RECENT J. (2023), 69:029-050
https://doi.org/10.31926/RECENT.2023.69.029

A Sustainable Approach to Plastics; Bioplastics

Şeyma Nur ERKUL
Bursa Uludag University, Turkey, seymaerkul@butekom.org
Mehmet KARAHAN
Bursa Uludag University, Turkey, mkarahan@uludag.edu.tr
Ali ARI
Ostim Technical University, Turkey, ali.ari@ostimteknik.edu.tr

Abstract
This article aims to analyze bioplastics at the global level and provide information about alternative bioplastics instead of traditional plastics. By examining the literature studies, the relationship of bioplastics with plastics, their environmental effects, advantages, and disadvantages are compared. Plastic wastes cause toxic effects on soils due to chemical degradation and turn into microplastics that easily enter the environment through primary and secondary sources. Accordingly, biobased and biodegradable bioplastics emerge as potential solutions. There are norms and standards with different parameters to measure biodegradability. The leading standardization organizations are ISO (International Organization for Standardization), CEN (European Committee for Standardization), and ASTM (American Society for Testing and Materials). The literature indicates high degradation rates (>90%) for bioplastics in compost, soil, and seawater environments. The studies suggest that bioplastics are more advantageous than conventional plastics because of greenhouse gas emissions. On the contrary, they strongly impact the environment by acidification of soil and eutrophication. This article discusses plastic and bioplastic properties, the environmental impacts of plastics, biodegradability and compostability standards, and life cycle analysis.

Keywords
bioplastic, plastic, sustainability, LCA

1. Introduction

The European Green Consensus is the action plan outlined by the European Commission to tackle the ever-growing environmental and climate challenges facing our society. This plan aims to transform the European Union into a modern society with zero net greenhouse gas emissions and economic growth decoupled from resource use by 2050 (European Commission, 2019). A circular economy is an approach that will lead to significant changes in many branches of the modern economy in a short time (Primc et al. 2020). In this regard, the European Union points out several urgent problems with plastic pollution and production, including single-use items, excessive packaging and waste, microplastics, and oversized carbon footprints (European Commission, 2020).

Plastics, whose production dates back to the 1950s, have become necessary materials used in various daily applications (Geyer et al., 2017). The plastics industry has grown exponentially because of the diversity of plastics available and its relatively cheap petroleum production (World Economic Forum, 2016). Plastics are expected to contribute to daily life socially and environmentally, and their use will increase worldwide, including in developing countries. This increase is due to the "Future of Petrochemicals" (International Energy Agency, 2018) report and "The Essential Role of Chemicals: 17 Case Studies" (International Council of Chemical Associations, 2017) report. Plastics are used extensively in various industrial sectors, including packaging, construction, automotive, electronics, textiles, household goods, and toys, with current global production of approximately 350 million tons per year (t/year) (Plastics Europe, 2018). Binders, fillers, colors, plasticizers, and other additives make up most of them (White & Reid, 2018). These synthetic materials can be molded or sculpted with chemical additions and an organic polymer matrix (Baur et al., 2019). Additives aid in preserving and enhancing particular qualities (Andrews, 2010; Zweifel et al. 2009). Polyethylene (PE) is widely used in the production of plastic materials. PE, also defined as an ethylene polymer, is produced at high temperatures and pressure depending on the desired properties of the final product. PE is resistant to acids, water, alkali, and most organic solvents (Ronca, 2017). Lightness, expandability, flexibility, and resistance to microbial or any other natural degradation are just a few of the features that make plastic indispensable (Katiyar et al., 2014). The disposable concept, which has become increasingly widespread worldwide since the 80s, is the result of linear economy concepts. The most considerable side effect of the wide use of plastics is a large amount of plastic waste released into the environment (Schneiderman & Hillmyer, 2017). The persistence of plastic materials in the environment has quickly pushed the globe towards an overall state of unsustainability due to the disturbance of ecosystems and the threat to the survival of many animal and plant species (Comăniță et al., 2016; Wesch et al., 2016).

The circular economy is an economic system and production model that aims to maximize the reuse and recycling of resources, thus extending the life cycle of products while minimizing waste. The model responds to traditional and linear economics (Spierling et al., 2018). Globally, only 5% of the annual value of plastic produced remains in the economy, while 32% is lost in the ecosystem. Only 2% of plastics are recycled with the same or similar quality. This system is called a closed loop (Neufeld et al., 2016). Even in the world's most developed regions, recycling figures need to be higher to be sustainable. For example, approximately 31 million tons of plastic waste are produced in the USA each year, of which only 6.8% can be recycled (LeBlanc, 2017). The basic principle used in recycling is the remolding of plastic material. It is impossible to ultimately convert the entire mass of plastic into another reusable form. This mass loss in the recycling process is considered a plastic emission. Another disadvantage encountered during recycling is the high energy consumed in the process. The durability of these products is severely reduced compared to the original product. However, the best way to date for plastic is to reduce its use and dependence (Aryan et al., 2019).

Considerable accumulation of plastic waste in the environment is forcing many industrial areas to produce biodegradable plastics (Sankauskaitė et al., 2014). Therefore, the demand for new material solutions that are necessarily cost-effective and environmentally biodegradable is increasing (Bayer et al., 2014). A promising alternative to petroleum-based plastics is bioplastics, biobased plastics, or biopolymers derived from biomass such as corn and sugar cane as part of the biorefinery concept (Shogren et al., 2019). This request; emerged as a result of discussions on how plastic should progress in a sustainable society and circular economy, taking into account resource conversion and environmental protection (Kawashima et al., 2005).

