.d.) (Celeiro et al., 2021) (Bocca et al., 2009). In Europe, the Registration, Evaluation, Authorization, and Restriction of Chemicals organization (REACH) sets certain concentration limits on these harmful substances. It should be noted, however, that these concentrations are often attained or exceeded for certain chemicals and metals in the rubber granules (*Rubberkorrels en -strooisel op sport- en speelvelden - ECHA*, n.d.) (Diekmann et al., 2019).

Several thousands of tons of rubber granules end up in the environment every year, contributing to MP pollution as they can spread into the environment around the artificial grass fields through, e.g., rainwater or player's footwear and clothing. Senbis has developed a fully in-soil biodegradable grass infill for artificial grass fields as an alternative to the currently used SBR granules. Senbis' primary ground for developing GreenFill was to create an infill that does not pollute the environment around artificial grass fields with MPs. As a result, the product was created to be completely biodegradable in soil. In addition, the GreenFill can be completely composted in an industrial composting facility after its functional life. The granules were extensively tested in independent laboratories on (eco)toxicology; no PAHs or other hazardous substances, according to the REACH, were detected in the product (*Biodegradable Grass Infill - GreenFill*, 2022). GreenFill is composed of biodegradable polyesters; however, due to confidentiality reasons, Senbis was reluctant to share the exact polymer composition. In an attempt to compare the plastic structure of SBR with the GreenFill granules, the biodegradable polyester polyhydroxyalkanoate (PHA) is taken as an example of a polymer that could be found in GreenFill.

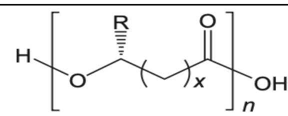
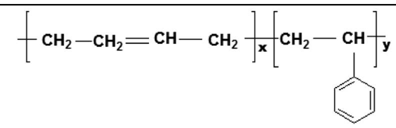

Figure 17: GreenFill granules (left) and SBR ELT granules (right) (Biodegradable Grass Infill - GreenFill, 2022) (Styrene-Butadiene Rubber | Chemical Compound, n.d.).

PHAs are polyesters produced by various microorganisms through bacterial fermentation of sugars and lipids and serve as carbon and energy storage. PHA molecules are of sufficient molecular weight and exhibit characteristics closely resembling some common petrochemical plastics (Naser et al., 2021). PHA monomers have been found in over 150 distinct forms, making them the most diverse category of biodegradable polyesters. PHAs are categorized based on the number of carbon atoms in their monomers. Short-chain length PHAs (scl-PHAs) have 4 or 5 carbon atoms in their repeating monomers, whereas medium chain length PHAs (mcl-PHAs) have 6 to 15 carbon atoms in their repeating monomers. The most common commercially available example of scl-PHAs is polyhydroxy butyrate (PHB), whereas for mcl-PHAs, it is Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) (Girdhar et al., 2013).

Several studies have reported PHAs to be highly biodegradable in a wide range of environmental conditions, including soil, aerobic and anaerobic sludge, marine, and freshwater environments. Overall, the biodegradability of PHAs is determined by (1) the composition and structure of the material (crystallinity, molecular weight, copolymer composition, chain mobility, hydrophilicity, and stereochemistry) and (2) the environmental conditions in which the material is released (temperature, pH, moisture content, nutrition supply, and microbial population) (Naser et al., 2021). Due to a number of unfavorable properties, PHAs have a limited range of applications. For instance, PHB's high degree of crystallinity gives rise to poor mechanical properties. Moreover, in terms of biodegradability, the slow rate of degradation and hydrophobic character of unmodified PHAs is unfavorable. Therefore, using PHAs as direct substitutes for conventional plastics continues to be a serious challenge. In order to meet specific applications, PHAs must be modified to obtain improved performance in mechanical properties, degree of crystallinity, hydrophilicity, and rate of degradation. For example, PHBV is formed by the addition of 3-hydroxyvalerate (HV) to PHB, where HV has a greater amorphous region, which is more susceptible to enzymatic attack. The amorphous regions can be altered by changing the copolymer mixture, and the resulting decreased degree of crystallinity in the copolymer directly leads to higher enzymatic activity. The ongoing development of PHAs, including PHA blends and composites, presents the potential for a broader set of applications (Meereboer et al., 2020).

According to the explained characteristics, it is understandable that companies are converting their raw material from the synthetic SBR into other 'more eco-friendly' materials. In this case, a biodegradable polyester is a viable option. Therefore, we attempted to compare the properties of SBR and biodegradable polyester (as PHA), as shown in Table 4.

Table 4: Comparison of the PHA and SBR properties (EduPack, C. E. S., 2014).

Parameter	PHA	SBR
Molecular Structure		
Composition	Linear polyesters composed of 3-hydroxy fatty acid monomers	Copolymer consisting of 25% styrene and 75% butadiene
Crystallinity	60% (as PHB homopolymer, incorporating monomers such as HV decreases the degree of crystallinity) (Dalton et al., 2022)	Does not crystallize due to its irregular molecular structure (*Styrene-Butadiene Rubber | Chemical Compound*, n.d.)
Tensile Strength	35 – 40 MPa	16 – 26 MPa
Elongation	6 – 25%	320 – 550%
Melting Temperature, T_m	171 – 182 °C	450 °C
Glass Transition Temperature, T_g	12 – 15 °C	-62 – -52°C
Biodegradability	Yes	Backbone chains remain intact, cross-linked suflur bonds can be cleaved
End-of-Life Options	Downcyclable, combustible for energy recovery, landfillable, and recyclable and biodegradable	Downcyclable and combustible for energy recovery and landfillable
Toxicity	Nontoxic additives	Exert toxic effects from additives and MP residues
Generation of MP Residue	Yes (upon inappropriate disposal)	Yes
Compostability	Yes, at an industrial composting facility	No

The CES EduPack software has been used to obtain the material properties of unfilled PHA and SBR reinforced with 30% carbon black. As demonstrated in several studies, the biodegradation rate decreases with an increasing degree of crystallinity, crystal size, and T_g. The glass transition temperature, T_g, is closely related to the mobility of the polymer chains, which determines the toughness, among other properties of the PHA polymers. Comparing the data regarding crystallinity and the T_g of both materials, SBR seems to be the more viable option to undergo biodegradation. However, as previously stated, PHA needs to be blended into a copolymer to generate fewer crystalline regions, enhance biodegradation, and be applicable for certain applications (Girdhar et al., 2013).

PHA is a biodegradable material, whereas SBR can only be downcycled; moreover, a key advantage of PHAs is that they are not considered to produce toxic biodegradation residues (Meereboer et al., 2020). Furthermore, when comparing the molecular structures of the two materials, it is observed that the backbone structure contains hydrolyzable bonds, unlike SBR. This does not imply that these bonds undergo bond cleavage in the environment; instead, because carbon-carbon bonds are exceptionally stable, polymers that lack chemical bonds that are easily cleaved do not biodegrade (SAPEA, 2020).

