Journal of Polymers and the Environment (2020) 28:3055–3075
https://doi.org/10.1007/s10924-020-01830-8

REVIEW

Benchmarking Bioplastics: A Natural Step Towards a Sustainable Future

Geetika Bhagwat[1] · Kelsey Gray[1] · Scott P. Wilson[2] · Sudhakar Muniyasamy[3,4] · Salom Gnana Thanga Vincent[5,6] · Richard Bush[7] · Thava Palanisami[5]

Abstract

The ubiquitous presence of plastic litter and its tending fate as marine debris have given rise to a strong anti-waste global movement which implicitly endorses bioplastics as a promising substitute. With 'corporate social responsibility' growing ever more popular as a business promotional tool, companies and businesses are continually making claims about their products being "green", "environmentally friendly", "biodegradable", or "100% compostable". Imprudent use of these words creates a false sense of assurance at the consumer end about them being responsible towards the environment by choosing these products. The policies surrounding bioplastics regulation are neither stringent not enforceable at both national and international stage which indirectly allow these "safe words" to be used as an easy plug to validate the supposed corporate social responsibility. Similar to conventional plastics, unregulated and mismanaged bioplastics could potentially create another environmental mayhem. Therefore, it is a crucial time to harness the power of law to set applicable standards with a high threshold for the classification of "bioplastics", which companies can aspire to, and customers can trust. In this review, we analyse the multifarious international bioplastics standards, critically assess the potential shortcomings and highlight how the intersection of law with science and technology is crucial towards the reform of bioplastics regulation.

Graphic Abstract

Extended author information available on the last page of the article

Keywords Bioplastics · Bio-based plastics · Bioplastic policies · Plastic pollution · Bioplastic standards · Biodegradable · Global policies

Abbreviations

AS	Australian Standard
ASTM	American Society for Testing and Materials
CEN	European Committee for Standardization
DIN	Deutsches Institut für Normung OR German Institute for standardization
JBPA	Japan BioPlastics Association
OECD	Organization of Economic Co-operation and Development
PLA	Poly(lactic acid)
PHAs	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate
PHBV	Poly(hydroxybutyrate-co-hydroxyvalerate)
PCL	Polycaprolactone
PBAT	Poly(butylene adipate-co-terephthalate)
PBS	Poly(butylene succinate)
PE	Polyethylene
PP	Polypropylene
PET	Polyethylene terephthalate

Introduction

Overwhelming environmental accumulation of plastic waste and its deleterious impacts have been underlined and validated with enough scientific evidence in the last couple of decades [1–4]. Several worldwide campaigns and perpetually increasing consumer awareness persuaded lawmakers from several countries in African, Asian and European continent to completely ban or implemented levies on the use of single-use plastic [5]. Consequently, Bioplastics (BPs) have started gaining attention as an "environment-friendly" alternative to conventional plastics with roughly a 25% growth estimated in their global market by 2023 [6]. With such a rapid growth expected, without assuming, it is critical to question if bioplastics offer a tangible solution to the global plastic waste problem and whether the rapidly growing bioplastic industry is being properly regulated.

To regulate the growing industry, a continuous emergence of bio-based, biodegradable and compostable plastic standards is taking place. However, several matters surrounding the operations and certification need immediate attention before bioplastics pollution emerges as the next environmental concern. First, "Bioplastics" is a poorly defined umbrella term creating misperception and tremendous confusion. According to European Bioplastics, a plastic is defined as a bioplastic if it is bio-based, biodegradable or features both properties [7]. The misperception originates when the connotation of "bio-based" and "biodegradable" is considered the same. "Bio-based" means that the origin of the product is either in full or partially derived from plant biomass explained frequently with a plethora of terms like 'plant-derived', 'new carbon' or 'organic carbon' etc. (see Table 1 for other bioplastic related terms). However, bio-based origin does not infer to the biodegradability of a material that indicates the environmental fate of a material. Therefore, a universal nomenclature for bioplastic products is the first essential step to ensure that consumers are well-informed and choose the correct waste treatment streams for bioplastic products.

Bio-based plastic products are designed to meet the necessary functionalities during their use. Upon disposal, it is expected to biodegrade within a specified time frame while leaving no toxic residues. However, there is no data to support the complete biodegradation of these products within a reasonably short period [8]. If the blurred distinction between bio-based and biodegradable bioplastics is not fixed soon, more microplastics will be generated from bioplastics disregarding their original purpose as an environmentally safe alternative. Therefore, benchmarking bioplastics using a universally accepted set of biodegradability parameters is crucial.

Finally, the multifarious international bioplastic standards follow dissimilar guidelines which are highlighted and discussed for their relevance (or absence) in the natural environmental setting. Since the substantiations of biodegradability of bioplastics differ between standards, the need for stronger regulation and compliance as per their life-cycle assessment (LCA) and recycling requirements is emphasised. The review has closely looked at the factors affecting biodegradability and the possible impacts of the potential environmental accumulation of bioplastic degradation products. We have also highlighted the importance of regulating the attractive labelling of products (as "biodegradable", "compostable", "degradable", "100% renewable" etc.) to ensure validity among the consumers. For the sake of clarity, different bioplastic certification standards introduced across the world are critically compared which include ISO (International organisation for Standardization), American Society for Testing and Materials (ASTM), Australian standard (AS), European Committee for Standardization (CEN), German Institute for standardization (DIN) and GreenPla (Japan).

Bioplastics: Definition and Types

The main issues encountered with the design and production of bioplastics are keeping production costs down and the optimisation of physical, chemical and mechanical properties to ensure biodegradability [9]. The lack of stringent

Table 1 Definitions of common terms used to classify polymeric materials [7, 60]

Term	Definition
Bio-based plastic	A plastic containing organic carbon of renewable origin like agricultural, plant, animal, fungi, microorganisms, marine, or forestry materials living in a natural environment in equilibrium with the atmosphere
Biopolymer blend	Biopolymer blend made up of renewable resource- based polymers, and their biodegradability depends on their polymer matrix. For example: (i)Biopolymer blends poly (lactic acid) PLA-polybutylene adipate terephthalate PBAT are biodegradable and compostable; (ii) biopolymer blend bio-based nylon-bio-based polyethylene are non-biodegradable
Biocompatible plastic	Biocompatible plastics are used in the medical field to enhance healing functions without causing injurious, negative physiological, allergic or toxic reactions
Biocomposite	A plastic material made by mixing renewable organic fillers like wood fibres, jute, hemp, flex etc. in its matrix
Biodegradable plastic	A degradable plastic in which the degradation results from the action of naturally occurring micro-organisms such as bacteria, fungi, and algae
Plastic as biomaterial	A plastics type which may be used in medical applications to support, enhance, or replace damaged tissue or a biological function and does not impair immunological functions of the body
Bioplastics	A plastic that it is derived from the biomass or issued from monomers derived from the biomass and which, at some stage in its processing into finished products, can be shaped by the flow
Compostable plastic	A plastic that undergoes biological degradation during composting to yield carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials and leaves no visually distinguishable or toxic residues
Degradable plastic	A plastic designed to undergo a significant change in its chemical structure under specific environmental conditions resulting in a loss of some properties that may vary as measured by standard test methods appropriate to the plastic and the application in a period that determines its classification
Drop-in bioplastics	A "bio-similar" copy of the petrochemical plastics which is made from biomass instead of fossil-oil and uses the same degradation pathway as the petrochemical plastics
Hydro degradable plastic	A degradable plastic in which the degradation results from hydrolysis
Oxidatively degradable plastics	A degradable plastic in which the degradation results from oxidation
Oxo-biodegradable plastic	A plastic which undergoes degradation only when combination of abiotic oxidation process and a cell-mediated processes act in a simultaneous or successive manner
Photodegradable plastic	A degradable plastic in which the degradation results from the action of natural daylight
Plastic	A material that contains as an essential ingredient one or more organic polymeric substances of large molecular weight, is solid in its finished state, and, at some stage in its manufacture or processing into finished articles, can be shaped by flow
Polymer	A large molecule composed of repeating units (monomers) typically connected by covalent bonds

policies and consumer awareness allows manufacturers to embellish their product names with safe words like "green" and "eco" creating a false sense of responsible behaviour among the consumers. Based on the origin of the raw material and environmental fate, all bioplastics can be assigned to the following three categories (Fig. 1).

Type I: Bio-Based and Non-biodegradable

The bioplastic products such as polylactic acid (PLA), thermoplastic starches (TPS), polyhydroxyalkanoates based on natural or renewable feedstock follow the same pathway, technology, equipment and machinery as their conventional counterparts. Thus, they are essentially a "bio-similar" copy of the conventional (fossil-based) plastics and are not biodegradable or compostable [10]. They are also known as 'drop-ins' or 'bio-blend' and sometimes can contain starch or other biodegradable components in smaller amounts to only accelerate their fragmentation [11, 12]. However, once fragmented into microplastics, these bioplastics essentially have the same environmental impact as fossil-based plastics.