Circular economy principles need to be applied to any material flow, and bioplastic is no exception, as biomass is a limited resource. While general circular economy approaches are widely available, only a few kinds of literature exist regarding specific circular economy indicators for bioplastics. In particular, its biodegradability is unique to bioplastics and provides more waste treatment options (Spierling et al., 2018). The European Strategy highlights the need to develop more sustainable, innovative materials and alternative raw materials for plastics in the circular economy compared to petrochemical plastics (European Commission, 2018). Since most biobased plastics are a potential alternative to petrochemical plastics, a life cycle assessment (LCA) is required to compare environmental impacts accurately. In order to compare biobased plastics with petrochemical plastics, different plastics must have a "full" life cycle (European Commission, 2018).

This article provides an overview of bioplastics, including definitions, polymers on the market, and applications. Existing standards and certificates were investigated to assess the compostability and biodegradability of bioplastics. The biodegradability of bioplastics and the LCA of bioplastics are reviewed.

2. Environmental Effects of Plastics

The vast majority of plastic products are fossil-based polymers, meaning resources derived from fossils are used as raw materials. Plastic is a substance obtained from its chemical transformation (Guler & Cobanoğlu, 1997, p. 13). Plastics can be synthesized through the polymerization of small molecules and are generally divided into thermoplastics and thermosets (Alauddin et al., 1995). Thermoplastics are linear chain macromolecules. On the other hand, thermoset plastics are formed by gradual growth polymerization under suitable conditions (Schick, 1992). Overall, they offer low bulk density, inertia, and excellent mechanical and barrier properties, making them superior materials for many applications (World Economic Forum, 2016). Plastics are increasingly used in sectors such as packaging due to their easy processing, flexibility, lightness, and health-friendly properties. Considering the increasing energy costs and decreasing natural resources, plastics are preferred among packaging materials because they are economical. In this respect, it is expected result that the use of plastic will increase gradually (Erozturk, 1997). Plastic production increased from 1.5 million metric tons (mmt) in 1950 to about 335 mmt in 2016 and 359 mmt in 2018, with an average annual growth rate of 8.7% from 1950 to 2012. Global plastic production is predicted to triple by 2050 (Statista, 2020). Today, plastic waste management, recycling, and disposal are essential issues. Depending on the quality of the recovered waste fraction, plastics have the potential to be recycled many times while retaining their value and functional properties and thus contribute significantly to the European Union's efforts towards a circular economy (European Commission, 2015). However, most plastics (about 70%) in the USA are now dumped in landfills or incinerated for energy recovery (Plastics Europe, 2017).

Vogt et al. (2021) argued that low recycling rates result from various economic and technical challenges that do not encourage recycling. Due to the generally poor miscibility of polymer blends, efficient waste separation is critical to the quality of products from mechanical recycling (Vogt et al., 2021). In principle, thermoplastic plastics are easily recycled, but the process is more demanding. The innovation and increasing complexity of plastic-containing products are evolving faster than recycling facilities and systems can adapt, increasing the challenge of collecting and sorting post-consumer plastic waste (Bennett & Alexandridis, 2021). Most plastic products are manufactured from a formulation containing additives such as colorants, dyes, fillers, UV protectors, fire retardants, supplements, and plasticizers (Vogt et al., 2021). The presence of these additives means that they are only suitable for some recycling applications. Additionally, mechanical recycling processes break down plastics before remelting them, which means polymer chains are shortened. Unlike metals, which are essentially endlessly recyclable, shredding degrades quality with each recycling, and over time, plastic becomes non-recyclable. This problem is exacerbated in the developing world, where infrastructure to collect and sort plastic waste is often inadequate or unavailable (Browning et al., 2021). In addition, thermosetting plastics such as polyesters, polyurethanes, silicones, and epoxy cannot be remelted and remolded after being shaped due to their crosslinked structure (Seay & Ternes, 2022). In addition to the technical challenges, the economic challenges of conventional recycling are also significant. Only pure waste streams, such as polyethylene terephthalate and high-density polyethylene bottles, are commercially recycled for post-consumer plastic. In contrast, potentially recyclable plastics such as polystyrene, polypropylene, polyethylene films, and mixed polyolefins are generally disposed of (Larrain et al., 2021). In addition, low oil prices are also affecting the recycling market by reducing the cost of virgin resin. The need for policies to increase the demand for recycled products, such as imposing minimum recycled content targets, is therefore critical to the economic viability of recycling operations (Larrain et al., 2021).