4.1 GreenFill Biodegradable Grass Infill

Senbis has commissioned the external testing institute Organic Waste Systems (OWS) in Belgium to perform tests on the product GreenFill. All biopolymers used to produce GreenFill have been certified by TÜV Austria with the OK Home Compost label. This means the following tests have been conducted on the biopolymers:

- Test on disintegration, the physically falling apart of the product in smaller fragments
- Test on biodegradation, the chemical breakdown of the polymer
- Test on the heavy metal content
- Test on ecotoxicity to ensure the product does not exert any adverse effect on plants conform to EN 13432

Moreover, Senbis states GreenFill is biodegradable in soil within six months, according to ISO 17556: "*Plastics – Determination of the aerobic biodegradability of plastic materials in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved.*" The test results obtained by OWS were shared with TÜV Austria, and the certification for their OK Biodegradable SOIL was received (*Biodegradable Grass Infill - GreenFill*, 2022).

This international standard specifies a test protocol for the determination of the complete aerobic biodegradability of plastics in soil, where ultimate biodegradability is defined as the breakdown of an organic compound by microorganisms in the presence of oxygen into carbon dioxide, water and mineral salts or any other elements present (mineralization) plus new biomass. It states that the test environment should be maintained constant at a temperature of 25 °C within a range of ± 2°C. Moreover, ISO 17556 states: "*The test material should preferably be used in powder form, but it may also be introduced in the form of films, fragments or shaped articles*" (*ISO 17556:2019*, 2019). This international standard test protocol aims to verify a plastic material's intrinsic biodegradability by measuring the biodegradation under ideal circumstances rather than the environmental impact of a plastic product.

The GreenFill product was pretreated prior to testing, as the granules were made into powders. Therefore, the biodegradability of the GreenFill product as a whole will be evaluated under laboratory conditions in a first experiment. GreenFill will be used as a grass infill at sporting facilities. Between 1 and 5% of the infill is lost annually (Hann et al., 2018); the lost infill will mainly appear in soil and drainage canals sediments typically surrounding sporting facilities. As the granules may also end up in the laundry machine carried by the player's footwear and clothing, the lost infill could also appear in both aerobic and anaerobic sludge. GreenFill is claimed to be biodegradable in soil, where bacteria and fungi convert the infill into H_2O, CO_2, and humus. The biodegradation process goes faster under the higher availability of energetic organic material and higher temperatures. The assumption that the bacteria in all four environments will break down the GreenFill granules will be tested at two different temperatures.

4.2 Experimental Setup

4.2.1 Materials and Sample Preparation

To measure the biodegradability of the Greenfill in various environments, a test was designed using four distinct inocula: soil, drainage canal sediment, aerobic sludge, and anaerobic sludge, at two temperatures, 25 °C and 37 °C, resulting in eight different treatments. Two different temperatures were taken to increase the potential of finding bacteria that are able to break down the GreenFill granules, selecting the bacterial populations that thrive at 25 °C and 37 °C. The well-defined biodegradable polymer PHA is used as reference material in the configuration of PHA granules, resulting in 16 different treatments.

To ensure an abundant development of microorganisms, the inocula were enriched by the addition of essential elements for growing the bacteria. Bacteria require carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphate (P), sulfur (S), and some metal ions like iron (Fe), calcium (Ca), and magnesium (Mg) and trace elements, which are nutritional elements that are required in very small quantities for the proper growth of an organism. Assumed is that the bacteria will consume the GreenFill or the PHA as a carbon source. Therefore, no other carbon source is required, and only some glucose ($C_6H_{12}O_6$) is added to initiate the process. Bacteria require nitrogen to produce proteins; therefore, nitrogen is added as ammonium sulfate ($(NH_4)_2SO_4$). The addition of ammonium sulfate is, besides a source of nitrogen, a source for sulfur, which assists bacterial growth. Phosphate is used in the production of ATP, an essential energy source and building block for DNA, and is added in the form of monosodium phosphate (NaH_2PO_4) and dipotassium phosphate (K_2HPO_4). To ensure the proper functioning of enzymes as catalysts, the metal ions magnesium and calcium are added in the form of magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$), and some trace elements too (vishniac). All of this is added to the inocula to ensure that the only limiting factor will be either GreenFill or PHA for the development of the bacteria that originate from the tested inocula. The concentrations of the added chemical substances to one liter of H_2O are enlisted in Table 5.

Table 5: Chemical concentrations added to the inocula.

Chemical Substance	**Concentration**
Yeast extract	0,1 g/l
Glucose, $C_6H_{12}O_6$	0,2 g/l
Ammonium sulfate, $(NH_4)_2SO_4$	1 g/l
Monosodium phosphate, NaH_2PO_4	1,5 g/l
Dipotassium phosphate, K_2HPO_4	4,5 g/l
Magnesium chloride, $MgCl_2$	0,2 g/l
Calcium chloride, $CaCl_2$	0,1 g/l
Vishniac (trace element)	1 ml/l

20 ml of the obtained solution is added to all 16 centrifuge tubes, along with a small sample of the to-be-tested environment and ten either GreenFill or PHA granules. During stationary incubation, four centrifuge tubes containing the GreenFill granules and four centrifuge tubes containing the PHA granules were preserved at 25 °C. The remaining eight centrifuge tubes containing either the GreenFill or the PHA granules were preserved at 37 °C, also under stationary incubation.

After 14 days of incubation, a small drop of the solution is taken out of each centrifuge tube to be viewed under the microscope in order to determine the presence or absence of microorganisms. A phase-contrast microscope (PCM) is used; this is an optical microscopy technique in which phase shifts in the light passing through the specimen are translated into brightness fluctuations throughout the image. In the presence of microorganisms in the specimen, some light is scattered, making these visible in black-colored configurations. The obtained images were subjected to a magnification of 400 and are depicted in the tables below.

Table 6: Microscopic images of the incubated inocula with the GreenFill granules at 25 °C.

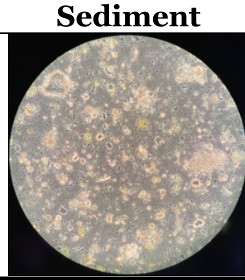
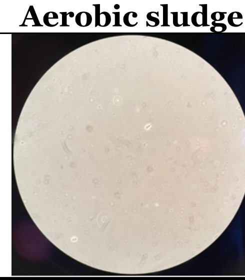
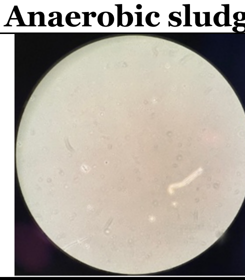
Soil	**Sediment**	**Aerobic sludge**	**Anaerobic sludge**
			

Table 7: Microscopic images of the incubated inocula with the PHA granules at 25 ℃.

