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PHA-Based Bioplastic: a Potential Alternative to Address Microplastic Pollution

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Abstract Petroleum-derived plastics are linked to a variety of growing environmental issues throughout their lifecycle, including emission of greenhouse gases, accumulation in terrestrial and marine habitats, pollution, among others. There has been a lot of attention over the last decade in industrial and research communities in developing and producing eco-friendly polymers to deal with the current environmental issues. Bioplastics preferably are a fast-developing family of polymeric substances that are frequently promoted as substitutes to petroleum-derived plastics**.** Polyhydroxyalkanoates (PHAs) have a number of appealing properties that make PHAs a feasible source material for bioplastics, either as a direct replacement of petroleum-derived plastics or as a blend with elements derived from natural origin, fabricated biodegradable polymers, and/or non-biodegradable polymers. Among the most promising PHAs, polyhydroxybutyrates (PHBs) are the most well-known and have a significant potential to replace traditional plastics. These biodegradable plastics decompose faster after decomposing into carbon dioxide, water, and inorganic chemicals. Bioplastics have been extensively utilized in several sectors such as food-processing industry, medical, agriculture, automobile industry, etc. However, it is also associated with disadvantages like high cost, uneconomic feasibility, brittleness, and hydrophilic nature. A variety of tactics have been explored to improve the qualities of bioplastics, with the most prevalent being the development of gas and water barrier properties. The prime objective of this study is to review the current knowledge on PHAs and provide a brief introduction to PHAs, which have drawn attention as a possible potential alternative to conventional plastics due to their biological origin, biocompatibility, and biodegradability, thereby reducing the negative impact of microplastics in the environment. This review may help trigger further scientific interest to thoroughly research on PHAs as a sustainable option to greener bioplastics.

Keywords Microplastics · Bioplastics · Polyhydroxyalkanoates (PHAs) · Polyhydroxybutyrates (PHBs)

1 Introduction

Plastic products are incredibly versatile due to their low thermal and electric conductivity, lightweight, rigid, long-lasting and corrosion resistance, which enable them to serve as an oxygen and water barrier. Their low cost also contributes to their easy and widespread production, where they are utilized in

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numerous applications extending from food industry to medical and technological uses that benefit the society (Frias & Nash, 2019; Thompson et al., 2009). However, plastic waste has been visible as a worldwide pervasive pollution over the last decade. Around the world, plastics, and therefore its wastes and residues, can be found in land, ocean, and freshwater habitats, including in the most remote locations. Although global plastic production and utility are increasing, waste management and treatment in many places remains a major concern. As a result, at a staggering pace of 31.9 million metric tons per year, plastic ends up in the natural surroundings (Bucci et al., 2020; Jambeck et al., 2015). Currently, only a small portion of this plastic is recycled when it is disposed of, and the remaining bulk is released into the environment, where it may stay for many years before totally degrading. Over time, these plastics degrade in the environment, producing micro- and nanoplastics, which are tiny particles or fibers generally harmful to living organisms (Pellini et al., 2018). Immoderate usage of plastics has wreaked havoc on the environment, with humans producing about 34 million tons of plastic recently. Only 7% of production gets recycled, with remaining 93% ending up in landfills, oceans, and seas (Shah et al., 2021). Arikan and Ozsoy (2015) mentioned several environmental and economic issues in their study caused by widespread use of plastics, including landfill problems, plastic accumulation in oceans, incineration of plastics, non-degradability or durability, and economic problems such as crude oil competition and energy security. These negative consequences have the potential to harm humans and animals, as well as completely disrupt biological cycles and ecosystems. Therefore, finding a substitute for petroleum-derived polymers is becoming a pressing need to prevent the undesirable effects that traditional polymers have made in the environment due to their excessive utilization and improper disposal (Narayanan et al., 2020a). To find alternatives, researchers developed entirely biodegradable polymers that can be discarded in the environment and easily degraded by microorganisms' enzymatic activity. These materials are known as "Bioplastics" (Marjadi & Dharaiya, 2010). Because of their similar physical and chemical qualities, as well as their ability to biodegrade quicker than petroleum-derived plastics, bioplastics are regarded viable alternatives for petroleum-derived synthetic polymers (Mascarenhas & Aruna, 2017). The growing demand for environment-friendly products, along with the need to cut carbon emissions and microplastic and plastic pollution in earth's biosphere, has prompted the growth of new bioplastic supplies in recent years that meet a similar demand as existing plastics with lower environmental impact (Calero et al., 2021). Meereboer et al. (2020) examined recent developments and opportunities to use polyhydroxyalkanoates (PHA)-based bioplastics as an alternative to petroleum-based plastics. In contrast to the negative effects of disposing of plastics in landfills, PHA-based bioplastics exhibit biodegradable behavior in all anaerobic and aerobic environments as described by American Society for Testing and Materials standards and can be used to make fully compostable, soil- and marine-biodegradable goods.