Drop-in bioplastics include commodity plastics like bio-based Polyethylene (PE), Propylene (PP), Polyvinyl chloride (PVC) and Polyethylene terephthalate (PET). A noteworthy example is "Plantbottle", a material launched in 2009 by the Coca-Cola company (Fig. 2), in which the fossil fuel-based ingredient used to make a key ingredient in PET plastic, was replaced with renewable materials from plants (30% plant-based). Coca-Cola reported that "Plantbottle", has helped prevent 365,000 metric tons of potential CO_2 emissions since its introduction [13]. While the plant bottle is recyclable, the properties of the product are identical to their conventional versions (not biodegradable or compostable), though the leaf in its design suggests otherwise. The caveat here is that their success is relying on a 100% recycling rate, otherwise, plant bottles could produce microplastics similar to conventional plastic bottles. Other non-biodegradable technical/performance polymers (Fig. 1) included in this

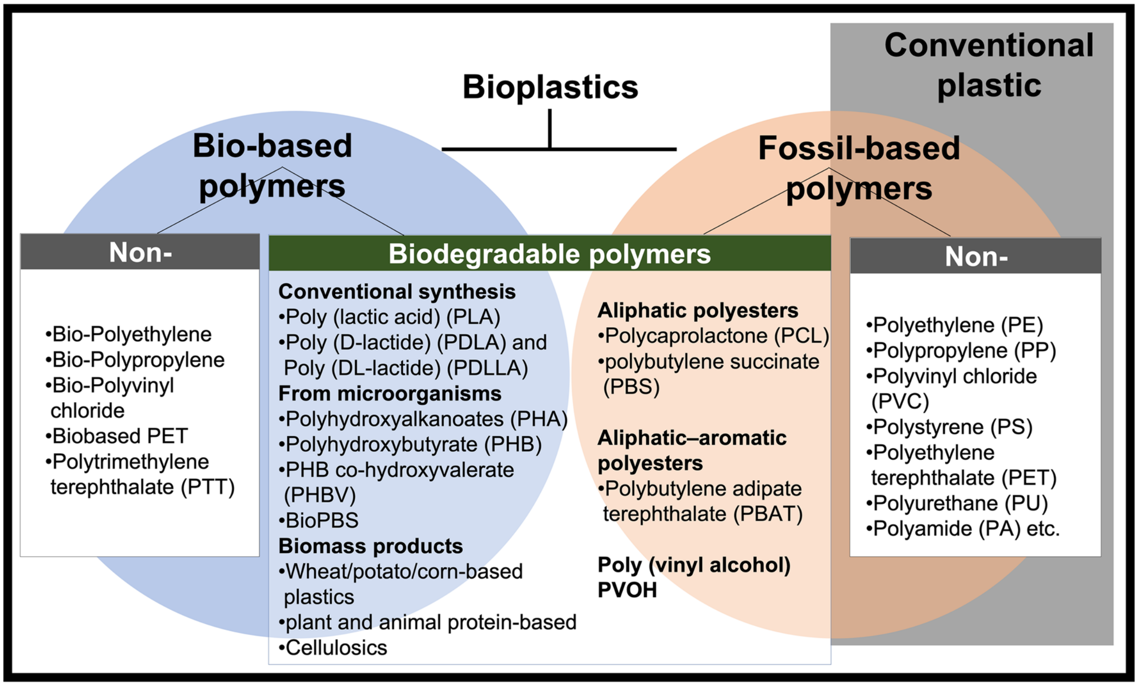

Fig. 1 Characterisation and examples of bioplastic materials based on their source and biodegradability (modified from EUPB [7])

Fig. 2 PlantBottle by Coca-Cola

category are bio-based polyamide (PA), polyesters like poly (trimethylene) terephthalate (PTT) and polybutylene terephthalate (PBT), polyurethanes (PUR) and polyepoxides typically used as textile fibres, whose operating life lasts several years but are clearly not biodegradable [7].

Drop-ins and conventional plastic differ in their price and environmental footprint. Drop-ins are more expensive due to lower processing capacity, lower investment in research and development and higher price of raw material compared to conventional plastics. The only conceivable advantage of drop-ins is their lower environmental footprint [14]. Briefly, conventional plastic production introduces new carbon-dioxide (CO_2) but the CO_2 released during the manufacture of drop-ins could be captured by the plants providing the raw material, thus theoretically completing the cycle.

Type II: Bio-Based and Biodegradable

Bioplastics belonging to this category could be produced from plant biomass, microbial fermentation products and animal-derived polymers to emulate the life cycle of biomass producing CO_2 and water while conserving fossil resources [7]. Plant-derived raw materials (which include vegetable oil, starch from wheat, rice, barley, oat and soy sources, fibres obtained from pineapple, jute, hemp, henequen leaves and banana stem, etc.) are used to extract thermoplastic starch, lignin, rubber, cellulose, etc. required for bioplastic production [15, 16]. Polyurethane foam with up to 50% renewable content is produced using biomass biopolyols from three residual biomass feedstocks: digested sewage sludge, hemp stalk hurds and sugar beet pulp [17]

Bioplastics derived from microbial sources are mainly polyesters [e.g. poly (3-hydroxybutyric acid)] which are storage polymers enzymatically produced by certain microbes to support their survival and growth when subjected to different nutrient and environmental stressors [18]. Given the high production and recovery cost, the use of microbial fermentation for bioplastic production is still very limited [19]. Animal-derived products such as chitin, silk, wool, casein, gelatine, gluten and fats are also be used in bioplastic production [20, 21]. Recently, collagen has been suggested as a potential source to create "bioplastic skin", mainly derived from animal hides, to tackle the issue of waste generated in the meat and plastic industries [22]. Commercial bioplastics belonging to this category include Polylactic acid (PLA), Polybutylene Succinate (Bio-PBS), Polyhydroxy butyrate (PHB) and polybutylene adipate terephthalate (PBAT) (Fig. 1).

Type III: Fossil-Based and Biodegradable

Some fossil-based polymers used for bioplastic production inherently possess a certain amount of biodegradability including aliphatic polyesters like polybutylene succinate (PBS), poly-caprolactone (PCL), polyglycolic acid (PGA) and polyvinyl alcohol (PVOH); aromatic polyesters like polybutylene terephthalate (Fig. 1) [20, 23, 24]. Polymer degradation studies suggest that chain characteristics like hydrophilicity, reactivity, functional group stability; and mechanical properties like molecular weight (M.W.) and elasticity generally dictate biodegradability, not the origin of the raw materials [25, 26]. For instance, PCL, which is not bio-based, can completely degrade after only six weeks in compost conditions that utilise activated sludge given that no additives are present [27]. In the presence of overlapping definitions for bioplastic products, it is imperative that a detailed classification and specialized nomenclature is prepared to represent bioplastic origin and biodegradability.

Biodegradation of Polymers

Biodegradation occurs due to the action of enzymes from naturally occurring microbes (bacteria, fungi and algae) resulting in a reduced molar mass of macromolecules forming the biodegradable material [28, 29]. The process of biodegradation can be divided into (1) primary degradation and (2) ultimate degradation. During primary degradation, the material undergoes weight loss, fragmentation, reduction in M.W. and is degraded into soluble low M.W compounds. Ultimate biodegradation or mineralization leads to the conversion of low molecular weight compounds (from primary degradation) into water (in aerobic conditions), CH_4 (in anaerobic conditions), CO_2 and cell biomass [24, 29–32]

Compostability is a subset of biodegradability meaning that most biodegradable plastics are compostable. According to American Society for Testing and Materials (ASTM standard D6400), compostable plastic is "a plastic that undergoes biological degradation during composting to yield carbon dioxide, water, inorganic compounds and biomass at a rate consistent with other known compostable materials and leaves no visually distinguishable or toxic residues. Thus, the overall criteria of compostability of a material involve biodegradability, disintegration, non-toxic by-products and no visual distinction from the surroundings [33]. To be characterised as compostable, the following criteria must be fulfilled [34]: (a) Material/chemical characteristics: Organic and inorganic matter content, (b) Biodegradability: Extent of biodegradation or mineralization defined as the conversion of the organic carbon to CO_2, (c) Disintegration: Degradation of material int visually undetectable components (<2 mm) under controlled composting conditions and (4) Ecotoxicity: The compost obtained at the end of the composting trial, eventually containing undegraded residuals from the product, should not affect the germination and growth of plants and also earthworms in some cases. These criteria are used in the next section to discuss current global standards for biodegradable plastics and identify potential shortcomings in context to addressing critical environmental issues surrounding the use and disposal of bioplastic materials.

The biodegradability of material is greatly governed by its polymer structure [35]. Most polymer structures have either a hetero-chain or carbon backbone. Hetero-chain polymers include polysaccharides, proteins, polymers sourced from plants such as PLA, PBS and microbially-synthesized polymers like PHVB. Hetero-chain polymers degrade via enzyme-mediated or non-enzyme-mediated hydrolysis which can be influenced by factors such as thickness, chemical bonds, co-polymer type, water uptake and morphology. Polymers with carbon backbone such as natural rubber and lignin, biodegrade via oxidation or enzyme mediated (oxidative) biodegradation which may take years and slower compared to hetero-chain polymers [36]. As discussed earlier, most materials referred as biodegradable are often biocomposites which are created by blending other biodegradable materials like potato peel waste fermentation residue [37], empty fruit branch fibres [38] with the main bioplastic material to enhance their biodegradability. Consequently, the addition of such eco-friendly composites does not guarantee enhanced biodegradation as the variability in temperature and other factors in the real field conditions across the globe are arduous to address [39].

Apart from polymer properties, the rate and degree of biodegradation is dependent on various abiotic and biotic factors. For instance, in compost and soil where the higher temperature is available for degradative reactions, the rate of biodegradation is higher [40]. Similarly, the concentration and diversity of microbial communities are higher in soil and compost that supports higher rates of biodegradation (Fig. 3) [41]. In the aquatic systems, microenvironments have been shown to have a profound impact on the degradation of biodegradable plastics. Therefore, to efficiently capture the complexity of the aquatic environments, test methodology needs to account for all the habitats (supralittoral, eulittoral, sublittoral benthic, deep-sea benthic, pelagic and sediments) along with abiotic stressors (pH, salinity, temperature, UV etc.) and microbial communities influencing degradation [41, 42]. Other factors impacting biodegradation of materials include salinity, humidity, oxygen presence, pH and UV radiation [43, 44]. Major studies on biodegradation of bioplastics conducted in the laboratory and natural conditions are summarized in Table 2.

Global Bioplastic Standards and Certification Bodies

The major standardizing bodies creating standards are ISO International Organization for Standardization), CEN (European Committee for Standardisation) and ASTM (American Society for Testing and Materials). Also, many national standardization organizations like Australian standard (AS), German Institute for standardization (DIN) and Japan Bioplastic Association (JBPA) have created their own standards by incorporating extra testing procedures for better regulation. Standardization introduces benchmarks for desirable product quality requirements and ensures that fraudulent market behaviour is prevented. For instance, European Bioplastic association describes two systems of product evaluation: (1) use of test methods which include procedures that need to be followed using the described methodology and (2) use of a definitive set of a pass and fail criteria as the requirements that need to be met for a product or material to be compliant with the standard [45]. While these two types are often paired, the use of the second system (pass/fail) ultimately defines standard compliance. Although compliance to a standard can be voluntary or mandatory in a country, an independent standards certification of compliance obliges a product be tested and examined by an independent certification body that recruits both systems of product evaluation explained previously (Fig. 4). Since the main objective of this review is to highlight the differences in the process of product evaluation in different parts of the world, detailed information on the certification requirements by major global standardization bodies is provided in the next few sections.