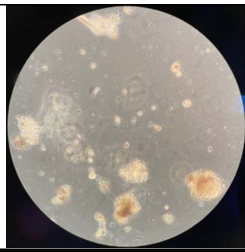
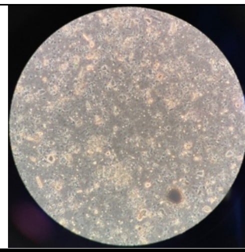
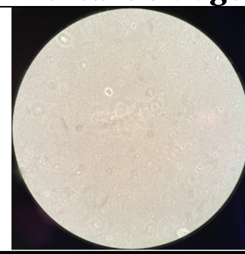
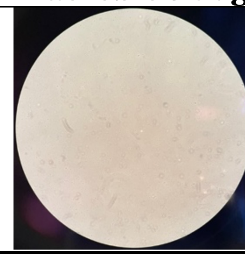
Soil	Sediment	Aerobic sludge	Anaerobic sludge
			

Table 8: Microscopic images of the incubated inocula with the GreenFill granules at 37 ℃.

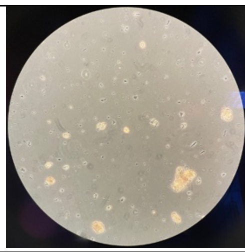
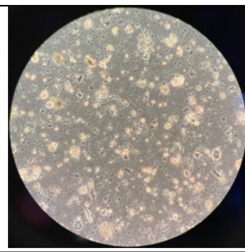
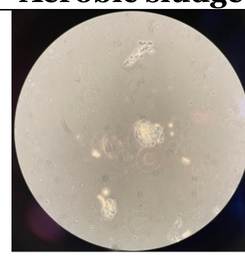
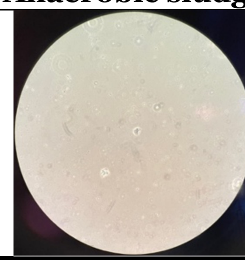
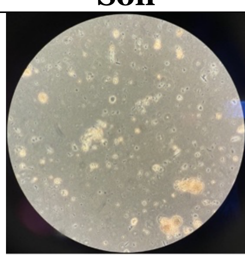
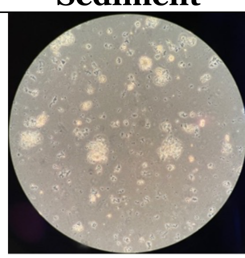
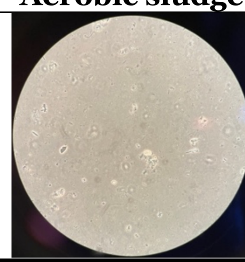
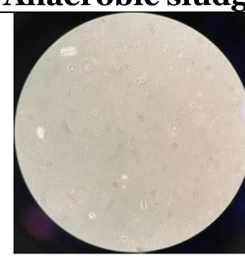
Soil	Sediment	Aerobic sludge	Anaerobic sludge
			

Table 9: Microscopic images of the incubated inocula with the PHA granules at 37 ℃.

Soil	Sediment	Aerobic sludge	Anaerobic sludge
			

Each microscopic image exhibits the presence of microorganisms, which entails the microorganisms were able to grow with the GreenFill, or PHA granules, as a carbon source. As some glucose was added to the inocula, the observed microbial growth could be the consequence of the glucose uptake as a carbon source. After another 14 days of stationary incubation, the GreenFill and PHA granules were separated from the solution in order to measure mass loss as an index of biodegradation. Prior to weighing the granules, they were collected and stored in an oven with a temperature of 105 °C to ensure only dry matter was incorporated and not any absorbed water.

4.2.2 Results and Discussion

After inspection of any surface changes in the product samples, no visible degradation phenomena were detected. As the GreenFill and PHA granules are not identical, an average of their mass is taken to analyze their mass loss after 28 days of incubation. For the GreenFill granules, the average weight (MGreenFill) of ten granules is 80,2 mg, whereas for the PHA granules, the average weight (MPHA) of ten granules is 232,3 mg. The following figures represent the specific mass losses for both the GreenFill and PHA granules after 28 days of incubation in four distinct environments and two distinct temperatures.

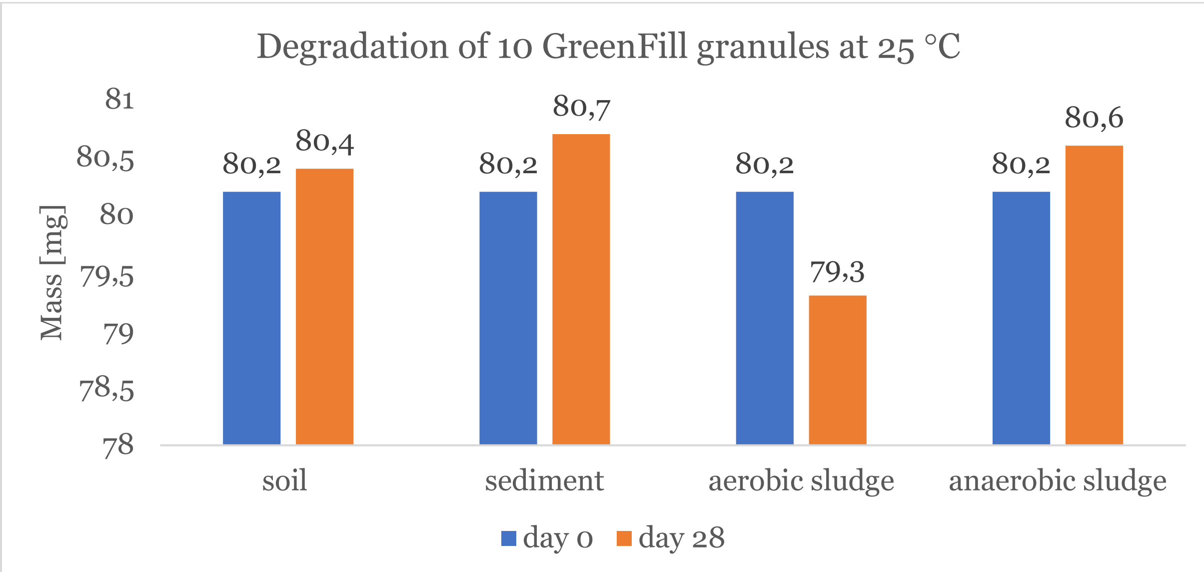


Figure 18: Degradation of 10 GreenFill granules at 25 °C.

