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REVIEW

Biodegradable/Bio-plastics: Myths and Realities

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Abstract
The plastics industry is proliferating continuously and the global plastics production in 2018 has reached around 360 million tones. This has further compounded the problem of waste plastics, which if not appropriately disposed cause serious environmental problems like land pollution, marine pollution and water source pollution. As an alternative, there has been a paradigm shift from substituting synthetic plastics i.e. fossil-based to bioplastics. However, the world of bioplastics is riddled with many problems as the current terminology used around such bioplastics is confusing and general public is not provided with reliable information about the true biodegradability/compostability of the products. As a result, "greenwashing" is on the rise, with brands even making spurious claims about the environmental benefits of their products. This review article scans the world of biodegradable/bioplastics, major players and production capacities, their current status with respect to production and application. The commercial biopolymers available in the market and their technology have been also discussed in detail. The article also reviews various technologies like enzyme-based technology and oxo-degradable technology being propagated as a tool to convert conventional plastics like PE/PP/PET etc. to a biodegradable plastic. Further, various issues with oxo-based technology and enzyme-based technology have been compiled. Besides, various standards, test methods (ASTM/ISO) related to testing, specifications of biodegradable plastics, their scope/limitations and potential misuse have been covered. Further, the review article discusses the limitation of the various standards and why changes in the standards are required. The article tries to focus on various myths & realities of biodegradable/bioplastics and the challenges and expectations of the real world.

Keywords Bioplastics · Biodegradation · Compostable · Standards

Introduction

Plastics are a wonder material and they are widely used in our daily life. Their demand is increasing as they offer cheap, light weight, strong, energy-efficient solutions, and can be tailored with different functionality and performance properties depending on the final application. Accordingly, plastics have emerged as the material of choice in various sectors for different applications ranging from packaging to agriculture to electronics etc. Plastics production in the past half-century has boosted 20-fold, increasing from 15 million tonnes (1964) to 359 million tonnes (2018) and is expected to double in the next 20 years. Out of total plastic production, production of Polypropylene (PP) is 19.3%, Polyethylene (PE)-29.7%, Poly (vinyl chloride) (PVC)-10%, Polyurethane resins (PUR)-7.9%, Poly(ethylene terephthalate) (PET)-7.7%, Polystyrene/expanded polystyrene (PS/EPS)-6.4% and others like polycarbonates, Polyacrylates, PTFE etc. is around 19% [1].

However, plastics have become a victim of their success. Littered plastic is seen all across the globe as it is not disposed of properly. Oceans have become a dumping yard with littered waste plastic, thereby resulting in the choking of marine life. Littered plastic enters into the food chain and hence, transforming part of maritime zones into a plastic bed. Around the world, plastic waste clogs the drain, causes animals death from ingestion and enters the food chain. In general, waste plastics if not disposed of properly causes serious environmental problem like land pollution, marine pollution, water pollution [2].

Most of the waste plastic globally comes from single-use plastic, and it is littered within few minutes of its first use. According to UN Environment Report, single-use plastics

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are often described as disposable plastics used mainly in packaging applications, which comprises items proposed to be used only once before they are discarded or recycled [3]. Most familiar single-use plastics found in the environment are plastic drinking bottles, plastic cups cigarette butts, plastic bottle caps, straws, plastic lids, food wrappers, stirrers, plastic grocery bags, take-away foam containers and other types of plastic bags.

The most conventional plastics such as polypropylene (PP), polyethylene (PE), poly(vinyl chloride) (PVC), polystyrene (PS), poly(ethylene terephthalate) (PET) etc. which accounts for 75% of global plastic production, are not biodegradable. Hence, their rapid build-up in the environment has been a hazard to the mother earth. Decomposition of plastic waste can take up to a thousand years when dumped in the environment or landfills. Due to this alarming issue, as an alternative in recent years, there has been a shift of advocating the replacement of synthetic based plastics with biodegradable/bioplastics, which are biodegradable and/or compostable [4]. These so-called biodegradable bioplastics are being perceived as a panacea to get rid of the harmful effects of plastics [5]. Due to the increased usage of bioplastics, considerable interest has arisen in biodegradation technologies like oxo-degradation [6] and enzymatic-based [7] to make even conventional plastics like PE, PP, PET etc. into biodegradable/compostable plastics. However, the world of bioplastics is riddled with many problems as the current terminology used around such bioplastics is confusing and general public is not provided with reliable information about the true biodegradability/compostability of the products. As a result, "greenwashing" is on the rise, with brands even making spurious claims about the environmental benefits of their products. As a result, the UK government has called for experts to help it develop standards for bioplastics and biodegradable plastics, amid rising concern over greenwashing. The UK government has published a document seeking evidence on potential "demand, benefits, and implications of standards for bio-based and biodegradable plastics". The call is set out in a paper, called standards for bio-based, biodegradable, and compostable plastics: call for evidence, which was published in 2019 [8].

This review article scans the world of biodegradable/bioplastics, major players and production capacities, their current status with respect to production and application. The commercial biopolymers available in the market and their technology have been also discussed in detail. The article also reviews various technologies like enzyme-based technology and oxo-degradable technology being propagated as a tool to convert conventional plastics like PE/PP/PET etc. to a biodegradable/compostable plastic. Various issues with oxo-based technology and enzyme-based technology have been compiled. Besides, various standards, test methods (ASTM/ISO) related to testing, specifications of biodegradable plastics, their scope/limitations and potential misuse have been covered. Further, the review articles discuss the limitation of the various standards and why changes in the standards are required. The article tries to focus on various myths & realities of biodegradable/bioplastics and the challenges and expectations of the real world. Though, there are large numbers of review articles on the broad topic of biodegradable, to the best of our knowledge, there is no single review article covering all the above aspects, which are so inter-related to the subject of bioplastics/biodegradable plastics.

Definition and Context

The literature around biodegradable plastic encompasses different terminology and it is of utmost important to correctly define and understand the true meaning of such terminologies. For example, literature uses various terminologies like bioplastic, biodegradable plastic, bio-based plastic, compostable plastic etc. The most accepted definitions of the above terms are as follows:

Bioplastics

According to European Bioplastics Organization [9], a plastic material is defined as a bioplastic if it is either biobased, biodegradable, or features both properties.

Biobased

The term ‘biobased’ can be defined as the material or product which is either fully or partially obtained from biomass (plants) [10]**.** Biomass used for bioplastics stems from e.g. corn, sugarcane, or cellulose. For example, if the ethylene monomer is obtained from dehydrogenation of alcohol, which in turns has been produced from biomass, then the Polyethylene produced from such ethylene can be termed as biobased or bio-polyethylene, though it will not be biodegradable/compostable.

Biodegradation

Biodegradation is a process defined as any physical or chemical modification in a material which occurs due to biological activity. It is a bio-chemical process in which microorganisms present in the environment are responsible for converting hydrocarbons like polymers into natural substances such as carbon dioxide, water, methane and compost. The degradation product depends on whether the process is aerobic or anaerobic [11]. The biodegradation process depends on encompassing environmental conditions (e.g. temperature or location), material, and application.

Biodegradable Plastics

Biodegradable plastics are defined as plastic that degrades under biological action as per the above described process.

Compostable plastics

Compostable plastics [12] on the other hand degrade under composting conditions (i.e. specific conditions of humidity and temperature). A compostable plastic must meet three conditions: (a) break down of plastic material under the activity of microorganism (bacteria, fungi, and algae), b) achieve hundred percent mineralization (conversion into carbon dioxide, methane, water, inorganic compounds or biomass under aerobic conditions) and c) the conversion i.e. mineralization rate must be very high and suitable with the composting process. Therefore, some of the plastics may be biodegradable but not compostable. For example, if in case a plastic biodegrades but the left over includes the toxic residues, it is then not considered as a compostable plastic.

Though in literature the term biodegradable plastics and compostable plastics are used interchangeably, it is essential to figure out the basic distinction between the two terminologies. The fundamental difference between the two terms is that composting is human-driven, while biodegradation is naturally occurring. Composting is an accelerated biodegradation process under defined and optimized circumstances. Therefore, the understanding in reference to relation and difference in biodegradable and compostable is needed at mass level, especially for user's awareness is necessary that the best method of disposal as industrial composting facilities is not the same as natural degradation. Some of the biodegradable plastics which are compostable degrade under controlled conditions. Hence, for the sake of brevity, the terms biodegradable and compostable can be used interchangeably, but they are not synonyms.

Being a bioplastic does not mean that all such bioplastics are biodegradable. The biodegradability of a material depends on its chemical structure and not on where it is derived from whether natural/synthetic based.

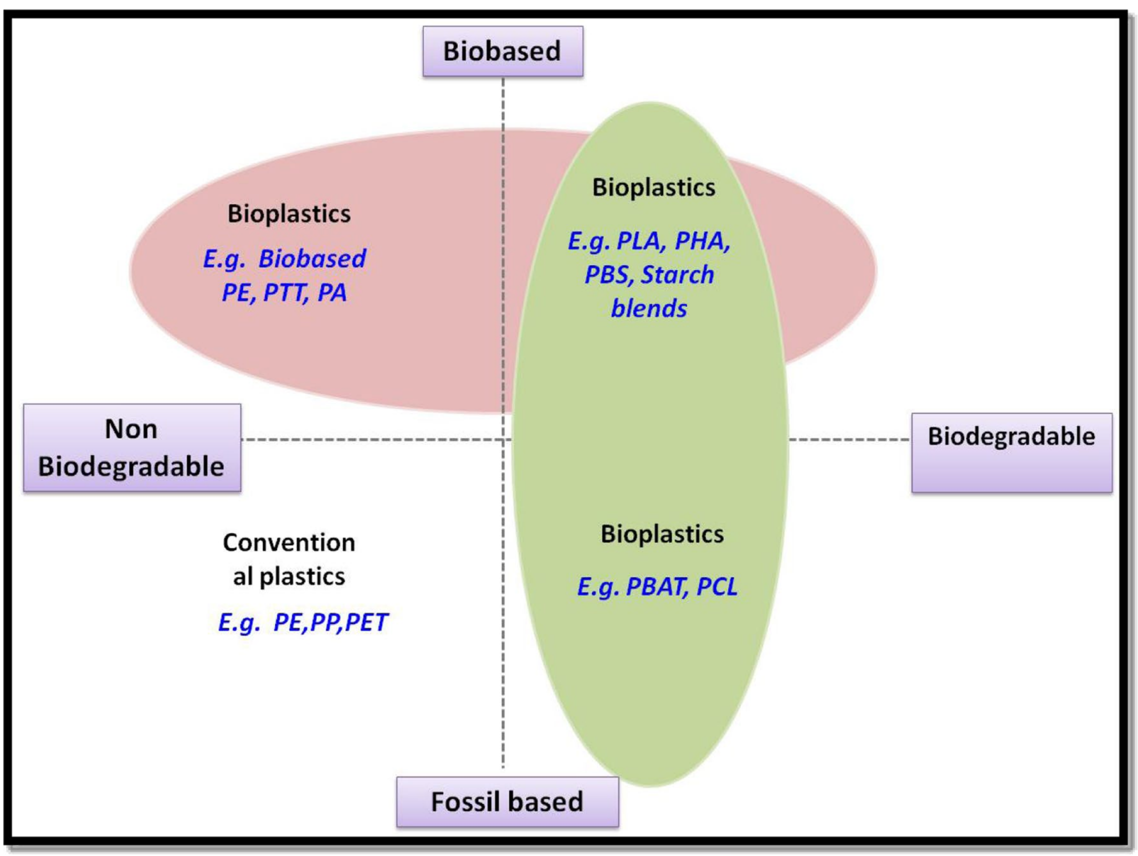

Fig. 1 Classification of Bioplastics Vs Fossil based plastics w.r.t. biodegradability [9, 13] (PTT-Polytrimethylene terephthalate, PA-Polyamide, PLA-Polylactic acid, PHA-Polyhydroxyalkanoates, PBS-Polybutylene succinate, PBAT-poly(butyleneadipate-co-terephthalate), *PCL* polycaprolactone