To produce bioplastics and associated biomaterials, PHAs may be extracted and refined from a variety of bacterial strains. This may help reduce the dependency of the present world on petroleum-derived plastics, which will reduce plastic pollution and safeguard the nature (Muneer et al., 2020). PHAs are typically produced by intracellular microbes and stored as carbon and energy in specialized sub-cellular organelles (carbonosomes) when they are exposed to nutritional limitations (Tanamool et al., 2013). Usually, limiting nutritional factors like phosphorus (P) and nitrogen (N) restrictions or the availability of an excess carbon (C) supply is known to stimulate polyhydroxybutyrate (PHB) production in bacteria. The requirements of C in living organisms are often greater than N. The proportion of these components (C:N) governs how bacteria utilize an organic substance. According to Wei et al. (2011), when gluconic acid was utilized as the carbon source, the best C:N ratio for the efficient production of PHAs in *Cupriavidus taiwanensis* was 8:1, with a PHB concentration of 58.81%. Likewise, at a C:N ratio of 8:1, *Bacillus thuringiensis* IAM 12,077 produced the greatest PHB content of 72.3% utilizing starch as the carbon source, according to Gowda and Shivakumar's (2014) research. According to Lee et al. (2020), *Rhodobacter sphaeroides* produced the highest PHB content of 51.57% at a C:N ratio of 15:1 when succinic acid was used as the carbon source. Thus, depending on the kinds of bacteria and the carbon sources, the C:N ratio for the optimal generation of PHB varies. However, the carbon need is almost always greater than the nitrogen requirement. Based

Table 1 Production of polyhydroxyalkanoates (PHAs) by various microorganisms using variety of carbon sources

Microorganisms	Carbon source	Dry cell weight (DCW) (g/L)	PHAs yield (g/L)	PHAs accumulation (%)	References
Burkholderia cepacia ATCC 17,759	Glycerol	5.8	4.8	82.76	Zhu et al. (2010)
Bacillus aryabhattai	sweet sorghum juice	3.02	1.74	57.62	Tanamool et al. (2013)
Brevundimonas sp. NAC1	Cardboard industry waste water	–	4.042	77.63	Bhuwal et al. (2013)
Enterococcus sp. NAP11	Cardboard industry waste water	–	5.236	79.27	
Bacillus sp. NA10	Cardboard industry effluent	7.8	5.202	66.70	Bhuwal et al. (2014)
Bacillus thuringiensis IAM 12,077	Starch	3.6	2.6	72.3	Gowda and Shivakumar (2014)
Cupriavidus necator	Fructose	11.6	7.48	64.48	Aramvash et al. (2015)
Pseudomonas aeruginosa	Mustard oil	–	9.01	20.1	Javed and Jamil (2015)
Bacillus sp.	Sugarcane bagasse	9.0	5.0	55.55	Getachew and Woldesenbet (2016)
Pseudomonas putida	Waste frying oil	4.90	2.80	57	Gatea et al. (2018)
Bacillus siamensis PD-A10	Orange peel	2.66	2.16	81.2	Vijay and Tarika (2019)
Bacillus subtilis JCM 1465	Onion peel	3.33	2.93	88	
Staphylococcus aureus JH1	Onion peel	1.56	1.29	83	
Bacillus megaterium	Molasses	–	19.52	60.02	Joyline and Aruna (2019)
Bacillus cereus NDRMN001	Rice bran	36.26	33.19	91.54	Narayanan et al. (2020a)
E. coli	Sago molasses	33.26	27.1	81.47	Narayanan et al. (2020b)
Paraburkholderia sp. PFN29	Glucose	5.14	5	97.3	Sriyapai et al. (2022)