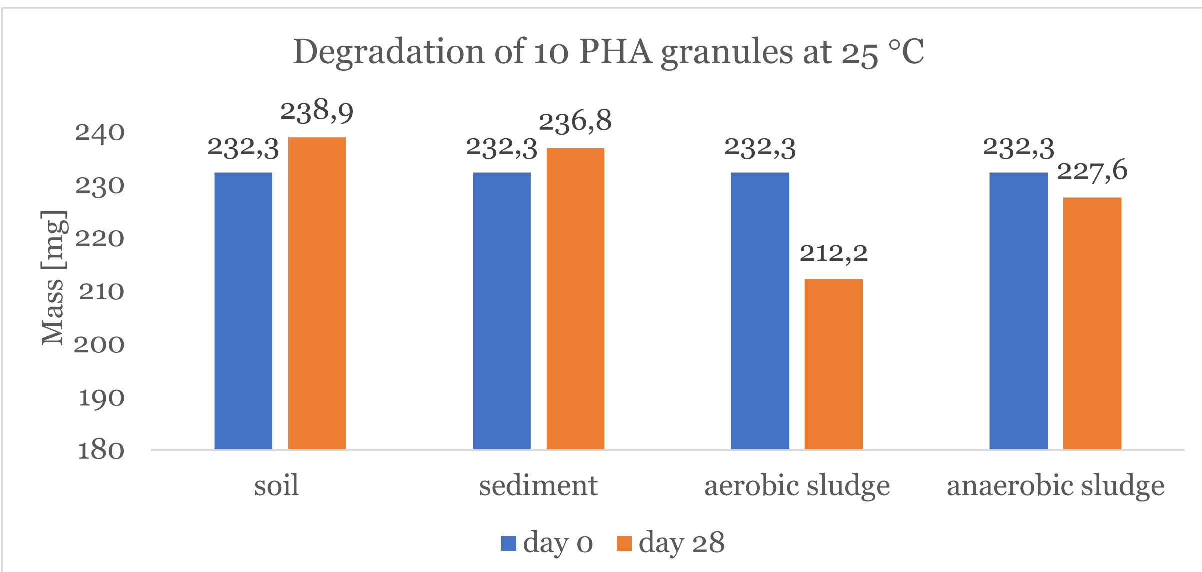


Figure 19: Degradation of 10 PHA granules at 25 °C.

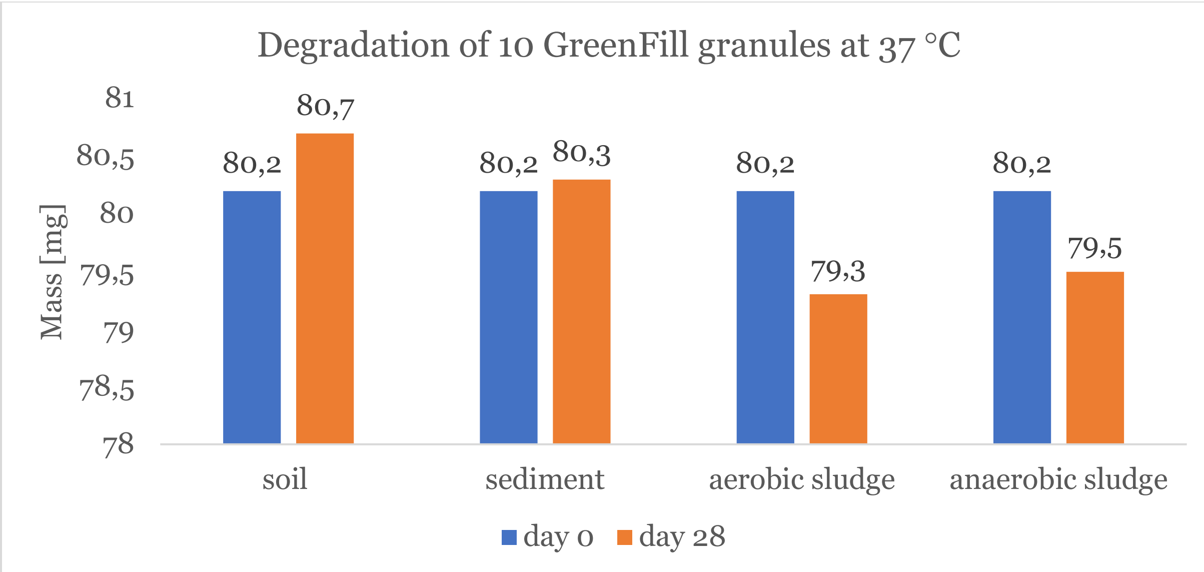


Figure 20: Degradation of 10 GreenFill granules at 37°C.

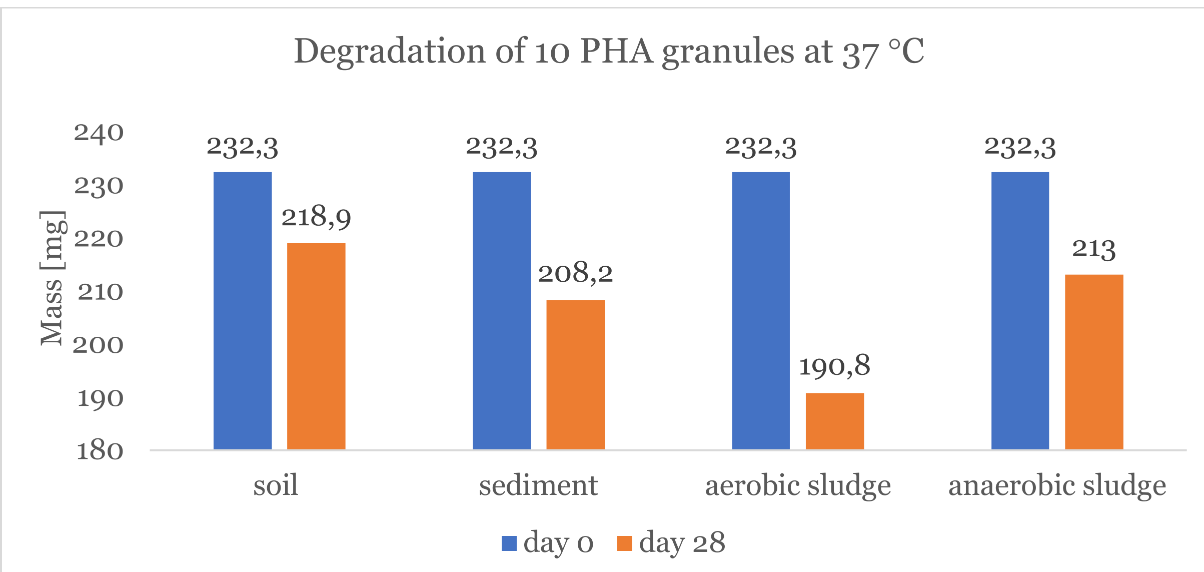


Figure 21: Degradation of 10 PHA granules at 37°C.