European Committee for Standardisation

In Europe, independent certificates for biodegradable plastics are issued by DIN Certco (based on EN 14995 or ISO 17088) and Vincotte (based on EN 13432) which also certify products which can degrade in home composting, soil and water. The plastic used in packaging can provide proof of their compostability by successfully meeting the harmonised European standard, EN 13432:2000 or EN 14995:2006 which defines the technical specification for the compostability of bioplastics products.

- Material characterization: European standard CEN/TS 16137:2011: Plastics—Determination of bio-based carbon content specifies the calculation method for determining the bio-based carbon content in monomers, polymers and plastic materials and products, based on the ^{14}C content measurement (described in EN 15440 and ASTM D6866). It is currently the most important guideline for substantiating marketing claims regarding a material's or product's bio-based carbon (total and organic) content. Additionally, EN 16640:2017 and EN 16785:2018 contain methods to determine bio-based content using elemental analysis and material balance method.

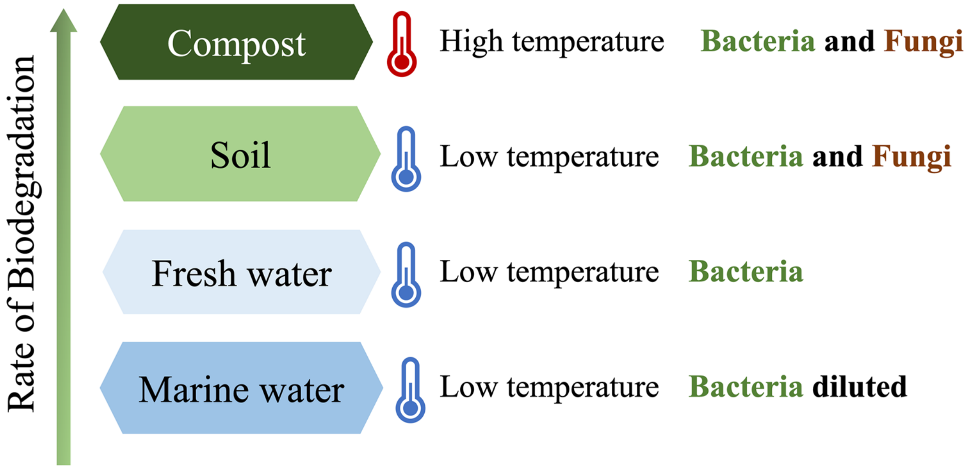

Fig. 3 Rate of biodegradation in different environments

Table 2 Major studies on biodegradation of bioplastics in different environments

Environment	Bioplastic type	Range of degradation conditions	Biodegradability method	Biodegradability	No of days	References
Compost	PLA-based	58 °C, 60–70% humidity Aerobic conditions	Weight loss and produced CO_2	13–84%	28–60	[61–64]
	PHB	55–58 °C, 70% humidity	Produced CO_2	~80%	28–60	[63] [65]
	Potato starch-based bioplastic	58 °C, aerobic	Weight loss	~85%	90	[66]
	Mater-bi (starch + resin)	23 °C, 58% humidity, aerobic	Weight loss	26.9%	72	[67]
	PA-based Nylon 4	25 °C, 80% humidity, pH 7.5–7.6	Weight loss	100%	120	[43]
	PBS composites	58–65 °C, 50–55% humidity, aerobic, pH 7–8	Produced CO_2	90%	100–160	[68]
	PCL	55 °C	Produced CO_2	38%	6	[69]
Soil	PLA powder and composites	25–58 °C, 30–80% humidity	Weight loss	10- 60%	28–98	[38, 66, 70, 71]
	PHB-based	20–35 °C, natural conditions, 65% humidity	Weight loss and produced CO_2	35–98%	15–300	[72–78]
	Starch-based	20 °C, 60% humidity	Produced CO_2	14.2%	110	[75]
	PBS-based	25 °C, 60% humidity	Weight loss	1–24.4%	28	[71]
	Polyolefins with bioderived components (1), polyolefins with bio-derived components (2)	28 °C, simulated soil conditions	Weight loss	59.5–69.5% (1), 23.4% (2)	150	[79]
	PCL films	25 °C	Weight loss	31%	16	[77]
Sea/marine water	PHB-based	Static (21 °C) and dynamic (12–22 °C) incubation, average temperature (28.75 °C)	BOD biodegradability, weight loss	30–99%	14–160	[80, 81]
	Mater-bi (starch + resin)	Room temperature, marine water with sediments	BOD biodegradability	68.9%	236	[82]
	Mater-bi (starch + resin)	Marine water conditions	Weight loss	10–20%		[83]
	PA-based Nylon 4	25 °C	Weight loss	30%	21	[80]
	Polyolefins with bioderived components (1), polyolefins with bio-derived components (2)	28 °C, simulated marine conditions	Weight loss	69.7–87% (1), 55.4% (2)	150	[79]
Synthetic material containing compost	PLA	58 °C, aerobic	Weight loss	63.6–100%	28–90	[44, 66, 84]
Microbial culture from soil	PHB-based	Conditions required for microbial growth	Weight loss	~18%	18	[85]
Fresh water	PHB	20 °C, real river water condition	Weight loss	43.5%	42	[40]
	Mater-bi (starch + resin)	Temperate freshwater conditions	Weight loss	50%	150	[83]

Table 2 (continued)

Environment	Bioplastic type	Range of degradation conditions	Biodegradability method	Biodegradability	No of days	References
Brackish water sediments	PHB	20 °C, pH 7.06	Weight loss	100%	56	[86]
Municipal solid waste mixture	Cellulose-based	Conditions required for microbial growth	Weight loss	35–44%	14	[87]
Inoculum from a municipal wastewater treatment plant	PLA	30 °C, aerobic	Weight loss	39%	28	[44]
	PCL-based	30 °C, aerobic	Weight loss	7.6–53%	28	

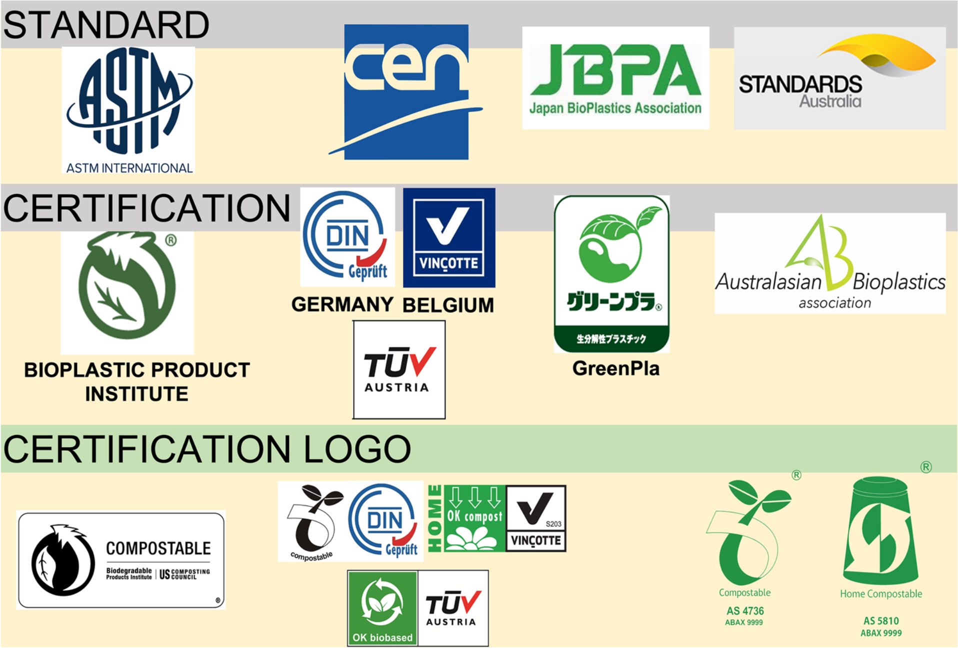

Fig. 4 Major global bioplastic standards and certification bodies

- Biodegradability: Biodegradation level of at least 90% must be reached in less than 6 months for any packaging products or biodegradable plastics, regardless of the type of polymer. The standard EN 17033 "Biodegradable mulch films for use in agriculture and horticulture—Requirements and test methods" specifies the requirements for biodegradable films, manufactured from thermoplastic materials, to be used for mulching applications in agriculture and horticulture, which are not intended to be removed. A degradation of at least 90% in two years at preferably 25 °C is required.
- Disintegration: After 84 days in a controlled composting test, no more than 10% of the original dry mass of material should remain after sieving on a 2 mm sieve.
- Ecotoxicity: The seedling growth test follows OECD Chemical Guidelines 208 (OECD, 2003) which involves comparing two higher plants (from Dicotyledonae and Monocotyledonae families), when one plant has added biodegraded plastics, and the other does not. The effect is observed as changes to plant germination and plant growth. The germination rate and plant biomass for both species should be 90% the same, as a minimum. The compost must not be negatively affected by control waste treatment processes and the parameters to be considered are volumetric weight, total dry solids, volatile solids, salt content, presence of nitrogen, ammonium, phosphorus and magnesium, and potassium. Acceptable heavy metal concentrations are specified (Table 3) and should not exceed the threshold.

International Standards organization

Currently, ISO 17088:2012 "Specifications for Compostable Plastics" specifies procedures and requirements for the identification and labelling of plastics, and products made

Table 3 A comparison of Prescribed threshold values for elements within constituents of bioplastics (EN13432 and ASTM D6400)

Element	Europe, Japan and Australia Limit values (mg/kg)	ASTM D6400 Limit values (mg/kg)
Arsenic	5	21.5
Cadmium	0.5	19.5
Copper	50	750
Cobalt	N/A	N/A
Chromium	50	N/A
Fluorine	100	100
Lead	50	150
Mercury	0.5	8.5
Molybdenum	1	N/A
Nickel	25	210
Selenium	0.75	50
Zinc	150	1400

from plastics, that are suitable for recovery through aerobic composting.