on previous investigations, production of polyhydroxyalkanoates (PHAs) by various bacteria using variety of carbon sources is presented in Table 1.

One of the most promising biopolymers is polyhydroxybutyrates (PHBs), a biogenic short-chain polyhydroxyalkanoates synthesized by the process of glycolysis where preferably soluble mono- and di-saccharides are utilized to produce acetyl-CoA which later converted into PHBs. PHBs are additionally harmless to the environment and people due to its biodegradability and biocompatibility as compared to petroleum-derived plastics. In contrast to traditional plastics, which have a life expectancy of between 100 and 1000 years, PHA-based bioplastic may degrade into water (H_2O) and carbon dioxide (CO_2) in 20 to 45 days if there is adequate humidity, oxygen, and a sufficient number of microbes in the open environment (Moshood et al., 2022). Its characteristics like flexibility, crystallinity, elasticity, and thermoplasticity are comparable to those of thermoplastics that are petroleum-derived, and it can be biodegraded by depolymerase enzymes found in bacteria and fungi that break down PHBs. Such bacteria and fungi exist extensively in various ecological systems (Awasthi et al., 2020). PHAs are utilized to develop bioplastics, which are of great interest to researchers in polymeric science due to their sustainability and effectiveness in achieving some of the related (e.g., environment; health; food security) sustainable development goals set forth by the United Nations. Moreover, they can help to reduce dependency on fossil fuels and uphold sustainability initiative (Muneer et al., 2020). However, the primary limiting factor that has restricted the marketable applicability of