$\bar{M}_{\text{GreenFill}}$ of 10 GreenFill granules equals 80,2 mg; however, not all obtained results exhibit mass loss after 28 days of incubation. The GreenFill granules incubated in soil, sediment, and anaerobic sludge at 25 °C and soil and sediment at 37 °C even exhibit an increase in mass. There are several explanations for the results to be opposite to what was assumed. Since not all GreenFill granules do not have identical masses, an average was taken; instead, higher accuracy could have been obtained if the to be incubated granules were weighed prior to incubation. Second, working with small masses, the deviating results could be the consequence of an instrument error, referring to an error in the measuring device, such as sensitivity to fluctuations in the air stream. Another explanation could be that during the oven storage, not all (if any) water absorbed by the granules was evaporated, increasing mass. Finally, microorganisms accumulate on a polymer's surface during the biodegradation process. This is an intermediate step before complete biodegradation, resulting in biofilm formation and increasing the mass of the granules. On the contrary, the GreenFill granules incubated in aerobic sludge exhibit the highest degree of mass loss at both temperatures, potentially indicating that the microbial population in aerobic sludge readily degrades the polymer composition present in the GreenFill product.

$\bar{M}_{\text{PHA}}$ of 10 PHA granules is equal to 232,3 mg; again, not all obtained results exhibit mass loss after 28 days of incubation. The PHA granules incubated in soil and sediment at 25 °C exhibit an increase in mass. The mentioned explanations for the increase in mass of the GreenFill granules also hold for the increase in mass of the PHA granules. Moreover, a significant discrepancy in results is observed between both materials. Since an average weight is taken, this could be the consequence of the fact that the PHA granules are substantially less similar to each other compared to the GreenFill granules, which is apparent in Figure 22.

Figure 22: GreenFill granules (left) and PHA granules (right) (Biodegradable Grass Infill - GreenFill, 2022) (Zylberberg, 2021).

The assumption that the bacteria in all four environments will break down the GreenFill granules cannot be acknowledged. Mass loss is only observed for the GreenFill granules incubated in aerobic sludge at 25 °C and in aerobic and anaerobic sludge at 37 °C. The PHA granules used as reference material demonstrate mass loss in aerobic and anaerobic sludge at 25 °C and in all four environments at 37 °C. Because the well-defined biodegradable polymer PHA was used as reference material in the physical form and size comparable to that of GreenFill, it could indicate that the GreenFill granules are less readily biodegradable in the environment than their current certification suggests.

The uncertainty in the obtained experimental results can be allocated to the several mentioned uncertainties related to the experimental inputs. These include the uncertainty created by taking an average weight of the granules, potential error in the measuring device, and a failed dry matter determination. Moreover, 28 days of incubation is not a feasible time frame to determine complete biodegradation. In this case, the granules' weight could be attributed to potential biofilm formation on the product's surface, which is an intermediate step in the biodegradation process. Finally, on the field, the GreenFill can be mechanically degraded due to tear and wear from the players, resulting in mechanically degraded granules ending up in the environment. Non-weathered granules were utilized in this experiment but weathered granules could be a more viable option for obtaining more realistic results.

4.2.2 Further Experimentation

To ensure an abundant development of microbial growth, essential nutrients for microorganisms were included in the centrifuge tubes. Among others, glucose was added to the solution to assist the bacteria in initiating the biodegradation process. The only carbon source available to the bacteria is GreenFill or PHA when the glucose runs out. At this point, the bacteria that can break down these granules will use them as a new carbon source. If the breakdown of the granules is realized, the next step is to determine which bacteria were involved. Taking a small amount of the bacteria-carrying solution and exerting them in a new centrifuge tube containing the granules and the same concentrations of chemical substances as the original centrifuge tubes, except for the glucose. If microbial growth is observed under these circumstances, the only carbon source available is either GreenFill or PHA. These bacteria will then keep multiplying since in the original centrifuge tube, there were also bacteria that began to grow on the glucose. Therefore, in this sequential step, the proportion of bacteria that grow on the granules increases. Repeating this process several times will induce a microbial culture specific for the breakdown of GreenFill or PHA, and the effect of a particular parameter can be tested.

5. Discussion

This paper investigated why companies that have developed biodegradable alternatives for products that result in environmental pollution via MPs cannot communicate this unique characteristic of their product. In addition, a case study of biodegradable grass infill developed by Senbis was used. The underlying problem originates from the inconceivability of establishing a universally accepted definition for biodegradability.

A shared understanding of the definitions within the field is still lacking, which would be facilitated by appropriate clarifications, standardizations, and certification schemes. The audience should be made aware that although the terms biodegradable and compostable are related, they are not the same, especially in order to inform consumers of the best method of disposal, as industrial composting facilities are by no means equal to degradation.

While current test protocols follow a reproducible method to determine the biodegradability of plastics, the obtained results often significantly underestimate the time required within the natural environment. This is partly because test conditions resemble controlled conditions rather than a dynamic environment. Some parameters, such as mechanical degradation and temperature, can be closely simulated to reality; others, including the microbial population, are far more complex. Therefore, these current test methods can incentivize companies to design BDPs that perform well in biodegradability tests but do not degrade properly in the natural environment.

The lack of data prevents us from concluding the exact risks posed by BMPs. A proper assessment is certainly not straightforward, as MPs enter the environment and food chain through multivariable factors' complex and dynamic interplay. The exact fate of biodegradable (and compostable) plastics in the open environment needs further research to allow for enhanced predicament. However, it should not be taken lightly that stretching the claim of biodegradability as ready for littering is misleading. BDPs are not the solution to the litter problem and should not be considered as such.

6. Conclusion

Why are companies unable to communicate the fact that their developed product is biodegradable and, therefore, an environmentally safe alternative for the existing product that causes environmental pollution via microplastics?

Several physical and chemical properties influence biodegradability. Although a number of factors have been identified to promote plastic biodegradability, the lack of consistent data on the biodegradability of various plastics inhibits establishing a clear correlation between physicochemical properties and their final fate. Furthermore, comparing the physicochemical features of BDP products to those of their nondegradable counterparts does not always yield the predicted results. For instance, two plastics with the same degree of crystallinity are not necessarily equivalent in biodegradability. These kinds of comparisons can only be applied to one type of polymer, e.g., comparing the degree of crystallinity of PHB with that of PHBV.