- Material characterization: Chemical characterization of material including the analysis of organic content, nutrients and hazardous substance (organic and inorganic) is not specified in the standard.
- Biodegradability: To meet biodegradability/mineralization requirements, 60% of organic content from a homopolymer and 90% of all other (copolymers or blends) must be converted to CO_2 within 180 days.
- Disintegration: Given in ISO 16929:2013 "Plastics—Determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test"; according to which after 84 days in a controlled composting test, no more than 10% of the original dry mass of material should remain after sieving on a 2 mm sieve.
- Ecotoxicity: Low level of heavy metal concentration based on EN 13432 and a minimum of 50% volatile solids (APHA 2504G) is specified. Volatile solids are the solids obtained by subtracting residues after incineration at 550–580 °C from total dry solids content and is an indication of the amount of organic matter in the material. For ecotoxicity assessment, the terrestrial plant test as per OECD Chemical Guidelines 208 is required.

American Society for Testing and Materials

In the USA, Biodegradable Products Institute (BPI) provides certification based on ASTM standard. As per current standard ATSM D6400-19: "Standard Specification for labelling of plastics designed to be aerobically composted in municipal or industrial facilities", a material must biodegrade completely when exposed to an inoculum derived from a municipal waste stream. The United States Federal Trading Commission of USA requires ASTM D5338-15 as a requirement for making biodegradability claims about a product or material in which aerobic biodegradation of bioplastics for a minimum of 90 days but up to 180 days at a temperature greater than 50 °C is measured. It's primarily used for materials that have not made it to the waste stream yet, often being used for materials intended to test food and beverage containers.

- Material characterization: Chemical characterization of the organic constituent present more than 1% must be individually tested. Analysis of nutrients and hazardous substances (organic and inorganic) is not specified in the standard.
- Biodegradability: For products consisting of a single polymer (homopolymer or random copolymer), 60% of the organic carbon and for products consisting of more than one polymer like copolymers, blends and addition of low molecular additives, 90% of the organic carbon must be converted to CO_2 by the end of the test period within 180 days when compared to the positive control.
- Disintegration: After 84 days in a controlled composting test, no more than 10% of the original dry mass of a material should remain.
- Ecotoxicity: Levels of heavy metal concentration (based on EN13432) must be determined. Ecotoxicity assessment follows OECD Chemical Guidelines 208.

Standards Australia

Standards Australia is an independent, not-for-profit organisation recognized by the Australian Government as the prime non-government standards body. They adopt internationally aligned standards in Australia but are not responsible for enforcing, regulating, or certifying compliance with these standards. The Australasian Bioplastic association manages a voluntary verification scheme (https://www.bioplastics.org.au/certification/), for companies or individuals wishing to have their claims of compliance with AS verified which in turn provides the companies a competitive advantage. There are two Australian standards relating to biodegradable plastics

(a) AS 4736–2006: "Biodegradable Plastics Suitable for Composting and other Microbial Treatment"

- Material characterisation: The constituents of the plastic and the properties for each constituent, such as thickness and visual observations are recorded (Shah and others, 2008) along with the volatile solids content which must

form a minimum 50% of the plastic. The presence of metals and hazardous substances are analysed and must not exceed the standard values (Table 3). The organic carbon content and the total dry solids of the plastic are also recorded.
- Biodegradability: Standards test is conducted aerobically over 6 months and to pass the criteria the test material must degrade at least 90% of its dry weight. All organic constituents must be analysed, including dyes, inks, and colours. Biodegradability is to be determined for the whole material and any constituent present in the plastic at a greater concentration than 1%. The constituents forming less than 1% of the plastic composition need not be tested. An alternative method to test for biodegradation is the anaerobic test, expressed as the percentage of biogas production which must be greater than 50% within two months.
- Disintegration: A disintegration test is satisfied when there is sufficient degradation of the test material achieved within 12 weeks. No more than 10% of the dry weight of the material can fail to pass through a 2 mm fraction sieve. Also, the plastic material must not be able to be distinguished from other materials in the compost from 500 mm away.
- Ecotoxicity: Ecotoxicity assessment follows OECD Chemical Guidelines 208 but a further test that is unique to Australian standards testing involves toxicity test for earthworms that comply with ASTM E1676. According to this, less than a 10% difference in the morbidity or mean weight of surviving worms between the treated compost and the control, needs to be achieved to pass the test.

(b) AS 5810–2010: “Biodegradable plastics suitable for home composting”

Since home composting systems vary considerably in their design, construction and operation; their performance can also vary considerably compared to commercial composting facilities. Consequently, AS 5810–2010, in comparison to AS 4736–2006, uses lower temperatures in test environments and longer test duration, to account for such variations in the performance of different home composting systems. In the case of a plastic product formed from different components, where some are compostable and others not, the product itself, cannot be designated ‘home compostable’. The plastic product or plastic component is designated as ‘home compostable’ only if all the criteria set out below are met:

- Material characterisation: As with AS 4736–2006 above
- Biodegradability: As with AS 4736–2006 above, except period is up to 12 months and temperature should be 25 ± 5 °C and shall be kept below 30 °C for the duration of the test)
- Disintegration: As with AS 8746–2006 above, except period is up to 180 days and temperature should be 25 ± 5 °C)
- Ecotoxicity: As with AS 8746–2006 above.

Japan Bioplastic Association

Japanese Institute of Standards does not provide any generalised standard for the regulation of bioplastics. In Japan, GreenPla verifies biodegradable plastics using ISO methods and evaluates based upon the pre-established criteria by Japan BioPlastic Association (JPBA). They have developed a “Green Pla” biodegradable plastics certification system which adopts a similar framework for regulation but is still unique in much of its approach to regulation.

- Material characterization: All the constituents of material must be placed in a ‘Positive List’ provided by Green Pla (see Table 4 for details) and the constituents belonging to category A must at least form 50% of the weight or volume of a product and is biodegradable. Additionally, the upper limits are specified for metals and other elements (Table 3). However, there is no such limit to pass the test other than that it should be biodegraded by 60% of the parent material. Non-biodegradable high-polymer material can be present at concentrations less than 1% if it is proven that it serves a useful function.
- Biodegradability: To meet biodegradability/mineralization requirements, 60% of organic content from a homopolymer and 90% of all other (copolymers or blends) must be converted to CO_2 within 180 days.
- Disintegration: As per ISO 16929:2013
- Ecotoxicity: Ecotoxicity assessment follows OECD Chemical Guidelines 208 but a unique feature of the Green Pla certification system is its acute toxicity testing conducted on freshwater organisms which involve undertaking three types of tests: algal growth inhibitors, acute immobilisation tests on *Daphnia*, and acute toxicity tests on fish. This test records LD_{50} and ED_{50} where LD_{50} should be at least 2000 mg/kg.

As evident, the agreed product evaluation criteria are noticeably different for each standard which can complicate the process of benchmarking bioplastics. Particularly, the material characterization differs significantly between standards which not only can influence the life cycle of bioplastic but can significantly influence their environmental impact (discussed in the next few sections). A List of all the major published standards is provided in Table 5 and a snapshot of the significant differences between these standards is provided in Table 6.

Table 4 Positive list by Japanese Green Pla bioplastic certification system

Classification code	PL category	Remarks
A	Biodegradable plastics	Biodegradable synthetic high-polymer materials with a molecular weight (Mw) of at least 1000. This includes chemically modified starch and poly amino-acid based biodegradable high polymer materials
B (Additives)		
1	Stabilisers	Antioxidants, radical scavengers, and ultraviolet absorbers etc
2	Surfactants	Antistatic agents, antifog additives, dispersants, and emulsifiers etc
3	Lubricants	Mould release agents, organic anti-blocking agents, plasticizers, waxes, rosins etc
4	Inorganic materials	Inorganic anti-blocking agents and inorganic coloured fillers etc
5	Blowing agents	Includes auxiliary blowing agents
6	Other (1) organic materials	Food additives used under the Food Hygiene Law, etc
7	Other (2) organic materials with special functions	Specified functional materials, functional nonbiodegradable high polymer materials and nonbiodegradable adhesives etc. for exclusive use in Green Pla
8	Natural organic materials	Starch, cellulose, wood flour etc
9	Colour materials	Organic pigments, dyes, masking agents, food dyes, and inorganic pigments
C (other materials)		
1	Semifinished products	Raw materials where the total amount of biodegradable plastic (Category A) and natural organic materials (Category B-8) accounts for at least 50% of the weight (or volume) of the product, and to which additives (Category B) have been added (does apply when the item itself does not constitute a finished product, such as master batch. Includes biodegradable inks)
2	Biodegradable adhesives	Reactive biodegradable adhesives, etc

Shortcomings in Bioplastics Benchmarking and Environmental Impacts

Globally, compliance to a bioplastic standard could be voluntary or mandatory which the United Nations has commented on the lack of international cohesion, stating that until there is an internationally agreed definition of biodegradability, the labelling of products as 'bioplastics' will not bring about a significant decrease in the amount of plastics entering the ocean [46]. The lack of regulation over what is considered 'biodegradable' could potentially enhance the post-disposal risks. For instance, most of the standards require that biodegradable materials must degrade (not biodegrade) by at least 90% and are not visible at a 500 mm height. No further treatment is advised once the material reaches the microscopic size. Consequently, bioplastics microparticles could remain in the environment if they do not meet optimum biodegradation conditions (heat, water and microbes). Therefore, it is quite imaginable that bioplastics will behave like conventional plastics, find their way in landfills or the ocean and do not decompose in a reasonable amount of time.

Recognisability, the final test, is a subjective, consumer-based criterion, which requires plastics entering the biowaste stream to be recognised as compostable by the end-user. The key criticism is the failure of standards in enforcing the companies to provide details on adequate waste management for their product, which in turn, brings more responsibility to consumers. Contrastingly, incorrect labelling of bioplastic products as "green" or 'biodegradable", reduces the personal consumer responsibility which results in inappropriate disposal of bioplastic products. Dotted lines in Fig. 5 represent the lack of flow of appropriate information about the lifecycle and disposal of bioplastics.