Figure 1 shows different bioplastics and fossil-based plastics and also whether they are biodegradable or not. Polymers listed in the first quadrant like Polylacticacid (PLA), Polyhydroxyalkanoates (PHA), Poly(butylenesuccinate) (PBS), starch blends are derived from biobased polymers and are also biodegradable. Then, there are some plastics that are fossil-based (placed in the second quadrant) but are biodegradable, like poly(butylene adipate-co-terephthalate) (PBAT), Polycaprolactone (PCL). The conventional plastics like PE, PP, PET etc. are fossil-based and are non-biodegradable (3rd quadrant). Then, there are bio-derived polymers, but they are still not biodegradable. For example, bio-Polyethylene (Bio PE), produced using ethylene derived from bio-ethanol, is bio-based but not biodegradable. These polymers which originate from bio source though are non-biodegradable, but offer significant carbon reduction at the beginning of life. This is due to the fact that plants utilize atmospheric carbon dioxide (CO_2) during their growth period. These bio-polymers like bio-PE etc. are made from plants (biomass), and hence it can be said that such polymers remove CO_2 from the atmosphere and keep it stored throughout the entire product life.

Mechanism of Biodegradation

Depending on the environment, the biodegradation process can be classified into (1) aerobic and (2) anaerobic degradation (Fig. 2) [14]

1. Aerobic biodegradation: Aerobic biodegradation is the breakdown of organic contaminants by microorganisms when oxygen is present

$$\text{Polymer} + O_2 \rightarrow CO_2 + H_2O + \text{biomass} + \text{residue(s)}$$

2. Anaerobic biodegradation: Anaerobic biodegradation occurs in absence of oxygen and methane is produced instead of carbon dioxide

$$\text{Polymer} \rightarrow CO_2 + CH_4 + H_2O + \text{biomass} + \text{residue(s)}$$

Polymer degradation can occur through two primary routes i.e. abiotic and biotic [15]. Abiotic degradation is through hydrolysis and photodegradation (biodeterioration), which is physical decomposition leading to partial or complete degradation. The biotic route is through the biological processes (association of naturally occurring

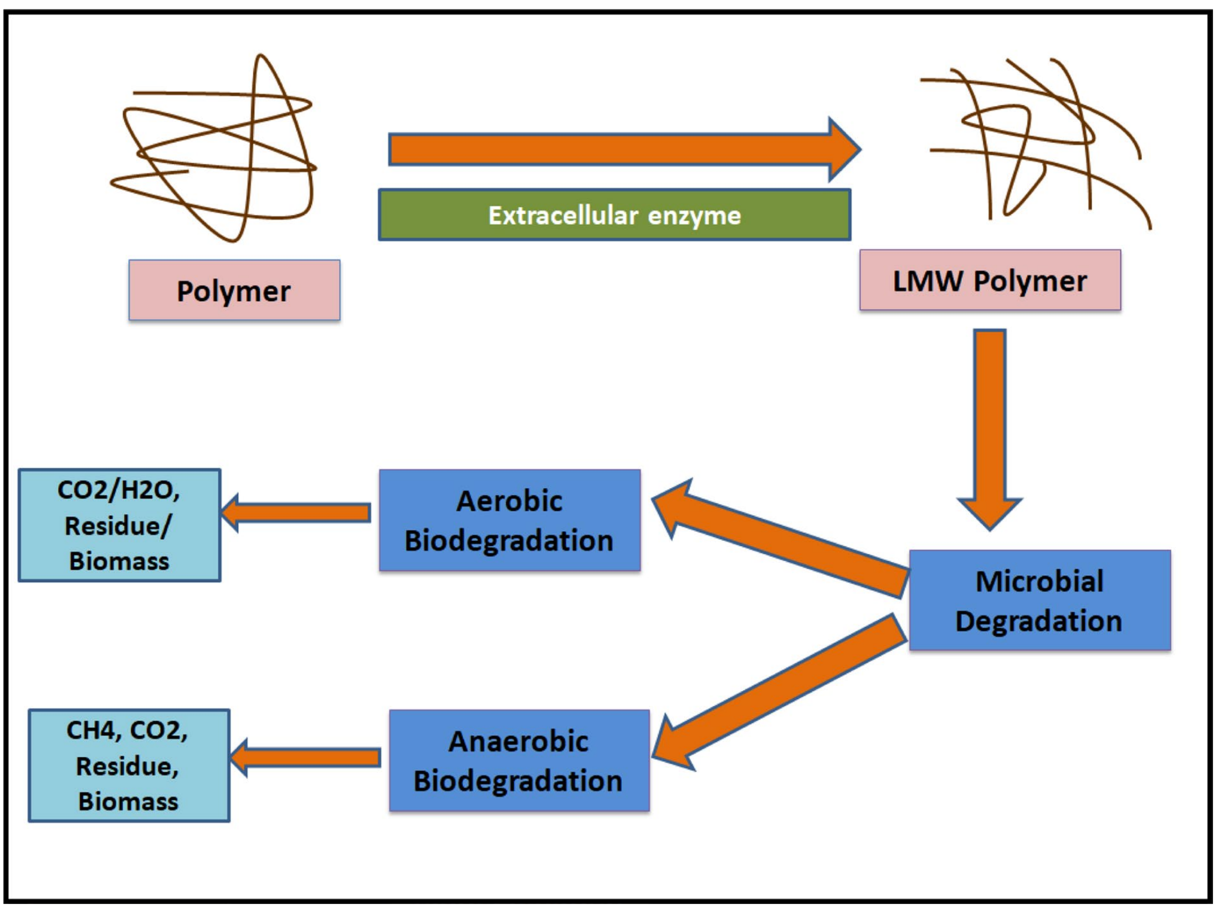

Fig. 2 Schematic diagram of byproducts formed during biodegradation of polymers under aerobic and anaerobic condition

microorganisms like bacteria, fungi, and algae) which can be further broken down into aerobic and anaerobic processes. The biodegradability of polymer depends on molecular weight, molecular form and crystallinity of polymer. The process of biodegradation is said to be completed when there are no oligomers or monomers left. The process of biodegradation of plastics is usually heterogeneous. In this process, microorganisms are unable to transport the polymeric material directly into the cells where most biochemical processes take place because of a lack of water-solubility of the plastics and the size of the polymer molecules. They must first excrete extracellular enzymes which in turn depolymerize the polymers outside the cells. As per the literature available, the biodegradation of plastics is usually a surface erosion process as the extracellular enzymes are too large to penetrate deeply into the polymer material, and so act only on the polymer surface [16].

The mechanism for the biodegradation of plastics mainly consists of following steps as depicted in Fig. 2:

- *Interaction of microorganism onto the polymer surface* In this first step, the micro-organisms present in the soil/atmosphere get attached to the polymer surface forming a biofilm. The extracellular enzymes secreted by microorganisms cause the main polymer chain to break down into smaller fragments [17, 18]. Many enzymes are responsible for the biodegradation of polymers released by microorganisms which include lipase, proteinase K, and andhydrogenase. These enzymes act on large polymers and convert to oligomers, dimers and monomers which are of low molecular weight. In this phase, amorphous region of the polymer is first invaded by microorganisms.
- *Growth of microorganisms* In the next step, the microorganism gets attached to the polymer, grows further by degrading the plastics and reducing the molecular weight. This process is also termed as biofragmentation [19].
- *Ultimate degradation of the Polymer* In the last step, if the molecular weight of the plastic has been sufficiently decreased, thereby leading to the generation of water-soluble intermediates, these species can be then conveyed into the microorganisms and find a way into the appropriate metabolic pathway(s). Ultimate degradation of the polymer occurs only when these low molecular weight polymers formed are further used by microorganism as carbon sources. This process is termed as bio-assimilation and the generation of metabolites i.e. CO_2, H_2O and CH_4 is termed as mineralization. These products are thereafter utilized as carbon and energy source [20].

For quantification of percentage biodegradation of the substrate (Fig. 3), the test method detects the growth of microorganism by the release of carbon dioxide. Lag phase is the adaptation of the microbial population to the substrate followed by the biodegradation phase. This biodegradation phase occurs when the microbial population uses the carbon substrate for sustaining their cellular life. Final stage is the plateau stage when the substrate is completely used by microorganisms.

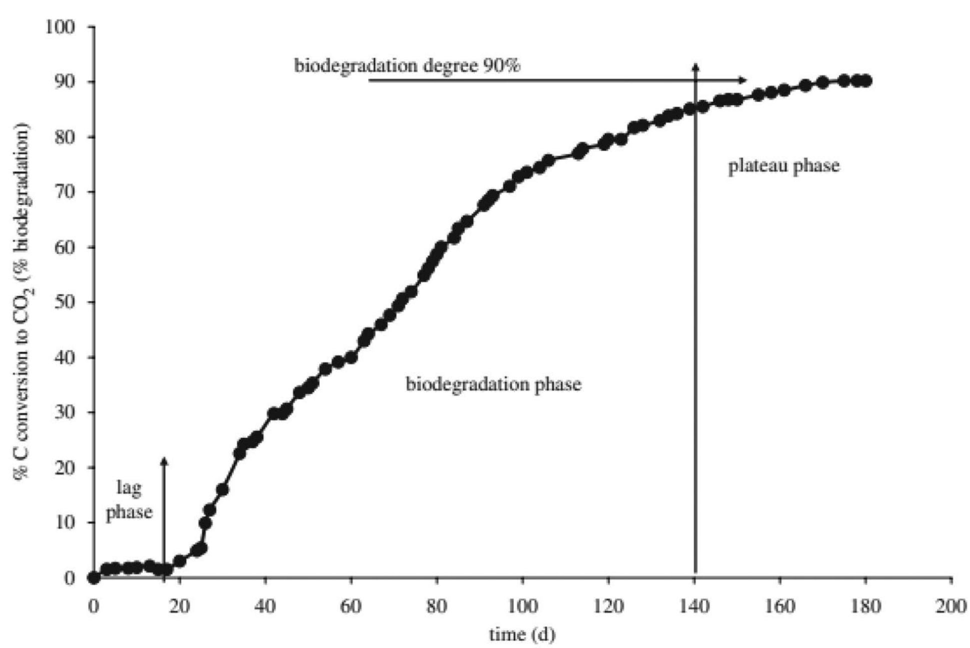

Fig. 3 CO_2 release curve shows typical lag phase, biodegradation phase and plateau phase [21]

Global Production

Despite increasing usage and enhanced attention bioplastics are getting in the last few years, their global production remains an area of concern. As shown in Fig. 4, the total bioplastics production globally in 2019 was around 2.1 million tonnes. This accounts for only about 1% of total plastics production all over the world.