The broad range of environmental factors involved in the biodegradation process of BDP products makes exact predictability of their environmental impact impossible. If complete biodegradation is realized, BDPs result to be an added source of carbon, which raises the possibility of an imbalance of element cycles, whereas if complete biodegradation is not realized, BMPs can be formed by BDPs entering the environment. Either way, there is a negative environmental impact induced by BDP littering.

The gap between laboratory tests and the natural environment is self-evident. A wide range of multivariable factors influence the rate of biodegradation, but laboratory testing cannot recreate the natural environment. Moreover, the to-be-tested plastics undergo size reductions prior to testing; however, laboratory testing must be conducted on the product in its final form, including potential additives. Current standards require only a certain percentage of biodegradation, but there exists a lack of predictability of whether 100% biodegradation will be reached in the open environment. Likewise, the closeness of fit between the material and its measurement for biodegradability should be examined.

Current labels for biodegradability recognize a broad range of standards to be applicable, some of which specify a method for determining compostability instead of biodegradability. Labels aim to simplify the communication on the complex process of the biodegradation of plastics; however, this should be done in a transparent manner to prevent misinterpretations.

BDPs have been presented as part of the solution to the problem of (micro)plastic pollution. Because some plastic products are difficult or impossible to collect after use, there is a great risk of ending up in the environment. At the same time, there are concerns that BDPs may lead to more energy or resource-intensive manufacturing processes (Schulze et al., 2017), with unforeseen environmental impacts. Innovative companies may claim their biodegradable alternative is the more sustainable option, but the public must be aware that this may not necessarily be the case.

7. Reflection

Starting the Bachelor Integration Project on MPs in the life cycle, the management question involved looking for alternative ways to indicate the risks of MPs, as the Life Cycle Assessment (LCA) methodology lacks a proper indicator to assess the risks of MPs and potential biodegradable alternatives. I chose the topic due to my interest in sustainability, and in the past, I did not profoundly question claims made by companies regarding their environmentally friendly approaches. Therefore, I was merely interested in reviewing the environmental impact of so-called biodegradable plastics, their certification procedures, and all other aspects involved.

As I have attempted to convey, the commercialization of biodegradable plastics faces serious challenges. What I learned is that the term "biodegradation" refers to a complex process that requires more clarity in order to provide adequate standardization and communication. Furthermore, it has become apparent to me that to create a sustainable society without any negative environmental impact, significant steps still have to be made regarding the biodegradation of all kinds of plastics.

My goal was to design a transparent communication framework to avoid misinterpretations and to end the perception of greenwashing. Given the size of the project, proposing a communication framework that provides clear and unambiguous information on a product's ability to biodegrade was not possible. I would have liked the project to have been extended for a longer period, to perform more detailed experiments over a longer timeframe, and to be able to provide a communication framework.

I really enjoyed the support of all project sponsors; the discussions and feedback of my supervisors was very much appreciated and have has enriched the content of my work. Moreover, the open and transparent approach of the stakeholder company Ecoras was valued.

8. References

[1] Abe, H., & Doi, Y. (1999). Structural effects on enzymatic degradabilities for poly[(R)-3-hydroxybutyric acid] and its copolymers. *International Journal of Biological Macromolecules*, *25*(1–3), 185–192. https://doi.org/10.1016/s0141-8130(99)00033-1

[2] Ahmed, T., Shahid, M., Azeem, F., Rasul, I., Shah, A. A., Noman, M., Hameed, A., Manzoor, N., Manzoor, I., & Muhammad, S. (2018). Biodegradation of plastics: current scenario and future prospects for environmental safety. *Environmental Science and Pollution Research*, *25*(8), 7287–7298. https://doi.org/10.1007/s11356-018-1234-9

[3] Bandopadhyay, S., Martin-Closas, L., Pelacho, A. M., & DeBruyn, J. M. (2018). Biodegradable Plastic Mulch Films: Impacts on Soil Microbial Communities and Ecosystem Functions. *Frontiers in Microbiology*, *9*. https://doi.org/10.3389/fmicb.2018.00819

[4] *Biodegradable grass infill - GreenFill*. (2022, June 7). Senbis - Sustainable Products. Retrieved 11 May 2022, from https://www.senbis.com/products/biodegradable-grass-infill-greenfill/

[5] Bocca, B., Forte, G., Petrucci, F., Costantini, S., & Izzo, P. (2009). Metals contained and leached from rubber granulates used in synthetic turf areas. *Science of The Total Environment*, *407*(7), 2183–2190. https://doi.org/10.1016/j.scitotenv.2008.12.026

[6] Bruice, P. Y. (2015). *Essential Organic Chemistry*. Pearson Education.

[7] *California Law - CHAPTER 5.7. Products [42355 - 42358.5]*. (2022, January). California Legislative Information. Retrieved 8 June 2022, from

https://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?division=30.&chapter=5.7.&part=3.&lawCode=PRC

[8] Celeiro, M., Armada, D., Dagnac, T., de Boer, J., & Llompart, M. (2021). Hazardous compounds in recreational and urban recycled surfaces made from crumb rubber. Compliance with current regulation and future perspectives. *Science of The Total Environment*, *755*, 142566. https://doi.org/10.1016/j.scitotenv.2020.142566

[9] Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., Abu-Omar, M., Scott, S. L., & Suh, S. (2020). Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry & Engineering*, *8*(9), 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635

[10] Chen, C. C., Dai, L., Ma, L., & Guo, R. T. (2020). Enzymatic degradation of plant biomass and synthetic polymers. *Nature Reviews Chemistry*, *4*(3), 114–126. https://doi.org/10.1038/s41570-020-0163-6

[11] Chinaglia, S., Tosin, M., & Degli-Innocenti, F. (2018). Biodegradation rate of biodegradable plastics at molecular level. *Polymer Degradation and Stability*, *147*, 237–244. https://doi.org/10.1016/j.polymdegradstab.2017.12.011

[12] Dalton, B., Bhagabati, P., de Micco, J., Padamati, R. B., & O'Connor, K. (2022). A Review on Biological Synthesis of the Biodegradable Polymers Polyhydroxyalkanoates and the Development of Multiple Applications. *Catalysts*, *12*(3), 319. https://doi.org/10.3390/catal12030319

[13] de Freitas Netto, S. V., Sobral, M. F. F., Ribeiro, A. R. B., & Soares, G. R. D. L. (2020). Concepts and forms of greenwashing: a systematic review. *Environmental Sciences Europe*, *32*(1). https://doi.org/10.1186/s12302-020-0300-3

[14] de Hoe, G. X., Zumstein, M. T., Getzinger, G. J., Rüegsegger, I., Kohler, H. P. E., Maurer-Jones, M. A., Sander, M., Hillmyer, M. A., & McNeill, K. (2019). Photochemical Transformation of Poly(butylene adipate-*co*-terephthalate) and Its Effects on Enzymatic Hydrolyzability. *Environmental Science & Technology*, *53*(5), 2472–2481. https://doi.org/10.1021/acs.est.8b06458

[15] Devlin, H. (2021, October 29). *Seabirds eat floating plastic debris because it smells like food, study finds*. The Guardian. Retrieved 30 May 2022, from https://www.theguardian.com/environment/2016/nov/09/seabirds-eat-floating-plastic-debris-because-it-smells-like-food-study-finds-algae-sulfur

[16] Diekmann, A., Giese, U., & Schaumann, I. (2019). Polycyclic aromatic hydrocarbons in consumer goods made from recycled rubber material: A review. *Chemosphere*, *220*, 1163–1178. https://doi.org/10.1016/j.chemosphere.2018.12.111

[17] EduPack, C. E. S. (2014). Cambridge: Granta Design Limited, 2014. *Computer software*.