Another discrepancy within the mentioned standards is around the characterization of biodegradable materials components. Standards follow a definite list of elements in which a product should comply to requirements for certification. However, threshold values of the elements greatly differ between all the standards (Table 3) which further complicates waste allocation and environmental impact assessment of bioplastic additives and degradation products [47]. Besides, currently, there is no standard providing clear pass/fail criteria for the degradation of plastics in seawater. ASTM D7081 "Standard Specification for Non- Floating Biodegradable Plastics in the Marine Environment" has been withdrawn without replacement and only the test methods that were referred are still in places such as ASTM D6692, ASTM D7473, OECD 306 and ISO 16221. None of these accounts for the variation between polymer types, or any variation arising from additives. Additionally, they do not account for unmanaged water systems, the dissemination of microplastics, or the overall toxicological effect of material for a complete assessment of habitat within a time frame.

The prevalent argument in support of expanding the bioplastic market is its sustainability and low carbon footprint.

Table 5 List of published standards for biodegradation of plastics

Standard	Description
AS 4736–2006	Biodegradable plastic suitable for composting and other microbial treatment
AS 5810–2010	Biodegradable plastics suitable for home composting
ASTM D6954 -04	Standard guide for exposing and testing plastics that degrade in the environment by a combination of oxidation and biodegradation
ASTM D5526-94	Standard test method for determining anaerobic biodegradation of plastic materials under accelerated landfill conditions
ASTM D5951-96	Standard practice for preparing residual solids obtained after 2002 biodegradability standard methods for plastics in solid waste for toxicity and compost quality testing
ASTM D5988-03	Standard test method for determining aerobic biodegradation in soil of plastic materials or residual plastic material after composting
ASTM D6002-96	Standard guide for assessing the compostability of environmentally degradable plastics
ASTM D6340-98	Standard test methods for determining aerobic biodegradation of radiolabelled plastic materials in an aqueous or compost environment
ASTM D6400-99	Standard specifications for compostable plastics
ASTM D6691-01	Standard test method for determining aerobic biodegradation of plastic materials in the marine environment by a defined microbial consortium
ASTM D6692-01	Standard test method for determining biodegradability of radiolabelled polymeric plastic materials in seawater
ASTM D7081-05	Standard specifications for non-floating biodegradable plastics in the marine environment
ASTM D5209-92	Standard test method for determining the aerobic biodegradation of plastic materials in the presence of municipal sewage sludge
ASTM D5338-98	Standard test method for determining aerobic biodegradation of plastic materials under controlled composting conditions
DIN V 54900–2	Testing of compostability of plastics—Part 2: testing of the complete biodegradability of plastics in laboratory tests
EN 13432:2000	Requirements for packaging recoverable through composting and biodegradation—test scheme and evaluation criteria for the final acceptance of packaging
EN 14045:2003	Packaging—evaluation of the disintegration of packaging materials in practical oriented tests under defined composting conditions
EN 14046:2003	Packaging—evaluation of the ultimate aerobic biodegradability of packaging materials under controlled composting conditions—method by analysis of released carbon dioxide
EN 14047:2002	Packaging—determination of the ultimate aerobic biodegradability of packaging materials in an aqueous medium—method by analysis of evolved carbon dioxide
EN 14048:2002	Packaging—determination of the ultimate aerobic biodegradability of packaging materials in an aqueous medium–method by measuring the oxygen demand in a closed respirometer
EN 14806:2005	Packaging—preliminary evaluation of the disintegration of packaging materials under simulated composting conditions in a laboratory-scale test
ISO 14851:1999	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium—method by measuring the oxygen demand in a closed respirometer
ISO 15314:2004	Methods for marine exposure ISO 16221:2001 water quality—guidance for the determination of biodegradability in the marine environment
ISO 14852:1999	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium—method by analysis of evolved carbon dioxide
ISO 14855:1999	Determination of the ultimate aerobic biodegradability and disintegration of plastic materials under controlled composting conditions—method by analysis of evolved carbon dioxide
ISO 14593:1999	Water quality—evaluation of the ultimate aerobic biodegradability of organic compounds in aqueous medium—method by analysis of inorganic carbon in sealed vessels (CO2 headspace test)
ISO 16929:2002	Plastics—determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test
ISO 20200:2004	Plastics—determination of the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test
ISO 17556:2003	Plastics—determination of the ultimate aerobic biodegradability in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved
CEN/TR 15822	Plastics: biodegradable plastics in or on soil—recovery, disposal and (under approval) related environmental issues
AFNOR NF U52-001	Biodegradable materials for use in agriculture and horticulture-mulching products—requirements and test methods

Table 6 Comparative summary of bioplastic standards around the world

Standards/certification bodies	Characterisation	Biodegradability (carbon converted to CO_2)	Disintegration (original weight remaining after sieving through 2 mm sieve)	Compost quality measurements	Additional requirements
ASTMD6400 (USA)	Heavy metal concentration NOTE: Percentage of organic content forming plastic is not specified	Non-homopolymers: 60% of organic carbon converted to CO_2 in 6 months Homopolymers: Overall 90% of carbon converted to CO_2 in 6 months using suitable reference material	No more than 10%	No more than 10% difference in biomass and germination rate when compared with cellulose compost	If the test material is radio-labelled, the testing period can extend to 365 days
AS4736-2006 (Australia)	Volatile solids, heavy metals, thickness, organic carbon content, total dry solids, colour constituents, more than 50% organic material	At least 90% of dry weight is degraded within 6 months	No more than 10% within 3 months Cannot be distinguished from other material at 500 mm	Volumetric weight, total dry solids, volatile solids salt content, pH, nitrogen, ammonium, phosphorus, magnesium, potassium	Recognised as compostable by end user
AS5810-2010 (Australia)	Volatile solids, heavy metals, thickness, organic carbon content, total dry solids, colour constituents, more than 50% organic material	At least 90% of dry weight is degraded within 12 months	No more than 10% within 6 months Cannot be distinguished from other material at 500 mm	No more than 10% difference in morbidity or mean weight of earth worms	N/A
CEN	Minimum organic content of 50%, heavy metals	90% of organic matter converted into carbon dioxide within 6 months	No more than 30%	Agronomical study of eco-toxic effects on two species of plants, following OECD Guideline 208 Measure volumetric weight, total dry solids, volatile solids, salt content, pH, and nutrient content	Practical test of compostability in semi-industrial facilities Optional anaerobic testing
DIN V54900 (Germany)	Organic constituents form more than 50% of material Total organic content, TC, volatile solids, ash content, elemental analysis of carbon, hydrogen, oxygen, sulphur, and nitrogen Nutrient analysis of nitrogen, phosphorus, potassium, magnesium, and calcium Analysis of hazardous inorganic substances (zinc, copper, nickel, cadmium, lead, mercury, chromium) Analysis of hazardous organic substances (PCB, PCDD/F)	Homopolymers degrade by 60% after 6 months, and copolymers degrade by 90%	No more than 10%	Visual inspection (content of unwanted residues) No loss of quality in comparison with blank compost of same maturity	Non-obligatory anaerobic biodegradability

Table 6 (continued)

Standards/certification bodies	Characterisation	Biodegradability (carbon converted to CO_2)	Disintegration (original weight remaining after sieving through 2 mm sieve)	Compost quality measurements	Additional requirements
ISO 17088:2012	Characterization and analysis of organic content, nutrients and hazardous substance (organic and inorganic) is not specified	Homopolymers degrade by 60% after 6 months, and copolymers degrade by 90%	ISO 16929:2013- After 84 days, no more than 10% of the original dry mass of a material should remain after sieving on a 2 mm sieve	As per EN13432- Amount of heavy metals has to be below maximum values and the final compost must not be affected negatively (no reduction of agronomic value and no eco-toxicological effects on plant growth	N/A
Green Pla (Japan)	All constituents placed on the positive list Bioplastics must be the constituent material Biodegradable and organic materials must account for 50% of weight or volume, inorganic material must be less than 50% of volume Threshold limits for elements and heavy metals	Substance must have biodegradability of 60% Non-biodegradable high polymer materials can be present at a concentration less than 1% if it proved to have a useful function	Satisfy the degradability tests according to ISO16929 No more than 10% within 3 months	Reproduction inhibition tests on two species, following OECD Chemical Guideline 208	Acute toxicity tests conducted on freshwater organisms: algal growth inhibitor, *Daphnia* acute mobilisation tests, and fish acute toxicity tests using LD_{50} and ED_{50}

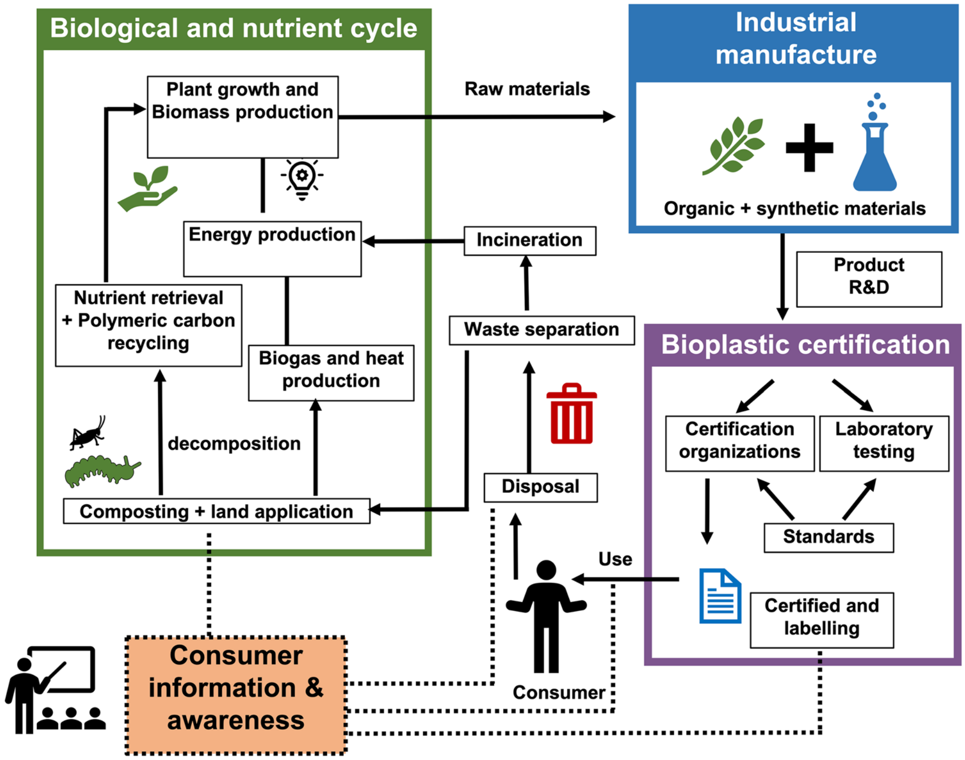

Fig. 5 Bioplastics and us- Dotted lines show the lack of consumer information surrounding the labelling, use, disposal and fate of bioplastic products

Detailed information on how to measure and report on the carbon footprint of products is provided in ISO 14067 "Carbon Footprint of Products". Additionally, the two standards ISO 14040 and ISO 14044 focus on describing the principles of LCA. In Europe, the equivalent standard is EN 16760 which is based on the ISO 14040 series and EN 16751 which standardises the sustainability criteria of bio-based products and provides specific LCA requirements. However, it does not include any thresholds or limits and is unsuitable for making claims on the sustainability of products or operations. There are many other certification schemes for the sustainability of biomass, for example, ISCC PLUS, RSB (Roundtable on Sustainable Biomaterials), or REDcert but they are not based on a standard but the provisions of the EU Directive 2009/28/EC (Renewable Energy Directive).