Recycling rates are low (14%) in plastic packaging on a global scale, so plastics tend to accumulate (Hahladakis & Iacovidou, 2018). To overcome this problem of waste accumulation, the European strategy for plastics in the circular economy draws attention to the policies surrounding the sustainable development of industrial production (European Commission, 2018; Geissdoerfer et al., 2017). Since these developments place a serious burden on environmental factors, it is essential to examine the effects of plastic products and wastes on human health and the environment in more depth (Nagy et al., 2016). The wide variety of plastic products mainly determines the diversity of plastic pollution. Thousands of plastic products are demanded in the consumer market daily. For example, the most used plastics in the market; PE (polyethylene), PP (polypropylene), PVC (polyvinyl chloride), PET (polyethylene terephthalate), and PS (polystyrene) (Bond et al., 2018). It has been documented that plastics can enter aquatic, terrestrial and atmospheric systems directly or indirectly through different means, such as wastewater treatment plants, domestic sewage, landfills, mismanaged plastic waste, agricultural activities, and even urban dust (Law 2017; Ziajahromi et al., 2017; Windsor et al., 2019; Bai & Li, 2020). The non-biodegradability of plastics and improper waste management poses many environmental hazards in terms of safety; can cause the clogging of sewers in cities and other production areas (Gu, 2021). Human populations are directly or indirectly linked in various ways to the distribution of plastic waste. Plastic additives (heavy metals, plasticizers, harmful coloring components, and stabilizers) leach into various aspects of the environment, causing water and soil pollution (Rahman & Brazel, 2004). Chlorine-containing plastics also leach toxic chemicals into the soil, which can leach into groundwater or a nearby body of water, causing ecosystem pollution. Trash plastic waste is another environmental threat when it decomposes and is released into the atmosphere as methane (CH4) and carbon dioxide (CO2). When plastic waste is burned openly, pollutants such as furans, polychlorinated biphenyls (PCBs), dioxins, and heavy metals are released into the air, causing health effects, particularly respiratory problems. When people come into contact with toxins used in plastic, they can also become infected through skin absorption (Chandegara et al., 2015). Plastics undergo abiotic and biotic degradation processes involving chemical, physical, and biological environmental reactions. UV radiation is mainly responsible for the initiation of degradation. Many advanced technologies have been developed to characterize the degradation of plastics. Decomposition causes oxidation and chain scission of plastic polymers, forming low molecular weight degradation products and causing changes in physicochemical and mechanical properties. The deterioration in tensile strength and shear strength as a result of deterioration causes the plastics to break down, and small plastic debris can be formed with the help of external forces. Further degradation of plastics can produce degradation products of sufficiently low molecular weight that can be assimilated and mineralized by microorganisms. In the natural environment, the degradation of conventional plastics is prolonged and is affected by their properties and the conditions of the exposed environment. The degradation of plastics is critical in determining their fate and environmental impact (Zhang et al., 2021). Due to chemical breakdown, plastic waste is poisonous to soils and easily enters the environment through primary and secondary sources as microplastics (e.g., Figure 1).

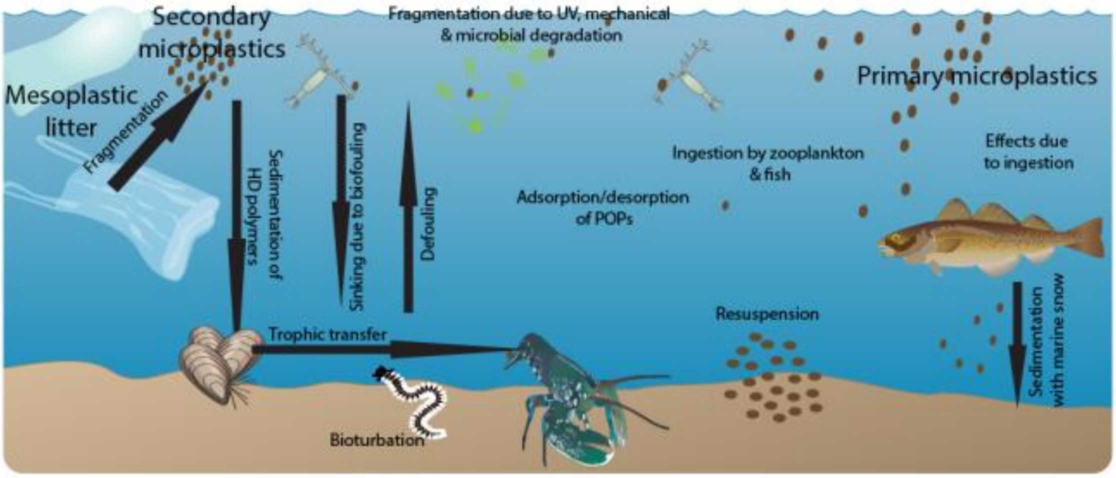

Fig. 1. Sources and interactions of microplastics in the aquatic environment (FanpLESStic-sea 2019)

Recent years have seen an increase in the study on environmental contamination focusing on microplastics in soil, air, and particularly aquatic habitats (Pannetier et al., 2019). Microplastics pose a danger to the health of humans and other living things due to their properties such as absorbing toxic pollutants and being swallowed by living things, not being able to be filtered in wastewater treatment plants, are easily transported in the atmosphere and water resources, and having a very long extinction period in nature (Yurtsever, 2018, p. 184). Microplastics are found in the soils of many terrestrial ecosystems (Zhang & Liu, 2018), including agricultural areas (Piehl et al., 2018), cities and industrialized areas (Fuller & Gautam, 2016), as well as highly remote areas (Scheurer & Bigalke, 2018). The accumulation of plastics, especially in the sea, causes severe effects on the ecosystem (Gregory, 2009). Between 2010 and 2025, one hundred million tons of plastic waste is expected to enter the oceans (Dilkes-Hoffman et al., 2019; Jambeck et al., 2015). Plastics entering the oceans have a wide range of environmental and economic impacts, including the spread of invasive organisms, the disruption of tourism and fishing industries, and the threat to marine organisms (Codina-García et al., 2013; Kedzierski et al., 2018; Moore, 2008).

3. Bioplastics

Due to the increasing human population and the demand for plastic materials, the search for sustainable materials is one of the main issues addressed by the Council of the European Union. Bioplastics are, therefore, an important research topic to overcome the limited availability of petroleum-derived plastic (Brodhagen et al., 2017; Steinmetz et al., 2016). The European Technology Platform for Sustainable Chemistry estimates that by 2025, up to 30 percent of raw materials for the European chemical industry will come from renewable sources (SusChem, 2017). According to Bioplastics, global bioplastic production in 2019 was below 1% (2.43 Mt) of global plastic production. Asia accounts for the largest share (45%) of bioplastic production. Europe followed with 25%, but this is expected to increase thanks to the European Commission's commitment to transition to a circular economy. The most popular applications of bioplastics are for food packaging (52%), followed by textiles (10%), consumer goods (10%), automotive (7%), agriculture (7%), coatings and adhesives (7%), construction (4%) and other sectors (3%) (European Bioplastics, 2019).