[18] EPA Network - Interest group on Plastics, & Maier, N. (2018, November). *Biodegradable plastics - Approaches and experiences from 16 members of the EPA Network*. https://epanet.eea.europa.eu/reports-letters/reports

[19] Farzi, A., Dehnad, A., & Fotouhi, A. F. (2019). Biodegradation of polyethylene terephthalate waste using Streptomyces species and kinetic modeling of the process. *Biocatalysis and Agricultural Biotechnology*, *17*, 25–31. https://doi.org/10.1016/j.bcab.2018.11.002

[20] Filiciotto, L., & Rothenberg, G. (2020). Biodegradable Plastics: Standards, Policies, and Impacts. *ChemSusChem*, *14*(1), 56–72. https://doi.org/10.1002/cssc.202002044

[21] Gartiser, S., Schneider, K., Schwarz, M. A., & Junker, T. (2017, January). *Assessment of environmental persistence: Regulatory requirements and practical possibilities – available test systems, identification of technical constraints and indication of possible solutions*. Umweltbundesamt. https://www.umweltbundesamt.de/en/publikationen/assessment-of-environmental-persistence-regulatory

[22] Ghosh, K., & Jones, B. H. (2021). Roadmap to Biodegradable Plastics—Current State and Research Needs. *ACS Sustainable Chemistry & Engineering*, *9*(18), 6170–6187. https://doi.org/10.1021/acssuschemeng.1c00801

[23] Girdhar, A., Bhatia, M., Nagpal, S., Kanampalliwar, A., & Tiwari, A. (2013). Process Parameters for Influencing Polyhydroxyalkanoate Producing Bacterial Factories: An Overview. *Journal of Petroleum & Environmental Biotechnology*, *04*(05). https://doi.org/10.4172/2157-7463.1000155

[24] Haider, T. P., Völker, C., Kramm, J., Landfester, K., & Wurm, F. R. (2018). Plastics of the Future? The Impact of Biodegradable Polymers on the Environment and

on Society. *Angewandte Chemie International Edition*, *58*(1), 50–62. https://doi.org/10.1002/anie.201805766

[25] Hann, S., Sherrington, C., Jamieson, O., Hickman, M., Kershaw, P., Bapasola, A., & Cole, G. (2018). Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products. *Final Report. London/Bristol.*

[26] Islam, S., Saha, S., Bakr, A., & Mondal, I. (2016). A Review on Biodegradations of Polymers and its Effect on Environment. *Journal of Composites and Biodegradable Polymers*, *3*(2), 46–54. https://doi.org/10.12974/2311-8717.2015.03.02.3

[27] *ISO 10210:2012*. (2012, August). ISO - Industrial Organization for Standardization. Retrieved 2 June 2022, from https://www.iso.org/standard/45851.html

[28] *ISO 17556:2019*. (2019, May). ISO - International Organization for Standardization. Retrieved 3 May 2022, from https://www.iso.org/standard/74993.html

[29] Kawai, F., Kawabata, T., & Oda, M. (2020). Current State and Perspectives Related to the Polyethylene Terephthalate Hydrolases Available for Biorecycling. *ACS Sustainable Chemistry & Engineering*, *8*(24), 8894–8908. https://doi.org/10.1021/acssuschemeng.0c01638

[30] Kawashima, N., Yagi, T., & Kojima, K. (2019). How Do Bioplastics and Fossil-Based Plastics Play in a Circular Economy? *Macromolecular Materials and Engineering*, *304*(9), 1900383. https://doi.org/10.1002/mame.201900383

[31] Koelmans, A. A., Redondo-Hasselerharm, P. E., Nor, N. H. M., de Ruijter, V. N., Mintenig, S. M., & Kooi, M. (2022). Risk assessment of microplastic particles. *Nature Reviews Materials*, *7*(2), 138–152. https://doi.org/10.1038/s41578-021-00411-y

[32] Krzan, A., Hemjinda, S., Miertus, S., Corti, A., & Chiellini, E. (2006). Standardization and certification in the area of environmentally degradable plastics. *Polymer Degradation and Stability*, *91*(12), 2819–2833. https://doi.org/10.1016/j.polymdegradstab.2006.04.034

[33] Lambert, S., & Wagner, M. (2017). Environmental performance of bio-based and biodegradable plastics: the road ahead. *Chemical Society Reviews*, *46*(22), 6855–6871. https://doi.org/10.1039/c7cs00149e

[34] Letcher, T. M. M. (2020). *Plastic Waste and Recycling: Environmental Impact, Societal Issues, Prevention, and Solutions* (1st ed.). Academic Press.

[35] Lucas, N., Bienaime, C., Belloy, C., Queneudec, M., Silvestre, F., & Nava-Saucedo, J. E. (2008). Polymer biodegradation: Mechanisms and estimation techniques – A review. *Chemosphere*, *73*(4), 429–442. https://doi.org/10.1016/j.chemosphere.2008.06.064

[36] Manavitehrani, I., Fathi, A., Badr, H., Daly, S., Negahi Shirazi, A., & Dehghani, F. (2016). Biomedical Applications of Biodegradable Polyesters. *Polymers*, *8*(1), 20. https://doi.org/10.3390/polym8010020

[37] Meereboer, K. W., Misra, M., & Mohanty, A. K. (2020). Review of recent advances in the biodegradability of polyhydroxyalkanoate (PHA) bioplastics and their

composites. *Green Chemistry*, *22*(17), 5519–5558. https://doi.org/10.1039/d0gc01647k

[38] Miri, S., Saini, R., Davoodi, S. M., Pulicharla, R., Brar, S. K., & Magdouli, S. (2022). Biodegradation of microplastics: Better late than never. *Chemosphere*, *286*, 131670. https://doi.org/10.1016/j.chemosphere.2021.131670

[39] Mishra, M. (2015). *Handbook of Encapsulation and Controlled Release*. Amsterdam University Press.