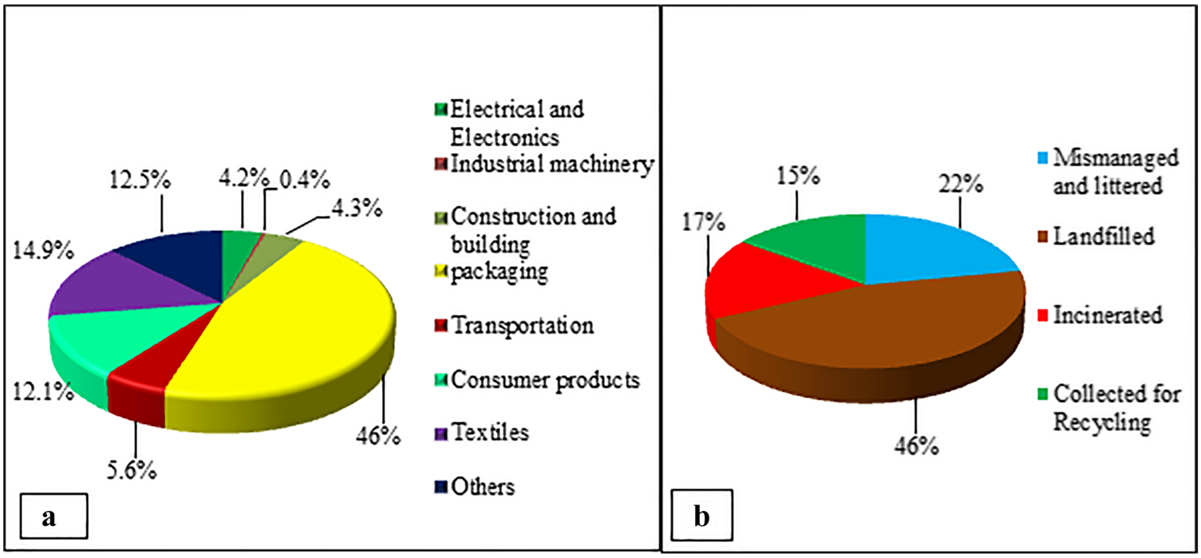

Fig. 1 **a** Pie chart of global distribution of plastics in various sectors (Statista, 2021) and **b** Pie chart of global plastic waste management before recycling, 2019 (OECD, 2022)

PHBs is its cost of production. Therefore, the development of PHBs as an ecologically friendly plastic for commercial uses will require a cost-effective process and hyper-producing strains (Kavitha et al., 2018). This paper is a preliminary review presenting PHAs as a potential alternative to conventional plastics, and highlights its limitations and future research direction.

2 Brief History of Plastic

Bakelite, the first genuinely synthetic polymer, was manufactured in 1907 by Leo Baekeland, a Belgian chemist, and numerous more plastics emerged within the next few decades (Thompson et al., 2009). Plastic was produced in 60 million metric tons over the world in 1980. By the year 2000, production had risen to 187 million metric tons, followed by 265 million in 2010, and 348 million in 2017 (Chalmin, 2019). Global plastic production was 335 Mt in (2016), 348 Mt (2017), 359 Mt (2018), 368 Mt (2019), and 367 Mt in 2020, excluding the recycled plastics. There is no other commodity in the world that has seen such expansion (Plastics Europe, 2021). According to Indian plastic Industry Report (2019), the Global market demand for major plastics from 2018 to 2019 was 280 million tons, whereas the Indian market demand for major plastics was 16 million tons. Furthermore, India's market share in the global market for Styrenics[1] is 5.7%. A study in Statista (2021) reported that a whopping 46% of the plastic garbage produced worldwide in 2018 came from packaging. This was significantly more than any other industry, with textiles accounting for around 15% of the entire bulk. Figure 1a shows the Global distribution of plastics in various sectors. In industrial facilities across the globe in 2019, 60 Mt of generated plastic trash, 6 Mt of residues from plastic recycling, and 1 Mt of collected litter were burned, whereas 162 Mt of generated garbage, 11 Mt of residues, and 1 Mt of collected litter were dumped in landfills (OECD, 2022). Figure 1b shows that 15% of global plastic wastes are collected for recycling, 17% are incinerated, 22% are mismanaged or littered, and remaining 46% are dumped in landfills.

The European plastics value chain, which consists of plastics producers, plastics converters, plastics recyclers, and machinery producers, witnessed a decline in both its production and demand levels in 2020 as a consequence of the COVID crisis.

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[1] High impact polystyrene (HIPS), also referred to as styrene, is an affordable, light-weight, and readily transportable expandable plastic substance.