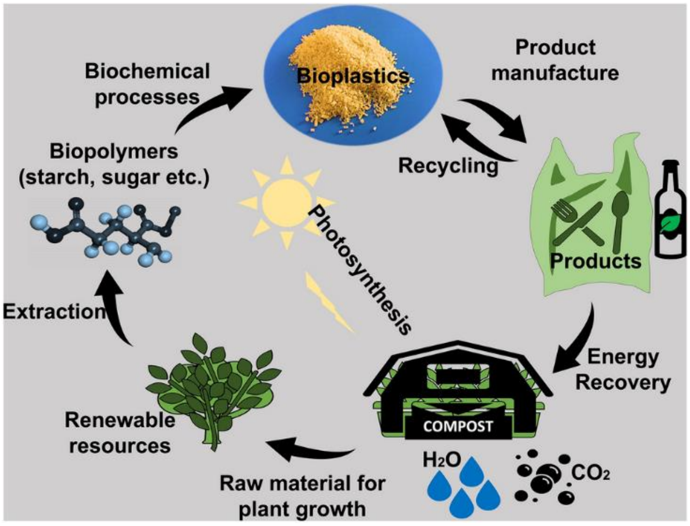

Fig. 2. The bioplastic cycle (Bhagwat et al. 2020)

Bioplastic if it is biobased or made from renewable materials with the potential for biodegradability (Mekonnen et al., 2013). The best-known properties of bioplastics are mainly mechanical and thermoforming properties, gas and water vapor permeability, and transparency (Huang et al., 2004). Its main advantages are; potentially lower carbon footprint, lower energy costs in production, no use of scarce oil, and biodegradability are the prevention of accumulation in landfills using bioplastics (Chen et al., 2014). In addition, it has disadvantages such as high production costs, workability with shared technologies, lack of technical knowledge, small market volume, and market redesign (Di Bartolo et al., 2021). It is widely known that bioplastic materials may outperform traditional synthetic plastics due to their inherent properties (Plastics Europe, 2018). To date, relatively few biobased products have been produced compared to conventional chemicals.

As seen in Fig. 2, bioplastics are generally polymers synthesized from renewable resources such as biodegradable (Flieger et al., 2003) produced from renewable natural resources such as polysaccharides, lipids, proteins, plant/microbic polyesters, or polyesters produced from bioderived monomers (Briassoulis, 2004; Nampoothiri et al., 2010). These plastics are environmentally friendly and a safer option than petroleum-based plastics. Biodegradable plastics decompose entirely into carbon dioxide, water, and inorganic compounds (Shah, 2021). The biodegradability of bioplastic materials is highly affected by their physical and chemical structure. At the same time, the environmental conditions in which they are placed play an essential role in their biodegradability

(Emadian et al., 2017). The material's biodegradability is primarily governed by its polymer structure (Leja & Lewandowicz, 2010). Most polymer structures have a hetero-chain or carbon basis. Hetero-chain polymers include polysaccharides, proteins, plant-derived polymers such as PLA and PBS, and microbially synthesized polymers such as PHVB. Hetero-chain polymers degrade via enzyme-mediated or non-enzyme-mediated hydrolysis, which can be affected by factors such as thickness, chemical bonds, copolymer type, water uptake, and morphology. Carbon-based polymers such as natural rubber and lignin degrade through oxidation or enzyme-mediated (oxidative) biodegradation, which can take years and is slower than hetero-chain polymers (Sudhakar et al., 2012). Most of the so-called biodegradable materials are biocomposites, usually formed by mixing other biodegradable materials such as potato peel waste fermentation residue (Wei et al., 2015), fruit branch fibers (Harmaen et al., 2015) to increase their biodegradability. Biotechnology of reinforced plastics or composite materials Production with degradable supplements and resins has also become a trendy topic in recent years (Jabbar et al., 2016). The use of natural fibers, especially fibers such as jute, flax, and hemp, instead of glass fiber and carbon fiber, which are widely used as reinforcing materials and require very high energy use in production, is increasing (Koyuncu et al., 2016).

Along with such fibers, resins and polymers obtained from plant products such as corn and olive are also used to produce biodegradable composites (Liu et al., 2019). Banana fibers used as reinforcing materials offer several advantages due to their environmental friendliness, relatively low density, and abundance (Li et al., 2008). Natural fiber-reinforced scientists and engineers have widely researched composites in different industries for their environmentally friendly properties, such as biodegradability, which can significantly reduce carbon footprint. Even advanced industrial sectors such as aerospace and automotive have tried using natural fiber-reinforced composites in critical applications to promote sustainable technologies. In the last few years, interest in using natural fibers as reinforcements in polymers has increased significantly. Natural fibers are strong, light, relatively inexpensive, and biodegradable (Kopparthy & Netravali, 2021).