Figure 4 also shows a break up production of different types of bioplastics. It can be seen that the most widely produced/used biodegradable bioplastics are starch based blends followed by PBAT and PLA based plastics. The largest field of application for bioplastics remains packaging with more than 53 percent (1.14 million tonnes) of the total bioplastics market in 2019. Another interesting fact is that out of the total bioplastics produced today, 43% are biodegradable and the rest 57% of the bioplastics are non-biodegradable. Such non-biodegradable bioplastics are predominately bio-based PE (11.8%), bio-based PET (9.8%), bio-based PA (polyamides; 11.6%) & small amount of bio-based PP (0.9%). PEF is comparable to PET but is 100 percent bio-based and possesses superior thermal properties and barrier properties. It makes it a suitable material for the packaging of food, drinks, and non-food products. Due to PHA significant growth rate -CAGR of 11.2% the production of biodegradable plastics is expected to increase to 1,33 million in 2024 [22].

The global bioplastics market is fragmented in nature, with the top players like Braskem, Novamont S.p.A., NatureWorks LLC, BASF SE, Total Corbio PLA, and Rodenburg Biopolymers accounting for around 34% of the global market.

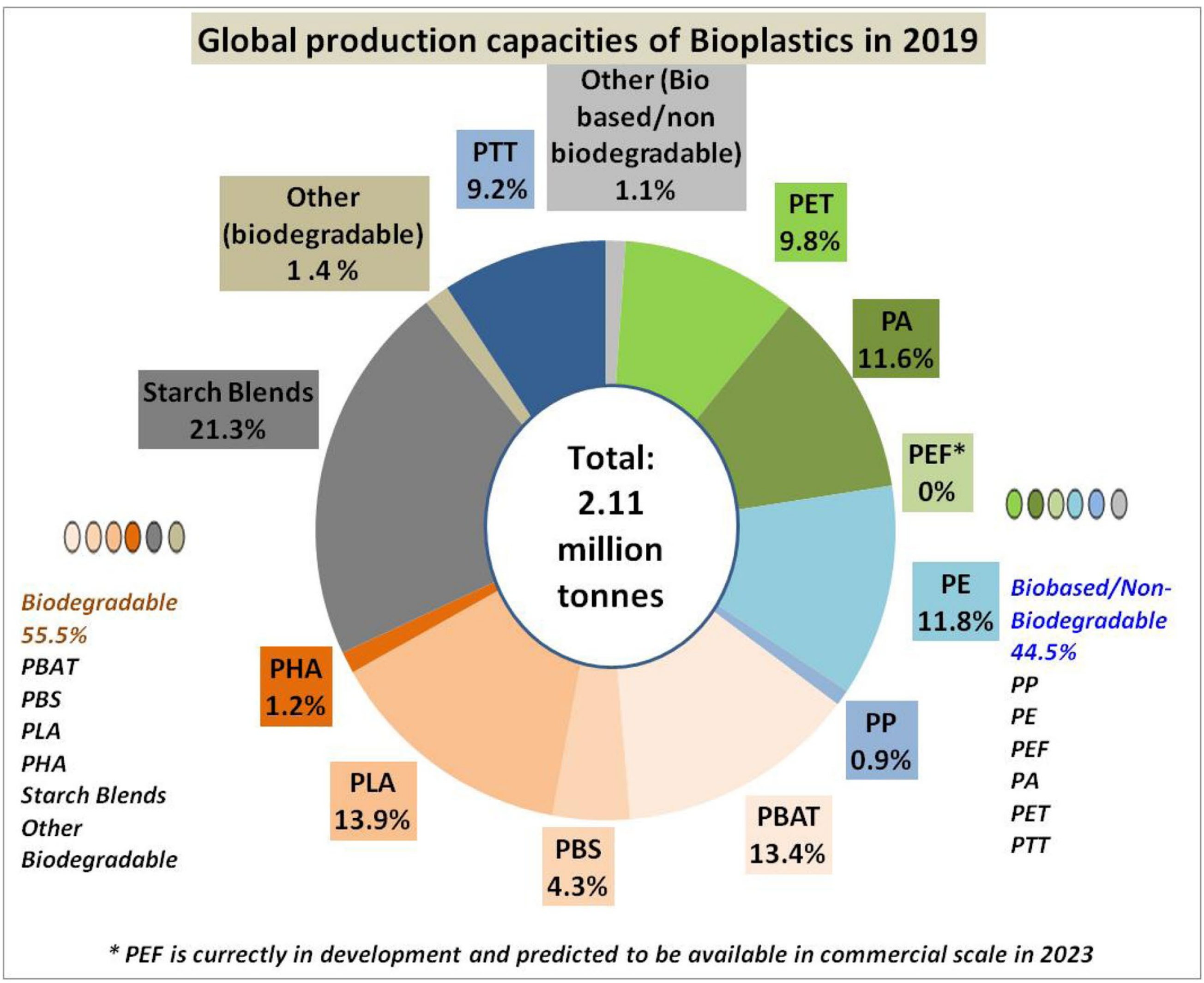

Fig. 4 Global Production capacities of Bioplastics in 2019 [22]

Braskem has annual production capacity of 200 KTA of green PE i.e. biobased PE [23]. It is made of made from ethanol, a renewable and sustainable resource produced from sugarcane.

Novamont group's has the annual production capacity of MATER-BI® compostable bioplastics of 150 KTA. MATER-BI® compostable bioplastics is family of high-value polyesters with a high content of renewable raw materials based on bio-monomers [24].

NatureWorks LLC produces PLA based biopolymer which is marketed under the brand name Ingeo and has annual production capacity among of around 150 KTA [25].

BASF has the annual capacity to produce 74 KTA of Ecovio in Ludwigshafen, Germany specially designed for mulch film application. BASF product Ecoflex has > 90% fossil-based polyester and some grades of BASF Ecovio are blend of biodegradable polyesters and polylactic acid (PLA) & contains raw material from 18% renewable resources [26]. Recently, BASF has licensed its proprietary technology of certified compostable aliphatic–aromatic co-polyester (PBAT) of 60 KTA to China's Red Avenue New Materials group. The facility is expected to start in 2022 [27].

Total Corbion PLA is a global leader production of Poly(lactic acid) having annual production capacity of 75 KTA in Thailand [28]. Further, Total Corbion has further announced its intention to build its second PLA plant with a capacity ramping up to 100,000 tons per annum which is expected to be operational in 2024. This expansion would make Total Corbion, the global market leader in PLA, firmly positioned to cater for the rapidly growing demand for Luminy® PLA resins.

Rodenburg Biopolymers situated in Netherlands produces starch base biopolymers at a annual production capacity of 60 KTA. Rodenburg Biopolymers sells these biopolymers under a trade name of Solanyl, Flourplast, Optinyl.

Asia–Pacific has the largest manufacturing capacity of bioplastics, with around 45% of the global capacity. Due to the growing environmental concerns across the globe, the usage of bioplastics is the highest in the packaging sector and is on rise.

In India, which is world's 3rd largest consumer of plastics after USA & China, the biodegradable polymer market is still in an infancy stage, with very few players in the segment. Increased eco-awareness among consumers and sustainable solutions has been the primary driver for the bioplastic market in India. This biodegradable polymer segment has a long way to go in terms of production, raw materials technology. The introductory step that needs to take toward bringing this change is environmental awareness and promoting the long-term benefits of bioplastics. M/s NatureTec, M/s Biotec Bags, M/s Envigreen, Ecolife, Plastobags, Earthsoul India, Truegreen etc. are significant players operating in the Indian bioplastic market.

NatureTec India Pvt Ltd: Natur-Tec India Pvt. Ltd., a subsidiary of Northern Technologies International (NTIC), is leading the marketing and sales effort in India and the subcontinent. NTIC's Natur-Tec® branded products are engineered using proprietary and patented blend of biodegradable polymers and natural materials to create biobased (renewable resource based) and certified compostable plastics [29].

EnviGreen As per the details available on the website, Envigreen produces India's first 100% biodegradable substitute to plastics products are made from natural starch, vegetable oil derivatives and vegetable waste. These products are non-toxic to the environment, animals and plants. Evergreen contains no conventional plastics at all [30].

Biotec Bags operates with enzyme compounded polyethylene constitutes of enzymes, sodium salts and oxidation agents with LDPE/HDPE AND LLDPE [31].

Ecolife products are based on innovative, renewable based bioplastics which meet ASTM 6400, EN 13432 & IS 17088 compostability standards. The product list includes Garment and Apparel Bags, Shopping Bags, Carry Bags, Garbage Bags, Binliners, Biodegradable & Compostable Cutlery, Biodegradable & Compostable Paper Cups etc. [32].

Plastobags As per details available from the website, plastobags products are mainly made up from corn starch and are TUV Austria, ISO-17088 certified [33].

Truegreen offers 100% compostable and biodegradable products like carry bags, bags on rolls, mulch film etc. [34]. However, the 'Truegreen' compostable products range is manufactured using Biolice® (Limagrain, France), a fully compostable and 100% biodegradable polymer. It is manufactured from naturally grown cereals, a renewable resource, Biolice®, which bears the OK COMPOST label and adheres with the U.S Norm (ASTM D 6400), European Norm (EN 13432), and International Norm (ISO 17088). It is a blend of biodegradable polyester and PLA.

Earthsoul India claims to be the first Indian company that provides 100% biodegradable and compostable carrier bags. Earthsoul is exclusive manufacturer licensees for Novamont, USA [35]. A dedicated bio-plastic product manufacturing facility with an installed capacity of about 960 metric tons per annum has been planned by J&K Agro Industries Ltd with its joint venture with M/s Earthsoul in Jammu & Kashmir, India [36].

GXT Green products Pvt Ltd. is affiliated with GXT-Green, USA. GXT Green, Inc manufactures a class of materials having lower carbon footprints and designed as an alternative to plastics in a vast range of applications, which includes injection molding, extrusion, blow molding and thermoforming [37].

Narendra Plastic Pvt Ltd. claims to have developed a substitute to non-degradable plastic bags that are made of materials that are derived from non-petroleum sources like starch and are 100 percent compostable, complying to ASTM D 6400, EN 13432, and ISO 17088 standards [38].

It can be observed from the above that most of the Indian companies don't manufacture biodegradable polymer and mostly import from BASF, NovaMont, Total Corbion etc.

The Central Pollution Control Board (CPCB), India has recently published on their website, a list of certified manufacturers and sellers of compostable carry bags and products. As per the list, there are around 120 certified manufacturers/sellers, which have been granted a license by CPCB [39] for marketing and selling of compostable carry bags/products in India.

As the plastic market has a great potential to grow in India and with increasing awareness about the environmental issues related to conventional plastics, it is expected that the bioplastics market in India shall also grow considerably in the next few years.

Status of Commercial Bioplastics: Chemistry and Technology

A wide range of bio-based materials are being introduced in the market for different applications and various kinds of technologies are being developed and used in order to commercialize and expand the area of bioplastics. The Table 1 lists all the technologies around bioplastics that are currently being used or under development by various companies across the globe.