Bioplastics in the Circular Economy

Global production capacities of bioplastics are predicted to reach about 2.62 million tonnes [6] in 2023, and this is the right time to investigate the environmental fate of so-called "Bio'-plastics" and make sure potential risks are addressed. To assess the environmental risks of bioplastics, the environmental impact of production, use and disposal of bioplastic ("cradle to grave") needs to be determined (lifecycle of bioplastics in Fig. 6). It is also known as life cycle analysis (LCA) which is based on characterising and comparing environmental impact (Table 7) using most important indices of environmental impact detailed below [48]:

(a) Abiotic depletion—this characterization factor considers the potential of abiotic depletion of the extraction of those minerals and fossil fuels and expressed as kg of antimony per kg of extracted material
(b) Global warming—This determines the potential of global warming of greenhouse gas emitted to the air

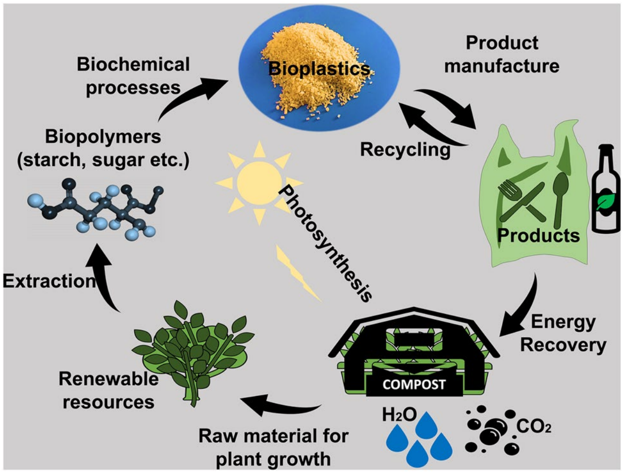

Fig. 6 Life cycle of Bioplastics

Table 7 Life cycle assessment of bioplastics compared to conventional plastics

Impact category (unit per kg)	[88]			[89]		
	PHB	PP	HDPE	PLA	PET	PS
Abiotic depletion (kg of Sb)	21.8	41.4	35.3			
Global warming (kg CO_2)	1960	3530	2510	735	763	730
Ozone layer depletion (kg CFC-11)	0.00017	0.000862	0.000766	0.0000915	0.0000948	0.0000871
Human toxicity (kg of 1,4-DCB)	857	1870	2590	257,000*	266,000*	260,000*
Freshwater aquatic toxicity (kg of 1,4-DCB)	106	234	176			
Marine aquatic toxicity (kg of 1,4-DCB)	1,290,000	1,850,000	1,230,000			
Terrestrial ecotoxicity (kg of 1,4-DCB)	8.98	44	33.7			
Photochemical oxidation (kg ethylene)	0.78	1.7	17.5	–	-	-
Acidification (kg SO_2)	24.9	48.8	22.5	5.66	4.97	4.87
Eutrophication (kg PO_4)	5.19	5.84	0.811	0.0886	0.148	0.0819
Respiratory organics (kg ethylene)	–	–	–	1.33	1.29	1.24
Respiratory inorganics (kg $PM^{\#}$ 2.5)	–	–	–	1.31	1.26	1.22

*Aquatic ecotoxicity, PM = Particulate matter, 1,4-DCB = 1,4-dichlorobenzene, SO_2 = sulphur dioxide

during the production of a material and expressed as kg of carbon dioxide equivalent per kg of emission

(c) Human toxicity—the characterization factor is the potential of human toxicity of toxic substances emitted to the air, water or/and soil and expressed as kg of 1,4-dichlorobenzene equivalent per kg of emission

(d) Freshwater aquatic ecotoxicology—it is the potential of freshwater aquatic toxicity of each substance emitted to the air, water or/and soil and expressed as kg of 1,4-dichlorobenzene equivalent per kg of emission

(e) Marine aquatic ecotoxicology—is characterization factor considers the marine aquatic toxicity of each substance emitted to the air, water or/and soil and expressed as kg of 1,4-dichlorobenzene equivalent per kg of emission

(f) Terrestrial ecotoxicology—it is the potential of terrestrial toxicity of each substance emitted to the air, water or/and soil and expressed as kg of 1,4-dichlorobenzene equivalent per kg of emission

(g) Photochemical oxidation—it is measured as the potential of photochemical ozone formation of each substance emitted to the air and expressed as kg of ethylene equivalent per kg of emission

(h) Acidification—the acidification potential of for each acidifying emission to the air expressed as kg of sulphur dioxide equivalent per kg of emission

(i) Eutrophication—it is the potential of eutrophication of each eutrophying emission to the air, water and soil and expressed as kg of phosphate ion equivalent per kg of emission.

From the greenhouse gas emission and energy demand point of view, the production of bioplastics might appear advantageous compared to conventional plastics [49] but the presence of non-biodegradable polymers in drop-ins significantly increases the energy demand and CO_2 emission compared to biodegradable bioplastics. The energy recovery by incineration of bioplastics is also low which can be justified due to their low calorific value compared to fossil-based plastics [50].

We are already facing a global challenge of mismanaged plastic waste due to insufficient capacity of collection, sorting and recycling which renders it difficult to transition towards a circular economy for plastic (European commission, 2019). With ever-evolving socioeconomic and material-level inventions, the bioplastic material landscape is continuously advancing. Hence, many innovative bioplastics are entering the markets, which is also the result of sustainability and circular economy influencing the bioplastics industry [51]. In 2019, the agro-based feedstock for the production of bioplastics (which is mostly 1^{st} generation) used about 0.016 percent (0.79 million ha) of the global agricultural area which is expected to increase to 0.021% (1.00 million ha) by 2024 [6]. Although currently, the land-use for feedstock production for bioplastics is low, the increase in demand can certainly put additional pressure on limited resources, such as land, water with implications for food security and climate change [52]. Thus, an alternative means of producing bioplastics in large quantities is important for supporting a sustainable source of plastics. In this context, micro and macroalgal biomass provide a potential source for producing bioplastics, both by directly using the biomass, as well as using it as a feedstock for secondary processes [53]. Due to their biodegradability and similarity to petroleum-based plastics, bioplastics derived from microalgae provide an ecological alternative as they can be used with the existing infrastructure and applications.

Table 8 Environmental impacts of production and/or use of commonly used bioplastics constituents modified from [56]

Bioplastics	Classification	Source	Feedstock production	Health hazards during product manufacture
Polyhydroxyalkanoates (PHAs)	Aliphatic polyesters	Microbial fermentation of renewable feedstocks such as sucrose, vegetable oils and fatty acids	Uses methods of industrial agricultural production, including GMOs and pesticides	Extraction requires halogenated solvents like chloroform, methylene chloride, and 1, 2 dichloroethane which are occupational carcinogens Other chemical that may be used include pyridine, methanol, hexane or diethyl ether Chemical digestion uses sodium hypochlorite, methanol and diethyl ether
Polylactic acid (PLA)	Thermoplastic aliphatic polyester	Polymerization of lactic acid derived from microbial fermentation of mainly corn starch or cane sugar	Uses methods of industrial agricultural production, including GMOs and pesticides	Recovery of lactic acid from fermentation used sulphuric acid and organic tin in the polymerization catalytic system Use of organotin compounds which can build up in living organisms
Bio-urethanes (BURs)	Easter of carbamic acid	Obtained by the reaction of isocyanates with the diol or polyol groups present in vegetables oils such as castor, soy, sunflower and linseed	Uses methods of industrial agricultural production, including GMOs and pesticides	Require the use of hazardous isocyanates which cause severe irritation to mucous membranes of the eyes and respiratory tract
TPS (thermoplastic starch)	Low crystalline linear polymer of D-glucose units attached α-1,4-, and amylopectin	Starch is obtained from Corn, potato, maize, wheat, tapioca etc. and the thermoplastic properties are achieved by extrusion of starch at high temperature which destroys the crystalline character of the material	Uses methods of industrial agricultural production, including GMOs and pesticides	Finely pulverized starch used as raw material can cause powerful explosions when suspended in the atmosphere
Cellulose	Polymer made of β linked D-glucose	Produced by chemical modification of natural cellulose and lignin obtained from wood and involves the use of elevated temperature, pressure and harsh chemical treatment with sodium sulphide and sodium hydroxide	Required high energy and large amounts of water Pollutants are emitted during kraft process	Exposure to disulphide, sodium hydroxide, sulphur, propionic, acetic, sulfuric, and nitric acid
Lignin	Cross-linked phenolic polymers	Lignin is a by-product of cellulose production		
Bio-based PTT (polytrimethylene terephthalate)	Linear aromatic polyester	Produced by the reaction of 1,3 propanediol (PDO), obtained by microbial (may be GMO) fermentation processes from glucose (of corn starch) with a dicarboxylic acid such as terephthalic acid (PTA) or dimethyl terephthalate (DMT)	Uses methods of industrial agricultural production, including GMOs and pesticides	Exposure to pesticides, terephthalic acid, dimethyl terephthalate, and methanol

Table 8 (continued)

Bioplastics	Classification	Source	Feedstock production	Health hazards during product manufacture
Zein protein	Prolamin protein	Extracted by wet milling of corn	Uses methods of industrial agricultural production, including GMOs and pesticides	Exposure to pesticides, alcohol, volatile solvents, formaldehyde, or glutaraldehyde
Soy protein	Globulin family of seed storage proteins	Extracted from dehulled and defatted soybean		

Potential Negative Impacts of Bioplastics on the Environment

The current bioplastic standards allow for the inclusion of additives and heavy metals. The US standard has the highest thresholds for toxic metals in bioplastics which are known to cause a myriad of effects on organisms and the environment [54, 55]. Aside from metals and other additives, the actual constituents of the bioplastics may themselves have adverse environmental impacts. For example, PLA is derived from corn starch which emits methane, a much more potent greenhouse gas than carbon dioxide, as it decomposes in a landfill. Production of PHA requires the use of harsh chemicals like pyridine and diethyl ether which have potential occupational hazards. The data on the energy requirement of bioplastics is still controversial and the environmental impacts of the bioplastic constituents during their production could be potentially hazardous (Table 8) and warrants further research [56].