Biobased product lines reduce adverse environmental and social impacts associated with petroleum feedstock (O'Rourke & Connolly, 2003) but still have significant environmental impacts. Further support for the biobased sector is also recognized as a way to enable circularity in the industry. However, challenges are also noted in the sourcing, labeling, and use of biobased, biodegradable, and compostable plastics (European Commission, 2020). Recently, the biodegradation of different bioplastics has been studied by numerous studies in the literature. Biopolymers are of great interest in the market as they meet the basic requirements of life cycle environmental impacts or life cycle assessments (Hottle et al., 2013). Proportionally, production in low quantities compared to petroleum-based plastics is a factor that increases the cost. Costs may decrease when the number of production increases. Recently, studies have focused on reducing production costs and improving bioplastics' mechanical and physical properties. There are many studies on the biodegradability of different bioplastics in different environments for specific periods. Bioplastics' ability to biodegrade under conditions found in natural environments is an essential property. Biodegradability depends on the chosen medium and may differ from one medium to another (Karamanlıoglu et al., 2017). Therefore, environmental conditions affect the decomposition rate (Endres, 2017; Nakasaki et al., 2006) and the test conditions used (Massardier-Nageotte et al., 2006). Therefore, the type of biodegradable polymer (Nakasaki et al., 2006) should be chosen correctly. Aerobic compost is the most widely studied degradation media and a standard waste treatment option (Ruggero et al., 2019). Other media of interest are soil, freshwater, or seawater (Shruti & Kutralam-Muniasamy, 2019). However, bioplastic degradation occurs only under certain conditions, and generally, the biodegradation process is prolonged under environmental conditions (Shruti & Kutralam-Muniasamy, 2019). Table 1 shows PLA in the soil in the studies reviewed. Its biodegradation (Palsikowski et al., 2018; Rajesh et al., 2019) was relatively low compared to its biodegradation in compost (Luo et al., 2019; Stloukal et al., 2015; Kale et al., 2007). High biodegradation rates (>90%) in soil and compost have also been detected in PHA-based bioplastics (Schröpfer et al., 2015; Boyandin et al., 2013; Gutierrez-Wing et al., 2011; Sintim et al., 2020). Bioplastic is expected to be highly degradable, and studies are carried out to accelerate biodegradation by bacteria that will provide this and fungi, which are known to be more resistant than bacteria (Arıkan & Bilgen, 2019, p. 294).

Table 1. Bioplastic degradation rates

Bioplastic Type	*Degradation Rate %*	*Type of environment*	*Time (Day)*	*Reference*
PLA	54%	Soil	57	Karamanlioglu & Robson, 2013
	16%		180	Palsikowski et al., 2018
	26.5%		90	Rajesh et al., 2019
PHA Based	30-100%	Soil	14-300	Emadian et. al., 2017
	35%		60	Wu, 2014
	48.5%		280	Gómez & Michael, 2013
	% 85.8 - 96.4		150 170	Šerá et al., 2020
	26.3%		10	Rudnik & Briassoulis, 2011
PHB	86.7%		56	Rehman et al., 2015
	32% – 31.6%		35	Thomas et al., 2020
	93%		35	Volova et al., 2017
	64.3%		180	Jain and Tiwari, 2015
	%100		180	Schröpfer et al., 2015
	98%		300	Boyandin et al., 2013
PHBV	40%		90	Casarin et. al., 2012
	18%		30	Wang et al., 2008
	10%		28	Gonçalves et al. al., 2018
	95%		45	Kulkarni et al., 2011
	35%			Rani-Borges et al., 2016
PLA	10-100%	compost	28-90	Emadian et. al., 2017
	53%		57	Karamanlioglu et al., 2013
	20%		180	Janczak et al., 2018
	78.9%		80	Luo et al., 2019
	70.86%		90	Stloukal et. al., 2015
	13%		60	Ahn et al., 2011
	84%		58	Kale et al., 2007
	70%		28	Tabasi & Ajji, 2015
	60%		30	Mihai et al., 2014
PHA Based	85-99%	compost	126	Sintim et. al., 2020
	79.7%		110	Weng et al., 2011
	%100		84-126	Gutierrez-Wing et al., 2011
	80%		28	Tabasi & Ajji, 2015
Cellulose acetate bioplastic	44-35%	compost	14	Mostafa et. al., 2015
PLA	90%	anaerobic sludge	60	Yagi et. al., 2012
PHB	83.9%±1.3%	anaerobic water	77	García-Depraect et al., 2022
PBHV	81.2% ± 1.7%		77	García-Depraect et al., 2022
PCL	77.6% ± 2.4	anaerobic water	177	García-Depraect et al., 2022
PHBV	85%	Marine	360	Deroiné et. al., 2014
	97%		200	Deroiné et. al., 2015
PHB	>30%		365	Greene, 2012
	71.3%		86	Ho et al., 2002
	88-99%		49-100	Thellen et al., 2008

4. Biodegradability and Biodegradability Standards

Biodegradation occurs through the action of enzymes from bacteria, fungi, and algae, resulting in a reduction of the molar mass of the macromolecules that make up the biodegradable material (Nanda et al., 2010). Many studies have been conducted under different environmental conditions, such as soil, compost, marine, and other aquatic environments, to investigate biodegradability. Most soil and compost environments have a great place due to their high microbial diversity (Anstey et al., 2014). A large amount of plastic waste is disposed of in landfills, which generates greenhouse gases and leachate. For this reason, it is thought that other solid waste management methods, such as composting or recycling, are preferred in the recovery of plastics. Composting is the conversion of organic matter to CO_2 and a soil-like substance (humus) by the activity of a mixed group of microorganisms (Kale et al., 2007). Compostability is a subset of biodegradability, meaning that most biodegradable plastics are compostable (Cesaro et al., 2015).