[40] Napper, I. E., & Thompson, R. C. (2019). Environmental Deterioration of Biodegradable, Oxo-biodegradable, Compostable, and Conventional Plastic Carrier Bags in the Sea, Soil, and Open-Air Over a 3-Year Period. *Environmental Science & Technology*, *53*(9), 4775–4783. https://doi.org/10.1021/acs.est.8b06984

[41] Naser, A. Z., Deiab, I., & Darras, B. M. (2021). Poly(lactic acid) (PLA) and polyhydroxyalkanoates (PHAs), green alternatives to petroleum-based plastics: a review. *RSC Advances*, *11*(28), 17151–17196. https://doi.org/10.1039/d1ra02390j

[42] *OK biodegradable*. (n.d.). TÜV Austria. Retrieved 28 April 2022, from https://www.tuv-at.be/green-marks/certifications/ok-biodegradable/

[43] Pires, J. R. A., Souza, V. G. L., Fuciños, P., Pastrana, L., & Fernando, A. L. (2022). Methodologies to Assess the Biodegradability of Bio-Based Polymers—Current Knowledge and Existing Gaps. *Polymers*, *14*(7), 1359. https://doi.org/10.3390/polym14071359

[44] Rana, K. I. (2019). Usage of Potential Micro-organisms for Degradation of Plastics. *Open Journal of Environmental Biology*, 007–015. https://doi.org/10.17352/ojeb.000010

[45] Ru, J., Huo, Y., & Yang, Y. (2020). Microbial Degradation and Valorization of Plastic Wastes. *Frontiers in Microbiology*, *11*. https://doi.org/10.3389/fmicb.2020.00442

[46] *Rubberkorrels en -strooisel op sport- en speelvelden - ECHA*. (n.d.). ECHA - European Chemical Agency. Retrieved 11 May 2022, from https://echa.europa.eu/nl/hot-topics/granules-mulches-on-pitches-playgrounds

[47] Ruggero, F., Gori, R., & Lubello, C. (2019). Methodologies to assess biodegradation of bioplastics during aerobic composting and anaerobic digestion: A review. *Waste Management & Research*, *37*(10), 959–975. https://doi.org/10.1177/0734242x19854127

[48] SAPEA, Science Advice for Policy by European Academies. (2020). *Biodegradability of plastics in the open environment*. Berlin: SAPEA. https://doi.org/10.26356/biodegradabilityplastics

[49] Schulze, C., Juraschek, M., Herrmann, C., & Thiede, S. (2017). Energy Analysis of Bioplastics Processing. *Procedia CIRP*, *61*, 600–605. https://doi.org/10.1016/j.procir.2016.11.181

[50] *styrene-butadiene rubber | chemical compound*. (n.d.). Encyclopedia Britannica. Retrieved 21 May 2022, from https://www.britannica.com/science/styrene-butadiene-rubber

[51] Sun, J., Prabhu, A., Aroney, S. T. N., & Rinke, C. (2022). Insights into plastic biodegradation: community composition and functional capabilities of the superworm (Zophobas morio) microbiome in styrofoam feeding trials. *Microbial Genomics*, *8*(842). https://doi.org/10.1099/mgen.0.000842

[52] *Synthetic Turf FAQs*. (2019, July 9). ESTC - EMEA Synthetic Turf Council. Retrieved 8 May 2022, from https://www.estc.info/synthetic-turf-faqs/#toggle-id-14

[53] Tokiwa, Y., Calabia, B., Ugwu, C., & Aiba, S. (2009). Biodegradability of Plastics. *International Journal of Molecular Sciences*, *10*(9), 3722–3742. https://doi.org/10.3390/ijms10093722

[54] Tournier, V., Topham, C. M., Gilles, A., David, B., Folgoas, C., Moya-Leclair, E., Kamionka, E., Desrousseaux, M. L., Texier, H., Gavalda, S., Cot, M., Guémard, E., Dalibey, M., Nomme, J., Cioci, G., Barbe, S., Chateau, M., André, I., Duquesne, S., & Marty, A. (2020). An engineered PET depolymerase to break down and recycle plastic bottles. *Nature*, *580*(7802), 216–219. https://doi.org/10.1038/s41586-020-2149-4

[55] van den Oever, M., Molenveld, K., van der Zee, M., & Bos, H. (2017). *Bio-based and biodegradable plastics: facts and figures: focus on food packaging in the Netherlands*. (Wageningen Food & Biobased Research; No. 1722). Wageningen Food & Biobased Research. https://doi.org/10.18174/408350

[56] van der Zee, M. (2014). Methods for evaluating the biodegradability of environmentally degradable polymers. In *Handbook of biodegradable polymers* (pp. 1-28). Smither Rapra.

[57] Verschuren, P., Doorewaard, H., & Mellion, M. J. (2010). *Designing a Research Project*. Van Haren Publishing.

[58] Wang, C., Yu, J., Lu, Y., Hua, D., Wang, X., & Zou, X. (2021). Biodegradable microplastics (BMPs): a new cause for concern? *Environmental Science and Pollution Research*, *28*(47), 66511–66518. https://doi.org/10.1007/s11356-021-16435-4

[59] Wei, R., & Zimmermann, W. (2017). Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: how far are we? *Microbial Biotechnology*, *10*(6), 1308–1322. https://doi.org/10.1111/1751-7915.12710

[60] Yu, Y., Griffin-LaHue, D. E., Miles, C. A., Hayes, D. G., & Flury, M. (2021). Are micro- and nanoplastics from soil-biodegradable plastic mulches an environmental concern? *Journal of Hazardous Materials Advances*, *4*, 100024. https://doi.org/10.1016/j.hazadv.2021.100024

[61] Zimmermann, L., Dombrowski, A., Völker, C., & Wagner, M. (2020). Are bioplastics and plant-based materials safer than conventional plastics? In vitro toxicity and chemical composition. *Environment International*, *145*, 106066. https://doi.org/10.1016/j.envint.2020.106066

[62] Zuo, L. Z., Li, H. X., Lin, L., Sun, Y. X., Diao, Z. H., Liu, S., Zhang, Z. Y., & Xu, X. R. (2019). Sorption and desorption of phenanthrene on biodegradable poly(butylene

adipate co-terephtalate) microplastics. *Chemosphere*, *215*, 25–32. https://doi.org/10.1016/j.chemosphere.2018.09.173

[63] Zylberberg, N. (2021, December 27). *Thinking Outside the Box: Turning Methane into Biodegradable Plastic*. Medium. Retrieved 10 June 2022, from https://medium.com/2030magazine/thinking-outside-the-box-turning-methane-into-biodegradable-plastic-9d8dd53a40aa