It can be seen from the Table 1 that most of the commercially available bioplastics are either starch, PBAT, PLA, PVA, PTT based or their blends. Major properties, applications of different biopolymers are as follows:

- *Polylactic acid (PLA):* Polylactic acid, an aliphatic polyester has been developed as a bioplastic (thermoplastic in nature) which can degrade on its own and is biodegradable. It is primarily derived from inexhaustible resources like sugar cane or corn starch. Production of PLA is done by the usage of two basic monomers which are lactic acid and lactide (cyclic de-ester). The major share in the raw material is taken up by PLA, which is used to produce bio-based, biodegradable plastics. The production method of PLA is by industrial polycondensation of lactic acid and/or ring-opening polymerization of lactide. Different sectors in which PLA is used are plasticulture, textile, medical and packaging industries. PLA degradation only depends on its exposure to prolonged higher temperatures (around 60 °C). It means that PLA will only biodegrade in an industrial compost facility (the temperature in the composting plant is 60 °C) but will not biodegrade in a natural environment (like PLA film littered) or in a landfill (anaerobic conditions). Although, PLA is compostable but there are certain issues like PLA has low strength, it imparts an off taste to water when used for water bottles, it melts when used in hot beverages and also expensive compared to PE and PP.
- *Polybutylene adipate terephthalate (PBAT)* is a random copolymer biodegradable in nature i.e. a co polyester of adipic acid, 1,4-butanediol and terephthalic acid. It resembles LDPE in its properties. Area of applications for this polymer is in coatings (e.g. of paper and cardboard), packaging (e.g. plastic films and bottles) and foam. Due to the presence of butylene adipate groups, PBAT is fully biodegradable when composted [78]. PBAT has the edge over PLA in its compostability, as in PLA industrial fermentation conditions (60ºC) are crucial [79].
- *Polybutylene succinate (PBS):* It belongs to the polyester family and is a thermoplastic polymer resin. It is aliphatic polyester with properties that are comparable to polypropylene. It's synthesis is done by poly-condensation of succinic acid and 1,4-butanediol. The melting point of PBS is 115 °C. Application of this polymer is in various sectors like agriculture, packaging/disposables, automotive, fibers/nonwoven and others. PBS decomposes naturally into water and carbon dioxide, so it is biodegradable [80].
- *Polyhydroxyalkanoates (PHA)* are polyesters and its manufacturing requires numerous microorganisms that carry out bacterial fermentation of sugars and lipids. They are either thermoplastic or elastomers in nature with a melting point in the range from 40–180 °C. PHA production comprises of various steps which includes fermentation, separation of biomass from the broth, biomass drying, PHA extraction, PHA drying, and packaging [81, 82].
- *Polycaprolactone (PCL):* It is biodegradable polyester with a low melting point of around 60 °C. PCL is suitable with a range of other materials which can be mixed with other biodegradable polymers to decrease its cost and enhance biodegradability. The preparation process consists of ring-opening polymerization of ε-caprolactone in the presence of a catalyst. The significance of PCL is in different kinds of biomedical applications such as in various tissue engineering applications etc. [83, 84].
- *PE and PP from biobased monomers:* Biopolyethylene (other name of renewable polyethylene) is polyethylene which is prepared from ethylene monomer obtained from bioethanol after a dehydration process. Bioethanol can be made from different biomass feedstocks, including sugar beet, sugarcane, and wheat grain etc. World's first refinery off gas-to-bioethanol production facility is under construction in India by Indian Oil Corporation Limited, India's flagship national oil company and LanzaTech, USA, a carbon recycling company [85, 86]. However, bio-PE is not biodegradable/compostable. Traditional

Table 1 A list of commercially available Bioplastics by different companies

Company name	Trade name	Chemistry	Application	References
BIOTEC GmbH & Co. KG, Germany	Bioplast	Starch based—100% biodegradable & Compostable	Used in various sectors of flat film, blown film, profiles and injection molded products, moldings	[40–42]
Cardia Bioplastics, Australia	Cardia BiohybridTM BL-F	Starch-based (66%) mixed with PE—Compostable	Used for thick and thin gauge film and blow molding applications, garbage bags, overwrap packaging, shopping bags, bin liners, disposable or industrial bottles	[43]
Green Dot Bioplastics, USA	Terratek BD	Starch based-biodegradable & compostable	It is a proprietary blend of starch-based ingredients and other materials	[44, 45]
Novamont, USA	Mater-Bi, MATER-BIOPOLYMER	Starch & biopolyesters based—biodegradable & Compostable	Used in the agricultural sector for mulching, packaging application like carry bags, disposable cutleries in food application etc	[46–48]
BioApply, Switzerland	–	Starch based-biodegradable & Compostable	Compostable bags are made from non-genetically modified thistle, corn starch and potato cull	[49]
Corbion	PURALACT	Lactide based—Compostable	Used in the sector ranging from packaging, electronics, automotive and textile sector	[50, 51]
Good Natured Products Inc, Canada		PLA based —Compostable	manufactures bioplastic pellets, sheets, and finished goods for food packaging and durable products	[52]
Greengran, Netherlands	–	PLA and natural fibres–Compostable	Application ranges from toys-, consumer articles, construction- and rigid packaging	[53]
Pyramid Bioplastics		PLA-Compostable	3D printers, mulch films, flexible packaging etc	[54]
Limagrain	Biolice	Biodegradable polyester and PLA (made from maize flour)—contain 45% of renewable content	Green waste bags Dustbin bags, compost bags, high quality bags with colored compostable masterbatches, liners for wheeled bins, all retail shopping bags etc	[55]
BASF, Germany	Ecovio&Ecoflex	Synthetic Polyester PBAT and PLA -Compostable	Ecoflex® properties are similar to conventional polyethylene but are fully biodegradable under industrial composting conditions. Mainly used in the production of flexible film products in the packaging industry	[56–59]
Showa Denko, Japan	Bionolle	Biopolyester bio-succinic acid-Compostable	Application: compost bags, shopping bags, agricultural purposes, etc	[60–62]
Metabolix, USA	–	Polyhydroxyalkanoates	Application: Plastic and Packaging (compostable application)	[63, 64]
DuPont, USA	Sorona	Polytrimethylene terephthalate from bio route	The polymer can be made into fiber with a stretch, unique softness and stain resistance that provides extraordinary value in carpet and apparel applications	[65–67]
Kaneka Corp, Japan	AONILEX	Polyhydroxybutyrate	It is a 100% bio-based polymer which is manufactured by microbial fermentation from plant oils	[68–70]
Wanwei, China	PVA	Polyvinylalcohol	Film, Textile, construction paper making & processing etc	[71]

Table 1 (continued)

Company name	Trade name	Chemistry	Application	References
Arkema, France	Rilsan	Polyamides produced from castor oil	It is used in packaging, automotive, sporting equipment, medical devices, cable, and electrical components	[72]
DSM, Netherland	EcoPaxx	Biobased polyamide, 72% biobased	EcoPaxx is DSM's most established biobased engineering plastic	[73]
Evonik, Germany	Vestamid Terra	Polyamides produced from castor oil	Vestamaid Terra is based on castor oil as a major part of its feedstock. Typical applications are injection molding, fibers, powders, extrusion, and films	[74, 75]
Braskem, US	I'M GreenTM Polyethylene	PE from bioethanol. Renewable carbon content in the range between 80 and 100%,	Green Polyethylene is a drop-in biopolymer. Applications include flexible, caps and closures, bags etc	[76]
Braskem		Green PP from sugarcane	Braskem produces first polypropylene made 100% from renewable resources, which was verified by ASTM D6866	[77]

polyethylene manufacturing requires fossil sourced raw materials such as oil or natural gas, whereas, bio-PE manufacturing results in capturing and fixing of CO_2 from the atmosphere during production of bioethanol, leading to a decrease in greenhouse gases emission and hence overall lower carbon foot print.

Similarly, bio-based polypropylene is a polymer manufactured using propylene monomer obtained from natural materials such as corn, vegetable oil, sugarcane, and some other biomass. Bio-based polypropylene possesses properties those are similar to synthetic polypropylene, but is not biodegradable/compostable. Recently, Borealis has started manufacturing of polypropylene (PP) based on Neste-produced renewable feedstock in its manufacturing facilities in Kallo and Beringen, Belgium. NEXBTL™ technology is used for producing renewable propane, thereafter renewable propane is supplied by Neste to the Borealis propane dehydrogenation plant in Kallo. Here, renewable propane is converted into propylene (renewable), which then is converted to PP, which can be classified as biobased [87]. Some of the other major players in the global bio-based polypropylene market include DowDuPont, SABIC, Braskem, Sinopec Group, Biobent Polymers, Neste, FKuR Kunststoff GmbH, Trellis Earth Products NovamontSpA, PTT Global, Global Bioenergies Inc., etc. [88].

It can be concluded from the above that there are a large number of biopolymers available in the market and most of them are starch-based, PLA, PBAT, PVA, PTT etc., or their blend. Commercial biobased polyethylene and biobased Polypropylene are also getting increasingly available.

Can Conventional Plastics Like PE/PP be Made Biodegradable?

As per the global demand and consumption data, conventional plastics like PE, PP, PET account for 75% of the total plastics consumed in the world. Being commodity plastics, it finds huge applications in carry bags, flexible packaging, etc. and are further responsible for creating the usual mess in the form of littering of our lands, rivers, oceans etc. as they are not biodegradable.

Therefore, the recent research is focused towards development of technological solutions for converting such conventional plastics into biodegradable products. Two of the most discussed technologies for biodegradation of conventional polymers like PE, PP, PET, PVC etc. are (a) oxo-degradation technology and (b) enzyme-mediated biodegradation technology.

Degradation is the terminology which takes into account mechanical, biological or microbiological aspect as well. The degradable plastic means breaking down of plastic. For example, there are certain additives which make conventional plastic to become brittle and crumble in sunlight and are normally referred as "oxo-degradable plastic". These additives are catalytic materials which help the products to degrade in a two-step process: oxidation and then biodegradation and utilized both abiotic and biotic factors. Oxidation process triggers the fragmentation of the polymer into low molecular weight species (Mw < 5000 g/ mol) followed by assimilation to form CO_2, H_2O, methane etc.

Whereas, enzyme-based biodegradation is the process by which the organic substances are broken down by the living organisms by a bio-fragmentation process followed by assimilation.

The broad differences between oxo-based degradation and enzyme-based biodegradation are processes are depicted in Fig. 5. Details of these technologies are discussed in the following section.

Oxo-Degradation Technology

Oxo-degradation technology claiming biodegradation of fossil-based PE and PP etc., though much talked about but is highly controversial [89–93]. In this technology, conventional plastics (e.g. LDPE, LLDPE, HDPE, PP etc.) are mixed with chemicals which are pro-oxidants e.g. inorganic catalysts containing transition metals such as manganese, cobalt, iron, etc. to expedite the oxidation. In this phase, the inorganic catalyst present in the polymer causes the oxidation process under the UV light and/or heat, and oxygen which enables rapid conversion of polymers into smaller fragments of low molecular weight [94]. The next phase includes action of microorganisms on the fragmented polymer via assimilation into carbon dioxide, methane, water. This rate of oxo-degradation process depends on the concentration of oxo-additives, the fragment size, and the environmental conditions; whether in soil/ compost/landfill conditions to which the material has been exposed. The activation time i.e. time for degradation during fragmentation can be controlled to an extent depending on the composition and concentration of the pro-oxidant.

Globally there are many companies supplying Oxo-degradation technology for example; M/s Symphony Environmental, M/s Wells Plastics, M/s EPI Global, M/s Unibag Maghreb, M/s Willow Ridge Plastics Inc, M/s Newtrans USA Company, M/s Licton Industrial to name a few.