Microbial communities play an essential role in regulating elemental life cycles and environmental degradation of various materials. When compared to conventional plastic bags, biodegradable bags were found to have substantially less chlorophyll on their surface in the marine environment indicating that the material type could be influencing the recruitment and/or persistence of algae. Additionally, a change in the physicochemical characteristics of marine sediments beneath plastic bags, with a linked reduction in sediment fauna abundance has been observed [57]. Bioplastics can also increase the susceptibility of coral to diseases, which subsequently has habitat implications for the marine environment [58]. More studies are warranted on the interaction of bioplastic with the microbial communities in the environment for a proper environmental assessment of bioplastics products and to avoid creating another environmental mayhem.

Bioplastics are difficult to dispose of given their longevity, toxicity, malleability, and potential to disintegrate into microplastic. The lack of bioplastic-specific recycling facilities increases the risk of degradation products getting collected through existing recovery systems for conventional plastics and contamination of the recycling stream. As a result, the mechanical properties will change significantly, and the quality of the recycled material will be low [11, 38, 59]. Contamination of the recycling stream can be minimised through improved sorting techniques, possibly using spectroscopic techniques, and by regular testing of the incoming materials [59]. Therefore, before we replace conventional plastics with bioplastics, all tiers of government must have suitable recycling policy and programs which enable bioplastics to be disposed of correctly at facilities specially designed for bioplastic waste.

Summary

Plastic pollution being a major scientific and environmental issue is likely to encourage the use of biodegradable plastics, as a suitable amelioration strategy. While we encourage research and development for better performing bioplastics, it is necessary to adopt a 'cradle to cradle' approach which assesses the environmental impact of bioplastic constituents and degradation products. The present disparities in bioplastic policies between jurisdictions, national, subnational and international platforms only prove that the bioplastic regulation is currently NOT on the global agenda. The common denominator for policymakers is to keep flexibility to prevent the development of intractable situations that can work against innovation. While bringing all the standard bodies together is an essential step, a policy framework which would encompass the following recommendations can be useful:

- Creating international agreement about LCA, biodegradability, compostability
- Introducing laws and strict policies which would relate to the standards and more closely regulate the improper use of labelling of 'biodegradable' to avoid doubt among the consumers
- Revoking standards to assess the impact of plastic additives, different temperatures, and other variables known to cause different rates of biodegradation which are not currently tested
- Utilising a broader range of testing environments to determine biodegradability under different conditions, including a range of aquatic environments present in various geographical locations
- Harmonisation LCA procedure while involving as many indices for environmental impact as possible
- Communicating to consumers the correct disposal methods of bioplastics through appropriate labelling, reinstating their responsibility for its right disposal
- Introducing effective and widespread recycling services and facilities which accept bioplastics for composting purposes; and
- Establishing additional tests and facilities so that the new researchers can quickly and easily test their products without wasting time

Acknowledgments We would like to acknowledge The University of Newcastle for providing access to research and library facilities. SGTV is grateful to the Association of Commonwealth Universities (ACU) for the Blue Charter Fellowship—2019–2020.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

References

1. de Souza Machado AA et al (2018) Microplastics as an emerging threat to terrestrial ecosystems. Glob Chang Biol 24(4):1405–1416
2. Villarrubia-Gómez P, Cornell SE, Fabres J (2018) Marine plastic pollution as a planetary boundary threat—the drifting piece in the sustainability puzzle. Mar Policy 96:213–220
3. Law KL (2017) Plastics in the marine environment. Annu Rev Mar Sci 9(1):205–229
4. Haward M (2018) Plastic pollution of the world's seas and oceans as a contemporary challenge in ocean governance. Nature Communications 9(1):667
5. UNEP, *SINGLE-USE PLASTICS: A Roadmap for Sustainability*, T. Cannon, Editor. 2018: Norway.
6. EUPB, N.i., *New market data: The positive trend for the bioplastics industry remains stable*. 2018: Berlin.
7. EUPB, *What are bioplastics? Material types, terminology, and labels—an introduction*. 2016, European Bioplastics.
8. Song JH et al (2009) Biodegradable and compostable alternatives to conventional plastics. Philos Trans R Soc B 364(1526):2127–2139
9. Leja K, Lewandowicz G (2010) Polymers and biodegradation and biodegradable polymers – a review. Polish Journal of Environmental Studies 19:12
10. Amin M, Abu-Sharkh B, Al-Harthi M (2012) Effect of starch addition on the properties of low density polyethylene for developing environmentally degradable plastic bags. J Chem Eng 26(1):3
11. CIWMB, *Performance Evaluation of Environmentally Degradable Plastic Packaging and Disposable Food Service Ware*. 2007, CIWMB.
12. Nolan-ITU, *Biodegradable Plastics - Developments and Environmental Impacts*. 2002: Canberra.
13. CocaCola, J. *More Sustainable Packaging: What We're Doing and How We're Doing It*. 2017 28 August 2017 [cited 2018 20th January 2018]; Available from: https://www.coca-colacompany.com/stories/our-progress-what-were-doing-and-how-were-doing-it.
14. Michael Carus LD (2017) Ángel Puente, Achim Raschka. Bio-based drop-in, smart drop-in and dedicated chemicals, in Road to Bio, Oliver Arendt
15. Jabeen N, Majid I, Nayik GA (2015) Bioplastics and food packaging: a review. Cogent Food Agric 1(1):1117749
16. Bioplastics, E. *Bioplastics market data*. 2016 [cited 2016 29 May]; Available from: https://www.european-bioplastics.org/market/.
17. Jasiūnas L et al (2020) Mechanical, thermal properties and stability of rigid polyurethane foams produced with crude-glycerol derived biomass biopolyols. J Polym Environ 28(5):1378–1389
18. Sudesh K, Abe H, Doi Y (2000) Synthesis, structure and properties of polyhydroxyalkanoates: biological polyesters. Prog Polym Sci 25(10):1503–1555
19. Luengo, J., et al., *Bioplastics from microorganisms*. Vol. 6. 2003. 251–60.
20. Song, J.H., et al., *Biodegradable and compostable alternatives to conventional plastics.* Philosophical transactions of the Royal Society of London. Series B, Biological sciences, 2009. **364**(1526): p. 2127–2139.
21. Müller C, Townsend K, Matschullat J (2012) Experimental degradation of polymer shopping bags (standard and degradable