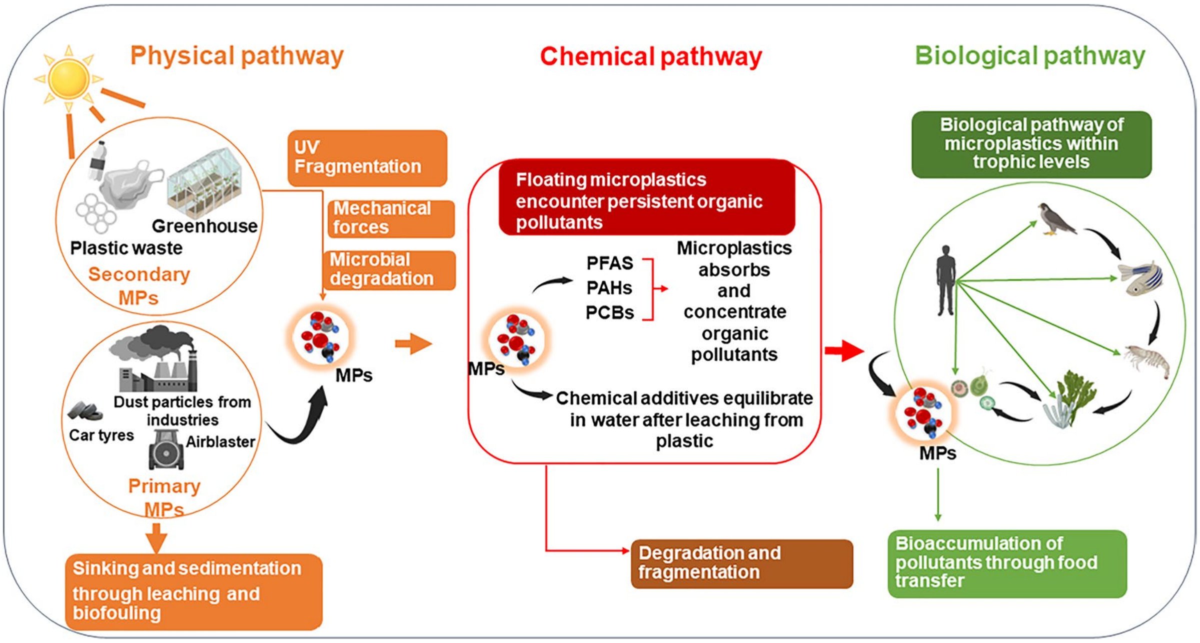


Fig. 2 Schematic illustration of the different occurrences and pathways of MPs (modified from Picó & Barceló, 2019)

Nevertheless, this industry managed to maintain a significant level of employment (Plastics Europe, 2021). The world's plastic manufacturing peaked in 2019 at 368 million tons, and then fell to 367 million tons in 2020, which was the first noticeable drop in the history of the plastics industry ever observed. However, the COVID-19 pandemic has induce a significant increase in plastic pollution due to overflow of medical waste, requirement for suitable personal protective equipment (PPE), rise in online shopping and food delivery, prohibition on reusable bags, among others (Shams et al., 2021). Despite efforts to break the plastic cycle and its harm to the environment, it is projected that over 40 million tons of plastic will arrive into the environment annually, of which 11 million tons will be the macro- and microplastic debris that ends up in the ocean (Sorasan et al., 2022).

3 Physical, Chemical, and Biological Pathway Associated with the Occurrences of Microplastics

Informally, the word "microplastics" is used in the literature to describe a surprisingly broad range of particle sizes, from those that are just a few microns to those that are around 5 mm in diameter (Gregory & Andrady, 2003). Microplastics (MPs) in the oceans, unlike large plastic waste, cannot be efficiently detected and collected for recycling or be treated by other regulated disposal. Since floating MPs counts can reach as high as 10^3–10^4 per m^3 in coastal areas, the lack of an efficient removal method is a severe concern because floating MPs in the oceans gather pollutants and carry them through ocean currents, as persistent organic pollutants (POPs) in the marine environment bind to the surface of plastic debris (Andrady, 2017). Figure 2 represents the schematic illustration of the different occurrences and pathways of MPs.

3.1 Physical Pathway of MPs

The prime source of MPs pollution is plastic pellet pollution, which is highly associated with the leakage during manufacture and/or transport. MPs are prevalent in areas near the plastics industry because emissions from this business may also transport plastic pellets. MPs are often utilized as an ingredient in personal care products, such as toothpaste, liquid bath, exfoliants in cleansers, scrubs, or microbeads for cosmetics (Kurniawan et al., 2021). Waldschläger et al.