The oxo-degradable plastics are finding applications in packaging like carrier bags, blister packaging, bottles etc. and are being marketed as a solution to plastic pollution. The claims by the manufacturers are that such oxo-based plastics degrade into non-dangerous residues when disposed into the environment within a short time frame (few months to years). However, many field reports/evidences illustrate that oxo-degradable plastics fragment simply into small pieces

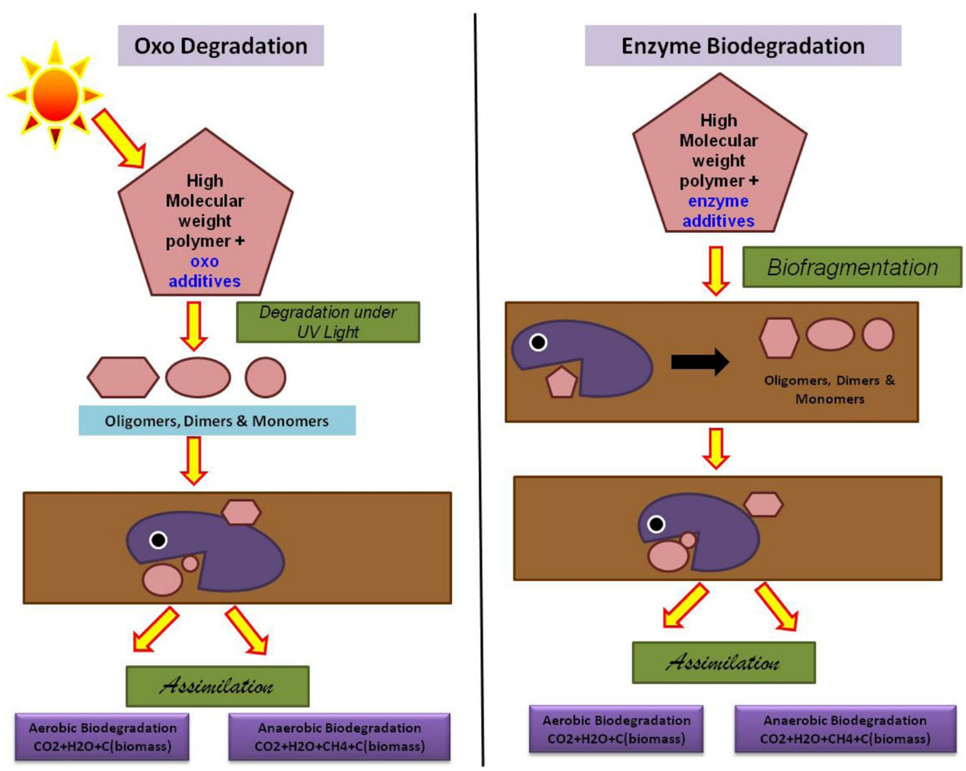

Fig. 5 Schematic diagram for oxo-degradation and enzyme-based biodegradation

including microplastics, which may even further degrade to residues invisible to the naked eye and hence are more detrimental. Further, the entire process of biodegradation requires time in excess to those claimed by the manufacturers. Therefore, much environmental risk is associated with so produced microplastics pollution, specifically in the ocean. Another point which goes against this technology is that oxo-degradable plastics are not considered appropriate for effective long-term reuse, recycling or composting [95].

- *Reuse* UV light is responsible for the degradation of oxo-degradable plastic. They have been designed to degrade after some period of time (end of service application). The addition of certain stabilizers can delay the degradation, but after the designed service life, it cannot be reused again and again.
- *Recycling* It is difficult for the processors/compounders/recyclers to differentiate between oxo-degradable film and conventional plastic film. As oxo–film would have already degraded during its service period, and hence loss of the properties. It will be challenging to estimate the extent of degradation in oxo films collected from a different source for recycling purposes. Hence, the challenge for the recycling industry
- *Composting* Oxo degradable plastics films do not conform to various composting standards like ASTM D6400, EN13432 etc. as the ultimate biodegradation process takes a very long time and also small micro particles remain in the compost, which finally affects the quality of the compost [96]. Certain plastic associations have refused to entertain oxo based films in composting facilities as they do not conform to the standard.

In view of the controversy attached to the usage of Oxo-Degradations technology, recently European Commission has concluded a detailed study and issued a report on "Study to provide information supplementing the study on the impact of the use of "oxo-degradable" plastic on the environment" [97]. This report is divided into 13 distinct hypotheses, each of which reflects either a claim from the Pro-oxidant Additive Containing (PAC) Plastic industry or a commonly held belief about the material. The summary of the report by EU based on above exercise is provided at Table 2.

Based on the above study, the European Union has concluded that oxo-based technology is not a sustainable solution to make plastics biodegradable. Over 150 organizations worldwide in 2017, including Ellen MacArthur Foundation's New Plastic Initiative support banning the oxo-degradable plastic packaging worldwide [98]. India is one of the countries that do not have a standard for oxo-degradation products.

Recently, M/s Polymateria, UK based company has developed time-controlled polymer additives for supporting and enhancing biodegradability in plastics. This additive is available in masterbatch and contains chemicals like catalysts and cocatalysts [99]. When added in Polyolefin's, after the dormancy period, the catalysts in the masterbatch break down the hard crystalline and amorphous structure into a wax-like substance through multiple chemical reactions, achieving carbon–carbon bond scission. The main claim of this technology is that during biodegradation, the polymer does not turn into microplastics (as in case of oxo-degradable technology), but converts into wax which can be further assimilated by microorganism to form CO_2 and water. It complies with PAS 9017:2020, and claimed to be food safe-FDA approved, recyclable and is tested as per ASTM D6954, ASTM D5988 & OECD 202, 207, 222 standards [100]. The patent filed by the company mentions that degradable polymer with polymer composition containing polyolefin, two or more transition metal compounds (0.15 to 0.6wt%), mono or poly unsaturated

Table 2 Summary of the Oxo-degradable Technology by European Union

Hypothesis	Supported by evidence
Hypothesis 1: In open environments, pro-oxidant additives will fasten the fragmentation of traditional polymers	Supported
Hypothesis 2: PAC plastics should not be considered compostable	Supported
Hypothesis 3: In open environments, PAC plastics biodegrade following their fragmentation	Partially supported
Hypothesis 4: PAC plastics do not biodegrade in landfill	Supported
Hypothesis 5: PAC plastics biodegrade in marine environments	Inconclusive
Hypothesis 6: In soil, fragmented and potentially partially degraded plastics and their additives pose limited negative effects to soil quality or ecosystems	Inconclusive
Hypothesis 7: The use of PAC plastic does not instill or promote a throwaway attitude	Inconclusive
Hypothesis 8: PAC plastic is a possible solution to reduce the problems of plastic marine litter compared with conventional plastic	Inconclusive
Hypothesis 9: PAC plastics can be identified and separated in collection systems	Refuted
Hypothesis 10: The presence of PAC plastics in recyclate does not affect the ability of manufacturers to guarantee specific business requirements relating to physical properties (such as tensile strength etc.)	Market dependent

C14-C24 carboxylic acid, ester, anhydride or amide (0.04 to 0.08wt%), synthetic rubber (0.04 to 0.2wt%), and optionally dry starch (0-20wt%), calcium oxide (0-1wt%), phenolic antioxidant (0–0.2wt%) [101].

Enzyme Mediated Biodegradation Technologies

Bioremediation is a well-established technology wherein waste oil (as in contaminated groundwater, an oil spill, or an industrial process) or pollutants are treated by the usage of microorganisms (such as bacteria) [102, 103]. The oil is a low molecular weight hydrocarbon molecule having C–C bond and C-H bonds. Being low molecular weight, it is susceptible to microbial degradation.

A similar concept can be applied in the case of biodegradation of polymers. Polymers are long-chain molecules having C–C, C-H etc. linkages. The only difference between the oil hydrocarbon molecules and polymer is the molecular weight.

Globally, few companies are offering biodegradable additives based on enzymatic technologies. These are M/s PEP Licensing, M/s Repsol (Partnership with enzyme technology to develop biodegradable polyolefin's), M/s BNT Force Biodegradable Polymers Private Limited [104], M/s Earth Nurture [105] M/s Biosphere Plastic LLC [106], M/s Enzymoplast [107]. Each of these companies has their respective patents in this domain [108–110] and claim to convert conventional PE/ PP into biodegradable products.

As per the claim by these companies, the mechanism proposed is that the polymeric materials can be degraded by microorganisms in the environment by their secreted enzymes, which act as a catalyst for the biochemical reaction. These enzyme complexes are incorporated into the polymer during the extrusion process. Once the polymer film comes in contact with the soil, the enzymes get activated under the specific condition of moisture, bacteria, concentration and temperature. The enzymatic complex triggers the de-polymerization of the polymer into an oligomer. This degraded polymer serves as a source of carbon and energy for bacteria already existing in the environment and the process continues until the biodegradation is over.

M/s BNT Force Biodegradable Polymers Private Limited claimed to have a Biodegradable Additive when added to any end use Polymer Profile produces a biodegradable product that converts/mineralizes to soil, or burial in damp earth. Polyethylene, Polystyrene and Polypropylene are converted to compost by the action of the Additive. The tests mentioned on the website are; ASTM D5338 (To Test Biodegradation of Plastic by the Composting Method), ASTM-D5209 (To Test Biodegradation of Film in Municipal Sewage/ Slurry) and ASTM D 5988–3 (To Test Biodegradation by the Desiccators' Method, at room Temperatures). ASTM D 5338 is a test method and not a certifying method.

M/s PEP Licensing provides a green enzyme technology (Pepzyme™) technology for the polymer industry. It combines a range of mixtures of plant-based extracts like peptides, enzymes and proteins to biologically breakdown polymers. Polyolefin already infused with Pepzyme™ will biodegrade at end of-life whereas for bio-remediation, the liquid solution can be used on non-degradable polymers for the same.

Enzymoplast® is a trademark of Advanced Enzyme Science Limited, a polymer technology company based in the UK. It has claimed to have developed the only non-bioplastic material which has achieved compostable status, certified to EN 13432 standard. Their technology is based on enzyme which promotes the enzymatic reaction within the polythene and other synthetic polymers accelerating the process of biodegradation and compostability. As per the website of the company, enzyme-based biodegradation technology has the ability to be utilized as a carbon source by micro-organisms to convert most plastics into carbon dioxide, biomass and water. Microbial breakdown is initiated where the carbonyl group is found. These functional groups are introduced in polyethylene during the photo thermal biodegradation process. The formulation of enzyme-based substrate consists of several ingredients narrowed down to the enzyme, protein and bacteria compound drawn only from natural resources and medicinal plants to make the process completely non-hazardous and non-toxic. Their product range include two grades; ENZO0001 Enzymoplast® Compostable Grade and ENZO0900 Enzymoplast® Biodegradable Grade.

Recently, Spanish energy and petrochemicals group; **Repsol** (www.repsol.com) has announced partnership with M/s PEP Licensing (website details not known) to develop biodegradable polyolefin's [111]. The companies said the alliance will allow the use of enzymatic technology for the development of two ranges of biodegradable polyolefin's of fossil origin—one that biodegrades in soil conditions and the other that is compostable. This agreement builds on a previous alliance between the two companies, established in 2015, for the development of biodegradable PE films for agriculture, by extending it to all possible polyolefin's applications, for both PE and PP.