Since plastic wastes are also widely disposed of in soil environments, their changes and effects in this area are being investigated. Mainly soil environments contain a wide variety of microorganisms. This makes degradation more feasible than in media such as water or air. Many studies in the literature have investigated the biodegradability of PHA and PLA (Emadian et al., 2017). In the marine environment, plastic waste has been found to accumulate essentially evenly. Due to their semi-permanent stability in the marine ecosystem, plastic waste creates marine pollution that could potentially impact marine animals (Volova et al., 2007; Sekiguchi et al., 2011). These plastics persist in aquatic environments for hundreds of years, as low temperatures and minimal UV in the ocean cause slow degradation (Andrady, 2015). Therefore, biodegradable polymers can be used to develop a sustainable environment in marine and water systems (Tosin et al., 2012). One proposed solution is to produce biodegradable plastics such as PHAs, which have shorter lifetimes in the marine environment. However, the time frame for the biodegradation of such seafood needs to be clarified (Dilkes-Hoffman et al., 2019). Understanding the longevity of biodegradable polymers begins with understanding the mechanisms by which biodegradation can occur. PHAs are biodegradable in most natural environments, including the marine environment, with PHA degraders under aerobic and anaerobic conditions (Jendrossek & Handrick, 2002; Shah et al., 2008). Under aerobic conditions, the resulting products are ultimately biomass, CO_2, and water. The products released under anaerobic conditions are biomass, CO_2, methane, and water (Gu, 2003). Biodegradation of PHA occurs by enzyme-catalyzed surface erosion (Guérin et al., 2010; Laycock et al., 2017).

According to the research that has stuck in recent years, seawater dissolution is also a consideration. The primary purpose of designing seawater degradation materials is to ensure that materials "disappear" as soon as they are thrown into seawater. From this point of view, PVA, a water-soluble polymer material, can meet this requirement well. PVA is not biobased but is biocompatible. It has excellent mechanical properties and water solubility and is obtained by the alcoholysis of polyvinyl acetate (Chiellini et al., 2003). The water solubility of PVA is adjusted by varying the degree of polymerization or alcoholysis. More importantly, compared to other synthetic water-soluble polymers, PVA is fully biodegradable in the presence of bacteria in wet environments such as sewage sludge (Corti et al., 2003; Chiellini et al., 1999) and river water (Ikejima et al., 1998). Based on these properties, PVA is recognized as the only biodegradable soluble polymer and has been applied in many fields, such as food packaging, coatings, textiles, cosmetics, and paper (Huang et al., 2019).

Biodegradability, norms, and standards have been established about biodegradability applied to different materials and with different parameters in different environments. The standardization bodies that set the standards are mainly ISO (International Organization for Standardization), CEN (European Standardization Committee), and ASTM (American Testing and Materials Association). In addition, many national standardization bodies, such as the Australian standard (AS), the German Institute for Standardization (DIN), and the Japan Bioplastics Association (JBPA), have created their standards, adding different testing procedures for better regulation. Standardization provides benchmarks for desired product quality requirements and prevents false market behavior (European Bioplastics, 2022). Their degradation standards in compost are mainly; ASTM 6400, ISO 17088, EN 13432, DIN V 54900 (Briassoulis et al., 2010), standards ASTM D5338, ISO 14855; EN 14046 (Table 2) and degradation standards in soil under aerobic composting conditions are mainly; ASTM D 5988 is ISO 17556 (Table 3).

According to the American Society for Testing and Materials (ASTM standard D6400), compostable plastic is a visually non-marking plastic that biodegrades during composting to yield carbon dioxide, water, inorganic compounds, and biomass in a ratio consistent with other known compostable materials. Thus, general criteria for a material's compostability include biodegradability, absence of degradation, non-toxic by-products, and visual separation from the environment (Cesaro et al., 2015).

Table 2. Biodegradable plastics under aerobic composting conditions

Current Versions of Standards	*Title*	*Method*	*Temperature (°C)*	*Duration (Month)*	*Citations*
ASTM D5338	Standard test method for determining aerobic biodegradation of plastic materials under controlled composting conditions	Generated CO_2 Analysis	35–58–50–35	6	Briassoulis et al., 2010 Vedrtnam et al., 2019 Kumar et al., 2019 Kalita et al., 2021 Sintim et al., 2019 Kale et al., 2007
ISO 14855	Determination of ultimate aerobic biodegradability of plastic materials under controlled composting conditions	Generated CO_2 Analysis	58	6	Briassoulis et al., 2010 Funabashi et al., 2009 Kunioka et al., 2007 Funabashi et al., 2007 Hoshino et al., 2007
EN 14046	Evaluation of final aerobic biodegradability of packaging materials under packaging-controlled composting conditions	Generated CO_2 Analysis	58	6	Briassoulis et al., 2010 Sikora et al., 2020 Ciriminna & Pagliaro, 2020 Kapanen, 2012 Jarerat & Tokiwa, 2001

Table 3. Standards for biodegradable plastics in soil

Current Versions of Standards	*Title*	*Method*	*Temperature (°C)*	*Duration (Month)*	*Citations*
ASTM D5988	Standard test method for determining the aerobic biodegradation of plastic materials in soil	Produced CO_2 Analysis, Sequential titrations	25 ± 2 (Room temperature)	6	Al-Salem et al., 2019 Goel et al., 2021 Tosin et al., 2019 Kishk et al., 2020 Pischedda et al., 2019
ISO 17556	determination of final aerobic biodegradation in soil by measuring the oxygen demand or the amount of carbon dioxide emitted	oxygen or Generated CO_2 Analysis	20–25	6	Ardisson et al., 2014 Briassoulis et al., 2020 Briassoulis & Degli Innocenti, 2017 Briassoulis & Mistriotis, 2018 Prapruddivongs et al., 2018
NF U52-001	agricultural and horticultural mulching products - requirements and test methods	Generated CO_2 Analysis	28	12	Deroiné et al., 2015 González et al., 2009 Belloncle et al., 2012 Briassoulis & Degli Innocenti, 2017