plastic, and biodegradable) in the gastrointestinal fluids of sea turtles. Sci Total Environ 416:464–467
22. Grapevine, T.R. *Reducing Animal Waste and Bioplastic Skin: Valdís Steinarsdóttir's Art Of Sustainability*. 2019 [cited 2019 10th June 2019].
23. Smith, R., *Biodegradable polymers for industrial applications 1st Ed. Cambridge, UK: Woodhead Publishing / Elsevier. 552pp*. 1 ed. 2005, UK: Woodhead Publishing 552.
24. Vroman I, Tighzert L (2009) Biodegradable polymers. Materials 2(2):38
25. EUPB, *European Bioplastics: Driving the evolution of plastics*. 2016.
26. Anderson, J., M., and Shive, M., S., 28, 5., *Biodegradation and biocompatibility of PLA and PLGA microspheres.* Advanced Drug Delivery Reviews, 1997. **28**(1): p. 20.
27. Rutkowska M, Krasowska K, Heimowska A, Smiechowska M, Janik H (2000) 9, 221, The influence of different processing additives on biodegradation of poly(epsilon-caprolactone). Iran Polym J 9(4):7
28. Nanda, S., Sahu, S., S., and Abraham, J., , *Studies on the biodegradation of natural and synthetic polyethylene by Pseudomonas spp.* Journal of Applied Science Management, 2010. **14**(2): p. 4.
29. Chauhan A (2012) Environment-friendly biodegradable polymers and their applications. Malays Polym J 7(2):6
30. M. Vert, Y.D., K.-H. Hellwich, M. Hess, P. Hodge, P. Kubisa, and M.R.a.F. Schue´, *Terminology for biorelated polymers and applications (IUPAC Recommendations 2012.* Pure Appl. Chem., 2012: p. 377.
31. Kawai, F., *Biodegradation of polymers (bioassimilation, biomineralization, biodisintegration, compost), overview*, in *Encyclopaedia of polymeric nanomaterials*. 2015, Springer: Berlin, Heidelberg.
32. Muniyasamy S (2013) Biodegradability and compostability of lignocellulosic based composite materials. J Renew Mater 1:253
33. Cesaro A, Belgiorno V, Guida M (2015) Compost from organic solid waste: quality assessment and European regulations for its sustainable use. Resour Conserv Recycl 94:72–79
34. Deconinck, S., de Wilde, B, *Benefits and challenges of bio- and oxo- degradable plastics, a comparative literature study. Final Study, O.W.S. for PlasticsEurope.* 2013.
35. Serwańska-Leja, K. and G. Lewandowicz, *Polymer Biodegradation and Biodegradable Polymers - a Review.* Polish Journal of Environmental Studies, 2010. **19**.
36. M. Sudhakar, A.C., and E. Chiellini, *Oxo- Biodegradation of Full Carbon Backbone Polymers under Different Environmental Conditions.* 2012, Saarbrücken: Lambert. Academic Publishing.
37. Wei L, Liang S, McDonald AG (2015) Thermophysical properties and biodegradation behavior of green composites made from polyhydroxybutyrate and potato peel waste fermentation residue. Ind Crops Prod 69:91–103
38. Harmaen AS et al (2015) Thermal and biodegradation properties of poly(lactic acid)/fertilizer/oil palm fibers blends biocomposites. Polym Compos 36(3):576–583
39. Rudnik E, Briassoulis D (2011) Degradation behaviour of poly(lactic acid) films and fibres in soil under Mediterranean field conditions and laboratory simulations testing. Ind Crops Prod 33(3):648–658
40. Volova TG et al (2010) Biodegradation of polyhydroxyalkanoates (PHAs) in tropical coastal waters and identification of PHA-degrading bacteria. Polym Degrad Stab 95(12):2350–2359
41. Sekiguchi T et al (2011) Biodegradation of aliphatic polyesters soaked in deep seawaters and isolation of poly(ε-caprolactone)-degrading bacteria. Polym Degrad Stab 96(7):1397–1403
42. Volova TG et al (2017) Microbial degradation of polyhydroxyalkanoates with different chemical compositions and their biodegradability. Microb Ecol 73(2):353
43. Hashimoto K et al (2002) Biodegradation of nylon4 and its blend with nylon6. J Appl Polym Sci 86(9):2307–2311
44. Massardier-Nageotte V et al (2006) Aerobic and anaerobic biodegradability of polymer films and physico-chemical characterization. Polym Degrad Stab 91(3):620–627
45. EUPB, *Bioplastics – Industry standards & labels*, in *Relevant standards and labels for bio-based and biodegradable plastics*. 2018.
46. UNEP, *Biodegradable plastics and marine litter*. 2015, United Nations Environment Programme: Nairobi. p. 38.
47. Harrison, J.P., et al., *Biodegradability standards for carrier bags and plastic films in aquatic environments: a critical review.* Royal Society Open Science, 2018. **5**(5).
48. Philp JC et al (2013) Bioplastics science from a policy vantage point. New Biotechnol 30(6):635–646
49. Escobar N et al (2018) Land use mediated GHG emissions and spillovers from increased consumption of bioplastics. Environ Res Lett 13(12):125005
50. Gironi F, Piemonte V (2011) Bioplastics and petroleum-based plastics: strengths and weaknesses. Energy Sources Part A 33(21):1949–1959
51. RameshKumar S et al (2020) Bio-based and biodegradable polymers—state-of-the-art, challenges and emerging trends. Curr Opin Green Sustain Chemi 21:75–81
52. Scarlat N et al (2015) The role of biomass and bioenergy in a future bioeconomy: policies and facts. Environ Dev 15:3–34
53. Rahman, A. and C.D. Miller, *Chapter 6 - Microalgae as a Source of Bioplastics*, in *Algal Green Chemistry*, R.P. Rastogi, D. Madamwar, and A. Pandey, Editors. 2017, Elsevier: Amsterdam. p. 121–138.
54. Hermabessiere L et al (2017) Occurrence and effects of plastic additives on marine environments and organisms: a review. Chemosphere 182:781–793
55. Jaishankar M et al (2014) Toxicity, mechanism and health effects of some heavy metals. Interdisciplinary Toxicology 7(2):60–72
56. Álvarez-Chávez CR et al (2012) Sustainability of bio-based plastics: general comparative analysis and recommendations for improvement. J Clean Prod 23(1):47–56
57. Green DS et al (2015) Impacts of discarded plastic bags on marine assemblages and ecosystem functioning. Environ Sci Technol 49(9):5380–5389
58. Lamb JB et al (2018) Plastic waste associated with disease on coral reefs. Science 359(6374):460
59. Greene, J., *Biobased Biodegradable and Degradable Plastics Effects on Recycled Plastics.* 2011.
60. ASTM, *D883–19c: Standard Terminology Relating to Plastics*. 2019.
61. Ahn HK et al (2011) Biodegradability of injection molded bioplastic pots containing polylactic acid and poultry feather fiber. Biores Technol 102(7):4930–4933
62. Kale G et al (2007) Biodegradability of polylactide bottles in real and simulated composting conditions. Polym Testing 26(8):1049–1061
63. Tabasi RY, Ajji A (2015) Selective degradation of biodegradable blends in simulated laboratory composting. Polym Degrad Stab 120:435–442
64. Mihai M, Legros N, Alemdar A (2014) Formulation-properties versatility of wood fiber biocomposites based on polylactide and polylactide/thermoplastic starch blends. Polym Eng Sci 54(6):1325–1340
65. Weng Y-X, Wang X-L, Wang Y-Z (2011) Biodegradation behavior of PHAs with different chemical structures under controlled composting conditions. Polym Testing 30(4):372–380
66. Sarasa J, Gracia JM, Javierre C (2009) Study of the biodisintegration of a bioplastic material waste. Biores Technol 100(15):3764–3768

67. Mohee, R. and G. Unmar, *Determining biodegradability of plastic materials under controlled and natural composting environments.* Waste management (New York, N.Y.), 2007. **27**(11): p. 1486–1493.
68. Anstey A et al (2014) Processability and biodegradability evaluation of composites from poly(butylene succinate) (PBS) bioplastic and biofuel co-products from Ontario. J Polym Environ 22(2):209–218
69. Nakasaki K et al (2006) Synergy of two thermophiles enables decomposition of poly-ε-caprolactone under composting conditions. FEMS Microbiol Ecol 58(3):373–383
70. Wu C-S (2012) Preparation, characterization, and biodegradability of renewable resource-based composites from recycled polylactide bioplastic and sisal fibers. J Appl Polym Sci 123(1):347–355
71. Adhikari, D., et al., *Degradation of Bioplastics in Soil and Their Degradation Effects on Environmental Microorganisms*. Vol. 05. 2016. 23–34.
72. Jain R, Tiwari A (2015) Biosynthesis of planet friendly bioplastics using renewable carbon source. J Environ Health Sci Eng 13(1):11
73. Boyandin AN et al (2013) Microbial degradation of polyhydroxyalkanoates in tropical soils. Int Biodeterior Biodegradation 83:77–84
74. Arcos-Hernandez MV et al (2012) Biodegradation in a soil environment of activated sludge derived polyhydroxyalkanoate (PHBV). Polym Degrad Stab 97(11):2301–2312
75. Gómez EF, Michel FC (2013) Biodegradability of conventional and bio-based plastics and natural fiber composites during composting, anaerobic digestion and long-term soil incubation. Polym Degrad Stab 98(12):2583–2591
76. Wu C-S (2014) Preparation and Characterization of Polyhydroxyalkanoate Bioplastic-Based Green Renewable Composites from Rice Husk. J Polym Environ 22(3):384–392
77. Tsuji, H. and K. Suzuyoshi, *Environmental degradation of biodegradable polyesters 1. Poly(ε-caprolactone), poly[(R)-3-hydroxybutyrate], and poly(L-lactide) films in controlled static seawater*. Vol. 75. 2002. 347–355.
78. Hoshino A et al (2001) Influence of weather conditions and soil properties on degradation of biodegradable plastics in soil. Soil Science and Plant Nutrition 47(1):35–43
79. P. Sangwan, A.K.D., *Degradable plastics packaging materials: assessment and implications for the Australian environment*. 2011, CSIRO. p. 94.
80. Tachibana K, Urano Y, Numata K (2013) Biodegradability of nylon 4 film in a marine environment. Polym Degrad Stab 98(9):1847–1851
81. Thellen C et al (2008) A Processing, Characterization and Marine Biodegradation Study of Melt-Extruded Polyhydroxyalkanoate (PHA) Films. J Polym Environ 16(1):1–11
82. Tosin M et al (2012) Laboratory test methods to determine the degradation of plastics in marine environmental conditions. Front Microbiol 3:225–225
83. ITU, N., *The impacts of degradable plastic bags in Australia*. 2003. p. 129.
84. Arrieta MP et al (2014) Disintegrability under composting conditions of plasticized PLA–PHB blends. Polym Degrad Stab 108:307–318
85. Woolnough CA et al (2008) Surface changes in polyhydroxyalkanoate films during biodegradation and biofouling. Polym Int 57(9):1042–1051
86. Sridewi N, Bhubalan K, Sudesh K (2006) Degradation of commercially important polyhydroxyalkanoates in tropical mangrove ecosystem. Polym Degrad Stab 91(12):2931–2940
87. Mostafa NA et al (2018) Production of biodegradable plastic from agricultural wastes. Arab J Chem 11(4):546–553
88. Harding KG et al (2007) Environmental analysis of plastic production processes: Comparing petroleum-based polypropylene and polyethylene with biologically-based poly-β-hydroxybutyric acid using life cycle analysis. J Biotechnol 130(1):57–66
89. Madival S et al (2009) Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology. J Clean Prod 17(13):1183–1194

Affiliations

Geetika Bhagwat[1] · Kelsey Gray[1] · Scott P. Wilson[2] · Sudhakar Muniyasamy[3,4] · Salom Gnana Thanga Vincent[5,6] · Richard Bush[7] · Thava Palanisami[5]

✉ Thava Palanisami
Thava.palanisami@newcastle.edu.au

[1] School of Environmental and Life Sciences, The University of Newcastle, Newcastle, NSW, Australia

[2] Department of Environmental Sciences, Macquarie University, Sydney, NSW, Australia

[3] Advanced Polymer Composite Research, Council for Scientific and Industrial Research (CSIR), Pretoria, South Africa

[4] Department of Chemistry, Nelson Mandela University, Port Elizabeth, South Africa

[5] Global Innovative Centre for Advanced Nanomaterials (GICAN), The University of Newcastle, University drive, Callaghan, NSW, Australia

[6] Department of Environmental Sciences, University of Kerala, Thiruvananthapuram, Kerala, India

[7] Monash Sustainable Development Institute, Monash University, Melbourne, Australia