Similarly, M/s BioSphere Plastic LLC claims to have an additive, that when added into polymers as masterbatch at 1% load, rapidly enhances the ability for plastic to biodegrade in anaerobic and aerobic environments. BioSphere biodegradable plastic additive enhances the ability for the plastic product to decompose by microorganisms leading to biodegradability in landfills, anaerobic digestion systems and aerobic facilities. BioSphere biodegradable plastic additive is claimed to work in PET, PP, PS, PE and all major resin types. Mechanism described is that BioSphere's biodegradable plastic additive will give microbes the ability to secrete acids and consume the product, turning it into CH_4,

CO_2, biomass and water [106]. Once, the biodegradable additives have homogenized with the plastic polymer, the additive reacts with the enzymes to reduce the polymer chain by hydrolysis created by the microorganisms. The microorganisms such as amylase or lipase consume the polymer to convert the plastic into CO_2, CH_4, biomass and water.

M/s Earth Nurture Additive**,** USA claim to have developed a third-generation biodegradable plastic product which is the standard fossil-based plastic with a masterbatch additive (ENA or Earth Nurture Additive,) that will cause it to biodegrade without the need of heat, UV light, mechanical stress, or oxygen. This third-generation plastic is called micro-biodegradable plastic, and it biodegrades when placed into the ground due to the action of micro-organisms naturally occurring in soil. As per the details provided on the website, ENA 2.0 masterbatch additive formulas for biodegrading all common plastics—Polypropylene, Polyethylene, HDPE, LDPE, LLDPE, Polystyrene, Expanded Polystyrene, Nylon, and many others, including PLA are available.

The claimed advantages of enzymatic biodegradation by most of the above companies are as follows:

- *Reuse:* Polymer containing enzyme will not degrade in its service life. The polymer will only degrade when it comes to contact with the soil/ compost under specific moisture, bacteria and temperature conditions. In view of this, the enzymatic based film can be reused again and again.
- *Degradation:* As per the claims by the vendors having enzymatic technology, the film containing enzymes can degrade in compost, landfill and even when it is in contact with soil (littered plastic).
- *Recycling:* Plastics containing enzymes can be easily recyclable with conventional plastics as properties do not deteriorate with time. However, author feels that the recycled polymer from this technology will not be biodegradable as the enzymes and other ingredient may not be able to sustain the additional heat cycle

As an independent assessment, in 2014, M/s OWS, Belgium, a certified and ISO accredited lab for biodegradation which has a vast experience in compostability, biodegradability, and ecotoxicity testing under (industrial/home) soil, (fresh/marine) water, composting landfill conditions and anaerobic digestion [112], conducted a study on different available enzyme-based technologies and following was concluded [113]:

- Details of the test results on biodegradation mentioned on the websites of various companies offering enzymatic technologies are coming from the laboratories which are not certified or accredited. It cannot be assured that the test protocol as per international standard is followed.
- None of the data shows complete biodegradation, only partial biodegradation is observed.
- In some cases, the percentage biodegradation is extrapolated, assuming that biodegradation will follow the straight line which is not correct.
- As per the standard, one should run positive control which is not followed in the most cases.

Enzymatic based technology seems very promising, but more data need to be generated before it is accepted for commercialized on a larger scale.

Measuring Biodegradability of Plastics—Standard Test Methods

To confirm that materials, products, processes and services are fit for their purpose, International Standard Organizations like ASTM (American Society for Testing and Materials) and ISO (International Standard Organization) and other national standard bodies etc. creates [114], guidelines, specifications or characteristics that can be used frequently. These standards are also helpful in promoting international trade. Conformity assessment is a terminology that is used to describe the steps initiated by manufacturers and other parties to check whether products, processes, systems, or personnel adhere to the requirements cited in a specified standard. The conformity assessment process has many advantages as it adds to consumers and other stakeholder's confidence that their products are reliable, safe, and of good quality.

Governments and regulators count on ASTM/ ISO/ other standards to help establish better regulation, knowing they have a sound basis thanks to the involvement of globally-established experts.

ISO-TC-61 and ASTM D-20–96 Committee is responsible for creating standards for plastics. Over the last few decades, these international organizations have created a large number of plastics standards revolving around the biodegradability of plastics. For brevity, only ASTM, ISO and European standards related to biodegradation of plastics are discussed. However, one crucial part to understand here is that all such standards fall under 2 main categories:

1. Standards describing Test Methods—Defines the detailed procedure/protocol as how to conduct a measurement/test e.g. CO_2 evolution. These standards have no pass/fail criteria.
2. Certification Standards—These can be used to certify/label products as biodegradable/compostable.

Table 3 Standards describing Test Methods (ASTM/ISO/European)

S.No	Standard	Application	Aerobic/anaerobic	Typical characteristics
1	ASTM D 5338 [118] Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions, Incorporating thermophilic Temperatures	Composting of Plastics	Aerobic	Medium/Inoculum: Compost Temperature: 58 ± 2 °C Measurement: CO_2 measurement Time: Minimum 45 days Reactor Size: 2-5L Total Reactors: 12 Nos (Blank: 3, Reference: 3, Sample: 3 Nos, Negative: 3 Nos)
2	ISO 14855–1 [119] Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions— Method by analysis of evolved carbon dioxide—Part 1: General method	Composting of Plastics	Aerobic	Medium/Inoculum: Compost Temperature: 58 ± 2 °C Measurement: CO_2 measurement by titration Time: Max 180 days Reactor Size: Minimum 2 L Total Reactors: 5 Nos
3	ISO 14855–2 [120] Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions— Method by analysis of evolved carbon dioxide—Part 2: Gravimetric measurement of carbon dioxide evolved in a laboratory-scale test	Composting of Plastics	Aerobic	Medium/Inoculum: Compost Temperature: 58 ± 2 °C Measurement: CO_2 measurement by Gravimetric method Time: Max 180 days Reactor Size: Minimum 500 mL Total Reactors: 9 Nos (Blank: 2, Reference: 2, Sample: 2 Nos)
4	ASTM D5988 [121] Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in Soil	Soil Biodegradation of Plastics	Aerobic	Medium/Inoculum: soil Temperature: 20–28 ± 2 °C Measurement: CO_2 measurement by titration method Time: Max 180 days Reactor Size: Minimum 2–4 L Total Reactors: 2 Nos (Blank: 2, Reference: 2, Sample: 2 Nos)
5	ISO 17556 [122] Plastics-determination of the ultimate aerobic biodegradability in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved	Soil Biodegradation of Plastics	Aerobic	Medium/Inoculum: soil Temperature: 20–25 ± 2 °C Measurement: CO_2 measurement by titration method Time: Max 180 days Reactor Size: Minimum 200–300 g Total Reactors: 6 Nos (Blank: 2, Reference: 2, Sample: 2 Nos)
6	ISO 14852 [123] Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium — Method by analysis of evolved carbon dioxide	Biodegradation of Plastics in aqueous medium	Aerobic	Medium: Water Inoculum: Sewage Treatment Plant Mixed Sludge Temperature: 20–25 ± 1 °C Measurement: CO_2 measurement by titration method Total Reactors: 5 Nos
7	ISO 14851 [124] Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium — Method by measuring the oxygen demand in a closed respirometer	Biodegradation of Plastics in aqueous medium	Aerobic	Medium: Water Inoculum: Sewage Treatment Plant Mixed Sludge Temperature: 20–25 ± 1 °C Measurement: O_2 consumption by titration method Total Reactors: 5 Nos

Table 3 (continued)

S.No	Standard	Application	Aerobic/anaerobic	Typical characteristics
8	ASTM D6691 [125] Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in the Marine Environment by a Defined Microbial Consortium or Natural Sea Water Inoculum	Biodegradation of plastics exposed to marine micro-organism	Aerobic	Medium/Inoculum: Natural sea water + micro-organisms Temperature: 30 ± 2 °C Reactor Size: 125-mL autoclave bottles Measurement: CO_2 measurement by titration method Time: 10–90 days Total Reactors: 13 Nos
9	EN14046 [126] Packaging—Evaluation of the ultimate aerobic biodegradability and disintegration of packaging materials under controlled composting conditions—Method by analysis of released carbon dioxide	Composting of Plastics	Aerobic	Medium/Inoculum: Compost Temperature: 58 ± 2 °C Measurement: CO_2 measurement by titration Time: 180 days
10	ASTM D6954 [127] Standard Guide for Exposing and Testing Plastics that degrade in the Environment by a Combination of Oxidation and Biodegradation	Oxo-Biodegradation	Aerobic	3 tier test: UV/thermal degradation at 20–70 °C CO_2 measurement as per ASTM D5338/ ASTMD 5988 Toxicity Test
11	ASTM D 5511 [128] Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under High-Solids Anaerobic-Digestion Conditions	Domestic garbage—Biodegradation of a plastic within a high-solids anaerobic digestion unit	Anaerobic	Medium/Inoculum: Anaerobic Inoculum, derived from a properly operating anaerobic digester with pretreated household waste as a sole substrate Temperature 37 ± 2 °C for mesophilic or 52 ± 2 °C for thermophilic Measurement: bio gas CO_2 & CH_4 measurement Time: 15–30 days Reactor Size: 2L Erlenmeyer Flasks having opening of at least 7 cm diameter Total Reactors: 12 Nos (Blank: 3, Reference: 3, Sample: 3 Nos, Negative: 3 Nos)
12	ISO 15985 [129] Plastics — Determination of the ultimate anaerobic biodegradation and disintegration under high-solids anaerobic-digestion conditions — Method by analysis of released biogas	Treated Domestic garbage—More than 20% solid	Anaerobic	Medium/Inoculum: Anaerobic Inoculum, derived from a properly operating anaerobic digester with pretreated household waste as a sole substrate Temperature: 52 ± 2 °C Measurement: bio gas CO_2 & CH_4 measurement Time: 15 days Reactor Size: > 750 mL Erlenmeyer Flasks Total Reactors: 9 Nos (Blank: 3, Reference: 3, Sample: 3 Nos)
13	ISO 13975 [130] Plastics—Determination of the ultimate anaerobic biodegradation of plastic materials in controlled slurry digestion systems —Method by measurement of biogas production gas	Biodegradability of plastic materials with a solids conc. not exceeding 15%,	Anaerobic	Inoculum: Slurry

Table 3 (continued)

S.No	Standard	Application	Aerobic/anaerobic	Typical characteristics
14	ISO 14853 [131] Ultimate anaerobic biodegradability in an aqueous system – method by measurement of biogas production	Exposure of the test material to sludge	Anaerobic	Medium/Inoculum: Sludge Temperature: 35 ± 2 °C Measurement: bio gas CO_2 & CH_4 measurement Time: 90 days Reactor Size: 100–1000 mL
15	ASTM D 5526 [132] Standard Test Method for Determining the Anaerobic Biodegradation of Plastic Materials under Accelerated Landfill Conditions	Biodegradation of plastic materials in an accelerated-landfill test environment	Anaerobic	Medium/Inoculum: Anaerobic Inoculum, derived from a properly operating anaerobic digester with pretreated household waste as a sole substrate Temperature: 35 ± 2 °C Measurement: bio gas CO_2 & CH_4 measurement Reactor size 4–6 L Total reactors: 27 Nos

Standards Describing Test Standards

Table 3 lists the major aerobic and anaerobic standards (ASTM/ISO and European Standards) which can be classified as test methods to determine the rate and time frame of biodegradation under specific conditions. These test methods have been created by mimicking the environment experienced by plastic at its end of life. As there are many standards revolving around the biodegradation of plastic, it is of utmost importance to understand which type of standard to be followed under what circumstances and under what applications. These can be further categorized as follows:

1. *Biodegradation under Composting Facility (Aerobic):* ASTM D5338, ISO-14855–1, ISO-14855–2, EN-14046 are the test methods for calculating percentage biodegradation and biodegradation rate in the composting condition. The test is carried at 58 °C. The basic difference between ASTM D5338 and ISO-14855–1 is the number of reactors used during the measurements. Other test parameters are similar in both the method. There are two different ISO methods namely ISO-14855–1 and ISO-14855–2 and they differ in the way evolved CO_2 is measured. In the former test method, CO_2 is measured based on titration-based methods and in the later CO_2 is measured gravimetrically. This test is done for 45 days and can be further extended depending on the activity of the compost.
2. *Biodegradation under soil condition (Aerobic):* This standard can be basically used for biodegradation tests on littered plastics. The littered plastics if biodegradable will biodegrade when they come in contact with soil. ASTM D5988 and ISO17556 are two standards available for biodegradation tests under soil conditions. During the test, the temperature is maintained in the range of 20–28 °C. Both the test methods differ in terms of reactor size and the number of reactors. The test duration is 6 months.
3. *Biodegradation of plastic under aqueous medium and marine conditions (Aerobic):* As, most of the waste plastic pollution reaches marine environments through different pathways, standards simulating to studying biodegradation of plastics in aqueous and marine conditions are there for example ISO 14852, ISO 14851, ASTM D6691. These test methods differ in terms of reactor size, the number of reactors etc.
4. *Oxo-biodegradation of plastics (Aerobic):* ASTM D6954 has been created so that the polymers undergo change in properties by thermal and photo-oxidation processes as well as the biodegradation and ecological impacts in defined applications and disposal environments after degradation which thereby helps in study compare and rank the controlled laboratory rates of degradation and

degree of physical property losses of polymers. The disposal environment in this condition varies from exposure in the landfill, soil, and compost in which thermal oxidation may occur and land cover and agricultural use in which photo-oxidation may also occur. This is a 3-tier test. In the first tier, UV/thermal degradation at 20–70 °C is carried, in the second tier, CO_2 measurement on UV degraded sample as per ASTM D5338/ ASTMD 5988 is studied and the last tier pertains to the Toxicity Test.

5. *Anaerobic biodegradation in landfill:* ASTM D5526 is an anaerobic biodegradation [115] standard which covers the determination of the degree and rate of biodegradation of plastic materials in an accelerated-landfill test environment. This test method is also created to produce mixtures of plastic materials and household waste and after different degrees of decomposition under conditions that are similar to landfill conditions. The test method involves mixing of test materials with pretreated household waste and thereafter exposing to a methanogenic inoculum derived from anaerobic digesters operating only on pretreated household waste. The conditions favorable for anaerobic decomposition are dry (more than 30% total solids) and static non-mixed conditions. After the test, the mixtures obtained can be used to determine the environmental and health risks of plastic materials that have been degraded in a landfill. In the landfill condition, there is the production of both methane and carbon dioxide. The test is carried at 35 °C.
6. *Anaerobic biodegradation in anaerobic digesters:* ASTM D 5511, ISO 15985, ISO 13975, ISO 14853 is an anaerobic biodegradation standard for plastic materials covers the determination of the degree and rate of plastic materials in high-solids and low solid anaerobic conditions [116, 117]. The test materials are exposed to a methanogenic inoculum derived from anaerobic digesters operating only on pretreated household waste. Different test methods differ in terms of reactor size, the number of reactors, test temperature, solid content for example ISO 13975 mentions biodegradability of plastic materials with a solids concentration not exceeding 15% whereas ISO 15985 mentions minimum 20% solid content.

Certification Standards

The standards listed in Table 4 are test method which tells in details the conditions during the biodegradation test. However, if a plastic is advertised to be biodegradable or compostable, certain minimum specifications should be laid down. It is ambiguous to claim biodegradability without

Table 4 Standard Method for Specifications of compostable plastic (ASTM/ISO/European)

S. No	Standard	Application	Specification
1	ASTMD 6400 [133] Standard Specification for Labeling of Plastics Designed to be Aerobically Composted in Municipal or Industrial Facilities ISO 17088 [134] Specifications for compostable plastics EN 13432 [135] Packaging. Requirements for packaging recoverable through composting and biodegradation. Test scheme and evaluation criteria for the final acceptance of packaging	Specification for compostable plastic	1. Disintegration: Satisfactory disintegration of plastic product is considered if after twelve weeks (84 days) in a controlled composting test, not more than 10% of its original dry weight remains after sieving on a 2.0-mm sieve 2. Using this test method, a plastic product must show a satisfactory rate of biodegradation within 180 days 3. The plastic or product shall have concentrations of regulated metals less than 50% of those prescribed for sludges or composts in the country where the product is sold 4. Ecotoxicity: The germination rate and the plant biomass of the sample composts shall be no less than 90% that of the corresponding blank composts for two different plant species following OECD Guideline 208

specifying any standard specification merely. A certification standard provides the results as pass/fail and the basis for making a claim, for example, to certify the material to be classified as compostable. Table 4 compares the standards for specification of compostable plastics.

It clearly cites that in order to classify the plastic material as compostable, 90% of the plastic material should disintegrate within 84 days, should have a satisfactory rate of biodegradation, should not have heavy metals and should pass the ecotoxicity test.

Recent Biodegradation Standard by UK

Recently (in October 2020), a new benchmark biodegradation standard, PAS 9017:2020 [100] entitled "Biodegradation of polyolefin's in an open-air terrestrial environment. Specification" has been developed by British Standards Institution (BSI). As per the standard, plastic will have to break down into organic matter and carbon dioxide in the open air within two years to be classed as biodegradable. As per the details available, this standard only applies to land-based plastic pollution. The test sample shall be deemed valid if 90% or greater of the organic carbon in the wax is converted to carbon dioxide by the end of the test period when compared to the positive control or in the absolute. Such standards with new ideas are very much required for Polyolefin industry so as to tackle the global challenge of plastic waste.

Perceived issues with Biodegradation Standards w.r.t. Conventional Plastics

To address the littering problem & non-biodegradability of conventional plastics, many bioplastics started emerging into the market. In view of this, international biodegradation standards were prepared to classify such bioplastics as biodegradable and/ or compostable plastics. Lately, other technologies like oxo-based and enzyme-based technologies have also emerged which claims to make conventional plastics like PE/PP/PET into biodegradable/compostable plastics. These technologies have not been proved conclusively and there is very little penetration of such technologies/products in the market.

- One of the major reasons is that all the biodegradability standards have been written keeping in mind the realm of bioplastics and not the conventional plastics, which are inherently non-biodegradable and are perceived as unthinkable to be a biodegradable with the intervention of any technology.
- In our view, this aspect also needs to be looked into and either standard need to be reviewed considering conventional plastics or new standards may be required to test such unconventional polymers when attempted to be converted to biodegradable/compostable plastic using enzyme-based technologies.

Following are some of the significant issues which need to be addressed:

- A major contradiction in the standard is w.r.t. biodegradation and disintegration time frames. As per the standard ASTM D 6400 the disintegration must happens within 84 days and the biodegradation in 180 days [133], these processes cannot be independent of each other. Processes of disintegration and biodegradation will go on simultaneously.
- Polyethylene has a high carbon content of 84% compared to PLA having 63% carbon content. Moreover, polyethylene has only C–C and C-H bonds which are very difficult to break and PLA has ester linkages that can be easily broken by hydrolysis. It is practically not feasible that both type of polymers having different linkages and carbon content biodegrade in same time frame.
- As per the composting standard (ASTM D6400), the polymer should biodegrade in 6 months. Whereas, some natural materials like a leaf, pine leaves, oak leaves, wood fibre etc. take more than 2 years to biodegrade. For example: wood fibre biodegrades 71% in 728 days, oak leaves 58.4% in 365 days etc. [136]. Therefore, the time frame needs to be redefined in the standards.
- As per the ASTM D6400 standard, the ultimate biodegradation is 90%. What are the criteria in selecting 90%? Why not 80% or 100%?
- There is no standard for certification of biodegradation of plastics in soil. While, in order to certify a plastic product as compostable, a standard like ASTM D6400 or equivalent exists, whereas no such standards exist for soil biodegradation of plastics.
- ASTM D5338 mentions use of distilled water to prepare the inoculum. Why distilled water, why not raw water or treated water, which shall better simulate the actual field conditions?
- Correlation of lab test results (ASTM) with field trial [15]: Not many studies have been published simulating lab biodegradation results and extending them to actual field trials. For example, if a biopolymer biodegrades as per ASTM D6400 in 3 months, then how much time it will take to biodegrade in actual field conditions or natural environment? To simulate such studies, it has to be ensured that the microorganisms used in a laboratory test have to be present in the natural environment, where a plastic item could possibly end up. Moreover, the lab tests are performed under controlled temperatures, controlled humidity and such type of conditions will not

be same during the field trials. Thus, the origins of a microorganism, temperature, humidity are some of the significant factors which need to be taken into account for the assessment of the biodegradability of polymers in real environments. Studies need to be carried out in this area and if required ASTM standards need to be modified so that there is smooth transition from lab results to field results.

- ASTM D6954 standard cautions that, "The results of any laboratory exposure in this guide cannot be directly extrapolated to actual disposal environments" [127].
- In an extensive review [15], authors have shown that biodegradation tests carried out in artificial environments lack transferability to real conditions like and marine waters, soil, and compost, as degradation kinetics differ drastically for certain polymers depending on the environment therefore, highlight the necessity of environmentally authentic and relevant field-testing conditions.
- In another study [137], Napper et al. examined biodegradable, oxo-biodegradable, compostable, and high-density polyethylene materials over a 3 year period. These materials were exposed in three natural environments; open-air, buried in soil, and submersed in seawater, as well as in controlled laboratory conditions. The study found that while in the marine environment, the compostable bag completely disappeared within 3 months; the same bag was still present in the soil environment after 27 months. The study concluded that none of the bags could show any substantial deterioration over a 3 year period in all of the environments.
- Further, author's lab has conducted multiple field trials with PE films prepared using enzyme-based biodegradation technology for studying compostability and soil biodegradation. Though, there was some reduction in the molecular weight of the samples, but the results were not reproducible and moreover many times blank also showed molecular weight reduction indicating photodegradation due to sun light. We could not establish any correlation with the lab results claimed by the technology supplier. The manuscript is under preparation and the study shall be published separately.