Three such ASTM Standard specifications mainly address biodegradable plastics in compost-type environments. These, ASTM D6400-04 Standard Specification for compostable plastics, ASTM D6868-03 Standard Specification for biodegradable plastics used as coatings on paper and other compostable substrates, and ASTM D7081-05 Standard Specification for non-floating biodegradable plastics. Apart from these, the ASTM D6866 method for biobased materials has been developed to document bioplastic's biologically derived ingredients (European Bioplastics, 2022). In current studies (Arcos-Hernandez et al., 2012; Chan et al., 2019; Gómez & Michel Jr., 2013), PHBV biodegradation was observed using the ASTM D5988 test method, and over 30% biodegradation was detected. As evidence of the biodegradability of bioplastics differs between standards, the need for stronger regulation and compliance concerning LCA and recycling requirements is highlighted (Bhagwat et al., 2020).

5. Life Cycle Analysis of Bioplastic and Plastic

The circular economy is based on a life cycle concept in which the entire life cycle of a product or process is evaluated from the moment the raw materials are extracted to the end of its life, and its environmental, cost, social and cultural impacts are measured (Lazarevic et al., 2012). LCA means evaluating the entire life of the industrial product, from raw material extraction to the various stages of material processing, production, distribution, and use (Gironi & Piemonte, 2011; Jawahir et al., 2006). The ISO 14000 international standard determines LCA methodology. ISO 14040; principles and framework, ISO 14041; purpose, scope, and inventory analysis, ISO 14042; lifecycle impact review, ISO 14043; lifecycle interpretation and ISO 14044; needs and directives (Özbilen et al., 2011).

End-of-life options for plastic products have yet to be addressed in the past. Due to their extremely high resistance to degradation in natural environments, plastics have accumulated extensively in aquatic and terrestrial ecosystems (Geyer et al., 2017; Kaur et al., 2018). Conventional plastics produced from petroleum raw materials cause high environmental impacts from plastic production methods (Zheng & Suh, 2019), 4% of global CO2 emissions from plastics production (Zheng & Suh, 2019), and significant methane emissions due to leaks in supply. (Grubert & Brandt, 2019). To limit this trend, coordinated global actions are needed to reduce plastic consumption, increase reuse and recycling, and accelerate innovation in sustainable substitutes (Fu et al., 2019). As most biobased plastics are created as a potential substitute for petrochemical plastics, an accurate comparison of the environmental efficiency of these different plastics through LCA is crucial (Bishop et al., 2021).

From a circular economy perspective and considering the waste management hierarchy proposed by the EU, the use of a refillable bottle is supported instead of any disposables. The end-of-life scenarios recommended by the EU are constant recycling or recovery for packaging materials as the preferred options compared to storage (Tamburini et al., 2021). However, recovery is only sometimes a viable solution. Currently, most synthetic organic materials are produced from fossil carbon raw materials regenerated on time scales of millions of years. Biobased alternatives are rapidly renewable in cradle-to-cradle cycles (1-10 years), and such materials extend storage life and reduce undesirable effects from material persistence (Rostkowski et al., 2012).

For life cycle analysis, the most common impact categories in the articles reviewed, excluding global warming potential, acidification potential, eutrophication potential, resource depletion, photochemical oxidant generation, ozone depletion, ecotoxicity, human toxicity, particulate matter generation, energy, land use, and water consumption. There is an increasing number of studies evaluating the environmental impacts of bioplastics and comparing biobased plastics with their petrochemical counterparts, emphasizing savings and trade-offs across impact categories (Pawelzik et al., 2013; Tsiropoulos et al., 2015; Karvinen, 2015). The literature focuses on bioplastics' energy consumption and global warming potential compared to petrochemical plastics (Brizga et al., 2020). However, it is limited to a small number of LCA studies.

Bioplastics have been shown to save on non-renewable energy use and greenhouse gas emissions compared to conventional materials (Dunn et al., 2015). Globally, bioplastics can save between 241 and 316 Mt CO2 per year by replacing 65.8% of all conventional plastics (Pawelzik et al., 2013). In a study considering the changes in global warming potential, acidification potential, and eutrophication potential impact categories, a decrease in global warming potential and an increase in acidification and eutrophication potential were determined using bioplastics instead of traditional plastics (Koch & Mihalyi, 2018). According to Piemonte & Gironi (2011), the use of bioplastics can provide significant energy and greenhouse gas impact savings over fossil-based plastics. Papong et al. (2014) conducted a comparative LCA study on environmental impact. Accordingly, the production of bioplastic bottles results in reductions in CO2 emissions, lower toxicity, and less demand for non-renewable energy than conventional plastics. Another study showed that it is possible to reduce greenhouse gas emissions by replacing petroleum-based plastics with bioplastics, measured using the Global Warming Potential

(GWP) guideline (Thelen et al., 2010; Ingrao et al., 2015).