Misuse/Misinterpretation of Standards and Case Studies

Biodegradable and compostable plastics are often being used interchangeably. The term biodegradable is a misnomer in marketing and advertising of materials and products that are not indeed friendly to the environment. There are many companies selling products labeled as biodegradable/compostable but not conforming to acceptable international standards. Some of the case studies as collected from literature are addressing the misuse of the standards are as follows:

- Recently, M/s Amazon was selling plastic products labeled as biodegradable/compostable. It has been alleged that Amazon advertised and sold plastic products misleadingly, which has been labeled as "biodegradable" or "compostable plastic products. The biodegradability claims are inherently misleading and not conforming to the required international biodegradation standards. In reference to this, the suit was filed by 23 counties in California. M/s Amazon has agreed to pay $1.5 M in California Consumer Protection Suit [138].
- Some studies use the "biodegradable" term to indicate that the PE samples were subjected to aerobic conditions. In the study, they measure the weight loss, molecular weight reductions using GPC, carbonyl index by IR, mechanical property loss of the films. These studies were used to certify that their plastic product is 100% biodegradable. However, fundamental data showing carbon utilization by microorganisms as measured by different standards was found to be missing. Hence, it was wrongly claimed [139].
- An Indian manufacturer M/s Chirag Industries was manufacturing oxo-degradable cutlery packed in a pouch labeled as Oxo-Biodegradable pouch. Initially, there was no mention of any conforming standard on the pouch (Fig. 6a). Lately, it was observed that the company started specifying whole lot of biodegradation standards on the pouch like; ASTM D6954, ASTM D5208 [140], ASTM D5338, ASTM D3826 [141], ASTM D6400, ISO17088 & EN13432, ISO14855 & Food Safety Norms i.e. IS 9833 [142] and IS 9845 [143]. As discussed in the previous section, ASTM D5338, ISO14855 etc. are standards describing the test methods and are not certifying standards and hence it is technically not correct to mention all the standards on the pouch. Moreover, standards like ASTM D6400, ASTM D5338 etc. are not relevant for oxo-degradable products, for which accepted standard is ASTM D6954.
- A company manufacturing plastic bags used the following biodegradable and compostable logo as shown in Fig. 6b [113]: ISO 14855 is a test method to determine % CO_2 evolved and is not a certifying standard and hence, by using this standard they are falsely claiming the products as compostable.
- Exploration of % biodegradability Data: As shown in the Fig. 6c, sometimes the data generated by biodegradation studies is extrapolated in order to find the correlation between the samples. This process if carried out will lead to wrong conclusion about the biodegradability of the samples tested [139].

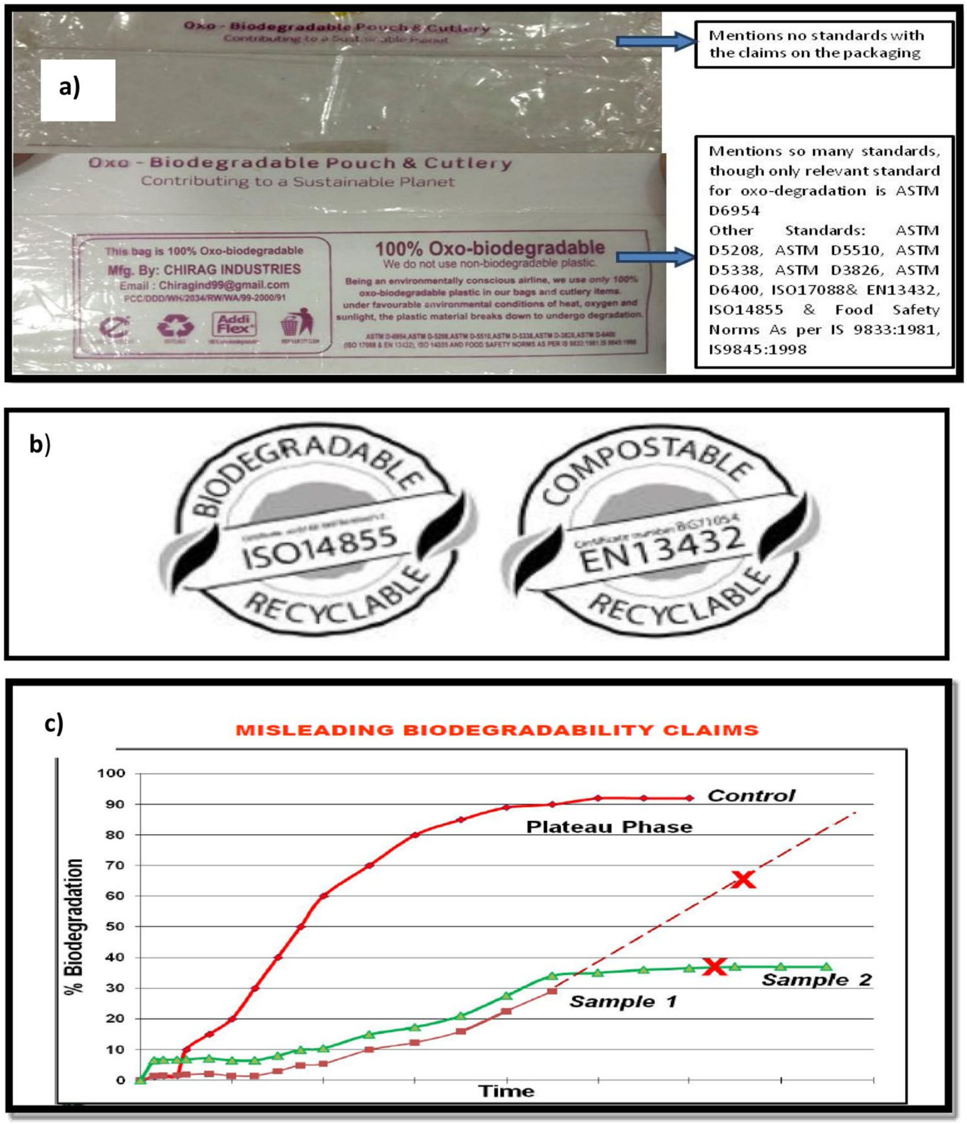

Fig. 6 Case studies-Misuse/Misinterpretation of Standards

- Recently, Central Pollution Control Board (CPCB) of India has issued a notification on 7th January 2019 [144], it is mentioned that 12 companies in India were selling plastic products in the name of compostable products based on fake certificates. However, as per the CPCB notification, these companies have not been authorized and issued a certificate by CPCB, resulting in non-compliance. Some of these companies created lot of hype initially in the newspapers about their biodegradable plastic products.

From the above examples, it can be seen that there is a widespread misuse of international standards (ASTM/ISO) across the globe while claiming one's product as biodegradable plastics or compostable plastics. Consumers have to be extremely careful while using such products, which otherwise do not comply with national/international standards, but still being sold in the market at a premium.

Myths and Realities of Bioplastics/Biodegradable Plastics

Many different biopolymers have been manufactured and consumed globally over the years to provide a solution for finding the best biodegradable solution in the market. Some of these bio-polymers are PLA, PHA, PBAT etc. These bioplastics are based on plant-based sources rather than oil based and are able to carry out the same function as synthetic based plastics. As the synthetic plastic, these so-called bioplastics can be recyclable, compostable or biodegradable. However, there are certain limitations. Though, bioplastics might seem to have many benefits but they have some darker side as well i.e. they aren't the perfect eco-friendly product we might hope. Although, designing and marketing are being done as environmentally conscious alternatives, but the reality is that bioplastics are confusing consumers. Recently, there is a lot of hype for replacing conventional plastics with biodegradable plastics or so-called bioplastics. However, there are specific issues associated with bioplastics and these alone cannot solve the problem of plastic pollution. Based on the extensive scan of literature, their critical examination, recent reports by various organisations, authors are of the view that the subject of Bioplastics-Biobased and /or Biodegradable/compostable plastics are surrounded by lot of misconceptions or myths, whereas real life situations present a different scenario. Some of the myths and realities associated with bioplastics are as follows:

(a) Myths: Biodegradable and compostable plastics are the same.

Whereas, the reality is that both the processes are quite different and claim about a product to be biodegradable and compostable has to be verified by different set of standards as described above.

(b) Myth: All biobased plastics are biodegradable including bio-PE, bio-PP, bio-PET etc.

Whereas, the reality is that though these biobased polymers exhibit similar mechanical properties to the fossil-based PE, PP or PET, these are non-biodegradable as fossil-based products. The false assumption that all bioplastics will biodegrade in the environment may increase the littering problem.

(c) Myth: All biodegradable/compostable bioplastic will degrade in all the conditions like soil biodegradation, compost etc.

Whereas, the reality is the bioplastics are designed to degrade in specific conditions only. There will be only a few which will compost in a back-yard compost bin and whereas others need industrial composting processes. This kind of situation thereby, results in a lot of confusion for consumers.

(d) Myth: All the bioplastics can be recycled in same way as that of conventional plastic.

Whereas, the reality is that the processing temperature of conventional plastics is quite different to that of bioplastics. Accidental mixing of small amount of PLA plastic is with PET plastics in the recycling stream, will result in recycled plastic products with low value. Hence, they need to be segregated from conventional plastic before recycling.

(e) Myth: Biodegradable/ compostable plastics are the panacea for solving the waste plastic littering problem and it is developed to make "Ready-for-Littering" packaging and products.

Whereas, the reality is that the littered bioplastic may not biodegrade or will take much longer time (more than few years) for complete biodegradation. Any biodegradable/ compostable plastic would still require controlled recovery after usage like any other conventional plastic.

(f) Myth: Bioplastics alone shall solve the plastic pollution problem.

Whereas, the reality is that to solve the problem of plastic pollution we have to look for various other solutions as well like segregation of plastic & recycling, other technologies like converting waste plastic to industrial fuels etc., converting waste plastic into paver block and other value-added products etc.

(g) Myth: Adding additive to bioplastic will make it biodegradable/ compostable.

Whereas, the reality is oxo-based additives can cause even more harm due to formation of microplastics to environment and if they go to landfill and buried, it will not degrade due to more exposure to sunlight. Enzyme based additives are promising but this technology has not matured enough and more data need to generated.

(h) Myth: Any standard can be used to claim biodegradab ility/compostability.

Whereas, reality is testing standard and certified standards are different.

(i) Myth: Bioplastics can easily replace fossil-based plastics.

Whereas, the reality is bioplastics are 2–4 times expensive compared to conventional plastics [145].

(j) Myth: Bioplastics biodegrade in landfills.

Whereas, the reality is bioplastics biodegrade at very slow rate in landfills as there is no availability of oxygen. Further, PLA is inert in landfill like other conventional plastics.

(k) Myth: Bioplastics are as harmful to environment as the conventional plastic

Whereas, the reality is bioplastics address beginning of the life of plastics and offer reduced use of fossil sources and hence reduced overall carbon foot print, when compared to conventional fossil base plastics. However, not all bioplastics address the issue of end of life for plastics.

Conclusions

There is no second opinion that wide spread use of plastics and their improper disposal after usage has resulted in serious environmental problem like land pollution in the form of littering, marine pollution and water pollution. Most of the waste plastic globally comes from single-use plastic, and it is littered within few minutes of its first use.

Due to this alarming issue, as an alternative in recent years, there has been a shift of advocating the replacement of such synthetic based plastics with biodegradable/bioplastics, which are claimed to be biodegradable and/or compostable. However, the world of biodegradable/bioplastics is riddled with many problems as the current terminology used around such bioplastics is confusing for the general public. As a result, "greenwashing" is on the rise, with brands even making spurious claims about the environmental benefits of their products.

Through this review article, authors have tried to collate & cover various aspects, which are so inter-related to the subject of bioplastics/biodegradable plastics, including general information like production status, global manufacturers of such products, clear definitions and distinction between various terminologies, applicable standards, lack of correlation between lab results and field results, status of technologies being propagated to convert conventional fossil based plastics into biodegradable products, besides highlighting issues with current standards when applied to conventional plastics, misinterpretation/issue of standards and also some of the myths & realities associated with biodegradable/bioplastics. Bioplastics at best address beginning of life of plastics and may or may not address end-of-life of plastics. Biodegradability is an end-of-life option that utilizes microorganisms in the selected disposal environment to completely eliminate biodegradable plastic without any toxic residues, whereas, compostability is one such specific environment where biodegradation occurs. However, the fact remains is that bioplastics/biodegradable plastics alone cannot solve the problem of plastic pollution and any false assumption on the biodegradability/compostability may in fact increase the littering.

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Compliance with Ethical Standards

Conflict of interest The authors declared no potential conflicts of interest.

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