To use fertilizers and chemicals in the cultivation of renewable raw materials used for bioplastic production. Bioplastics have a substantial impact on the environment for soil acidification and eutrophication. In some cases, copolymers can be added to improve the bioplastic properties. Because copolymers were added, the mechanical performance of biopolymers was improved at the expense of biodegradability. However, it should be noted that the presence of non-biodegradable copolymers in bioplastics leads to a significant increase in energy demand and CO2 emissions (Gironi & Piemonte, 2011). Literature studies in Table 4, generally recommend bioplastics for reducing consumption of non-renewable resources and greenhouse gas emissions while preferring conventional plastics for impact indexes on acidification and eutrophication (Walker & Rothman, 2020). According to the European Commission, research should focus on the future impact of alternative production techniques, the most efficient raw materials, and determining the sustainability of bioplastics in a circular, net zero carbon future (European Commission, 2019). However, replacing all petrochemical plastics with bioplastics is currently impossible, as this results in a significant increase in land and water use (Brizga et al., 2020).

Table 4. LCA findings

Polymer	***LCA Findings***	***Author***
Biobased or petrochemical raw materials	Substitution of bio-based products with products made from petrochemical raw materials CO_2 savings can be achieved.	Pawelzik et al., 2013
Bioproducts and their fossil-based counterparts	Bioproducts have been replaced by their fossil-based counterparts, reducing cradle-to-grave greenhouse gas emissions from 27% to 86%.	Dunn et al., 2015
Bioplastics and conventional plastics	A decrease in global warming potential and an increase in acidification and eutrophication potential have been found.	Koch & Mihalyi, 2018
PBS, PLA, and PET	In energy use and the climate change categories, fossil-based and bio-based polymers were found to show very similar data ranges. In acidification, biobased PBS and PET are disadvantageous. Biobased PLA has been found to have high environmental impacts in ecotoxicity, biobased PET, and eutrophication.	Walker & Rothman, 2020
Biobased high-density polyethylene and partially biobased polyethylene terephthalate	Biobased polymers were equal to or lower than their petrochemical counterparts. Petrochemical polymers outperform their biobased counterparts for human health and ecosystem quality, but the potential for further improvement in the environmental performance of biobased polymers remains to be explored.	Tsiropoulos et al., 2015
PS and PLA	In the comparative evaluation related to the life cycle performed, the global warming potential, PLA (4,826 kg CO_2) was lower than PS (5.11 kg CO_2).	Ingrao et al., 2015
Fossil-based and bio-based polymers	From petrochemical and bioplastics: greenhouse gas emissions from producing petrochemical polymer packaging from bioplastics are higher than greenhouse gas emissions.	Brizga et al., 2020
PLA and PET	Presence of non-biodegradable copolymers in bioplastics leads to a significant increase in energy demand and CO_2 emissions.	Gironi & Piemonte, 2011

Existing studies (Ingrao et al., 2015; Brizga et al., 2020; Dunn et al., 2015; Pawelzik et al., 2013) indicate that greenhouse gas emissions will decrease with the use of bioplastics instead of fossil-based plastics. However, it has been stated that the use of fossil-based plastics is advantageous in acidification and eutrophication potential due to pesticides, herbicides, and fertilizers used in raw material production (Walker & Rothman, 2020; Koch & Mihalyi, 2018).

6. Results

The European Union works for a zero-emission economy based on circularity and sustainability. The demand for plastic products is increasing with the increase in our global population and living standards. Considering a large amount of plastic waste accumulation in the environment and the environmental effects of the production, processing, and disposal methods of plastic products, biobased plastics come to the fore as an alternative. From an environmental point of view, it is promising that bioplastics effectively degrade in the soil environment, unlike fossil-based plastics that accumulate in the soil for hundreds of years without degradation (Chamas et al., 2020). Bioplastics have the potential to move various industries to a circular economy. However, the use of renewable resources alone does not mean sustainability. Sustainability depends more on how a material is made, where it is used, and how it can be recycled rather than on its building block. In this context, since bioplastics are not permanent in the environment, they are preferred over traditional plastics as a more sustainable option. Standardization organizations (ISO CEN, ASTM, AS, DIN, JBPA) have established specific standards to measure biodegradability. Their degradation standards in compost are mainly; ASTM 6400, ISO 17088, EN 13432, and DIN V 54900, and soil degradation standards are mainly; ASTM D 5988 is ISO 17556. There are many studies on biodegradability in specific environments, particularly in soil and compost media. High degradation rates (>90%) are noted in the literature for PLA and PHA-based bioplastics in compost, soil, and seawater environments (Schröpfer et al., 2015; Boyandin et al., 2013; Gutierrez-Wing et al., 2011; Sintim et al., 2020; Emadian et al., 2017; Deroiné et al., 2015).

While bioplastics generally have the essential advantages of being made from bio-based materials and are non-toxic, they show lower strength than conventional plastics. In some cases, additives are added to increase its performance, which negatively increases its environmental impact. As most biobased plastics are created as a potential substitute for petrochemical plastics, it is essential to accurately compare the environmental efficiency of these different plastics through LCA. While bioplastic can save in terms of fossil resources, it harms the ecosystem due to the use of different chemicals (pesticides, herbicides, fertilizers) to produce raw materials. While literature studies favor traditional plastics for impact indexes on acidification and eutrophication (Koch & Mihalyi, 2018), they suggest bioplastics for reducing consumption of non-renewable resources and greenhouse gas emissions (Koch & Mihalyi, 2018; Brizga et al., 2020; Dunn et al., 2015; Pawelzik et al., 2013). To ensure sustainable industry development, only bioplastics Regulations must be provided for their ability to decompose and their conversion to CO2 and water without the release of harmful chemicals. Durable bioplastics can act as a carbon sink if well integrated into the large-scale and long-term infrastructure. The possibility of using more bioplastic materials to improve society's lifestyle should be explored. The reduction in recycling costs, in particular, opens the horizon for new applications in agriculture, medicine, and more. The recent high prices for crude oil and the potential market for agricultural materials provide an economic impetus.

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