(2020) reported that MPs with particle size around 0.2–2 mm are used as abrasive materials in air-blasting and industrial technology. Air blasting technology is frequently used in the automotive, aviation, marine, telecommunication, and manufacturing industries (Sharma & Chatterjee, 2017). Plastics wind up in the aquatic environment due to inappropriate disposal, where they move into higher trophic levels often ending in human food. An explanation might be that the biofouling process, in which micro- and macro-organisms attach to the surface of MPs raise their average physical density, causing them to sink to the bottom of water body. Due to their greater surface area to volume ratios, small pieces of plastic fragments intend to be removed by biofouling more rapidly than large ones (Fazey & Ryan, 2016).

3.2 Chemical Pathway of Microplastics

MPs are more vulnerable to contamination by several airborne pollutants because they have a higher surface area to volume ratio than macroplastics. They serve as environmental reservoirs for dangerous chemicals because they are formed of hydrophobic compounds, which enable chemical contaminants to accumulate in or on their surfaces (do Sul & Costa, 2014). MPs found in the soil may eventually find their way into the groundwater system by percolating or infiltrating into soil pores. Moreover, being a possible sink for MPs, soil offers a direct path to aquifers or groundwater systems (O'Connor et al., 2019). Polyethylene (PE) and polypropylene (PP) are the two polymers that are typically found in soil environments around the world, with smaller levels of polyvinyl chloride (PVC) and polyethylene terephthalate (PET) also being present. Although the structure of these plastic polymers is simple, several additives (plasticizers, flame retardants, thermal stabilizers, lubricants, and pigments) are added to improve the performance of the plastics, which could greatly increase the ecological toxicity (Koelmans et al., 2019). The primary sources of macro- and microplastics inflowing agricultural soils are thought to include plastic mulch films, municipal rubbish, biosolids (anaerobic digestate and sewage sludge), plastic-coated fertilizers, and atmospheric deposition (Liu et al., 2018). Macroplastic residues usually break down into micro- and nano-plastics once they are in the soil, absorbing different heavy metals or releasing organic pollutants, particularly Phthalates, which could be deleterious to soil biology and public health (Wang et al., 2016a, b).

3.3 Biological Pathway of MPs

MPs are devoured by a varied spectrum of marine biota due to their minute size (1 μm–5 mm) and their presence in both benthic and pelagic settings. Pollutants' potential to absorb from water and pass to higher trophic levels via biomagnification, as well as difficulties with pollutant transfer in the food chain, pose a serious concern. MPs are composed of hazardous compounds and monomers with a high area-to-volume ratio, making them efficient absorbers of hydrophobic contaminants from bodies of water (Mato et al., 2001). For example, ciliates in heterotrophic plankton absorb MPs by phagocytosis (Laist, 1987). MPs can also sink to the bottom of the ocean due to biofouling wherein microorganisms form a biofilm layer over the tiny MPs increasing its material density. This leads to either the sinking or vertical oscillation of MPs (Kooi et al., 2017). Therefore, accumulating contaminants may move to higher trophic levels through such pathway, posing a major threat to the health of the marine ecosystem (Wirtz, 2012). The MPs that is consumed by seabirds like albatrosses, shearwaters, petrels, and northern fulmars when they feed at the water's surface accumulates in their digestive system and makes up about 30 to 35% of the plastics that originates in industrial pellets (Blight & Burger, 1997).

4 Overview of Plastic Degradation

Conventional plastics are generally not easily degraded and they usually remain in the environment for the next 1000 years depending on their properties and their surroundings. However, at a very slow pace the biotic and abiotic factors cause breakdown of plastics and bring changes in the inherent properties of the plastics (Zhang et al., 2021). The general process of degradation of plastics is illustrated in Fig. 3. Over time, the degraded plastics give rise to MPs that tend to accumulate in the nature and they are easily released to the aquatic environment and the biotic system as a whole via currents in ocean, tides, tsunamis or wind (Cai et al., 2018; Wang et al., 2016a, b).

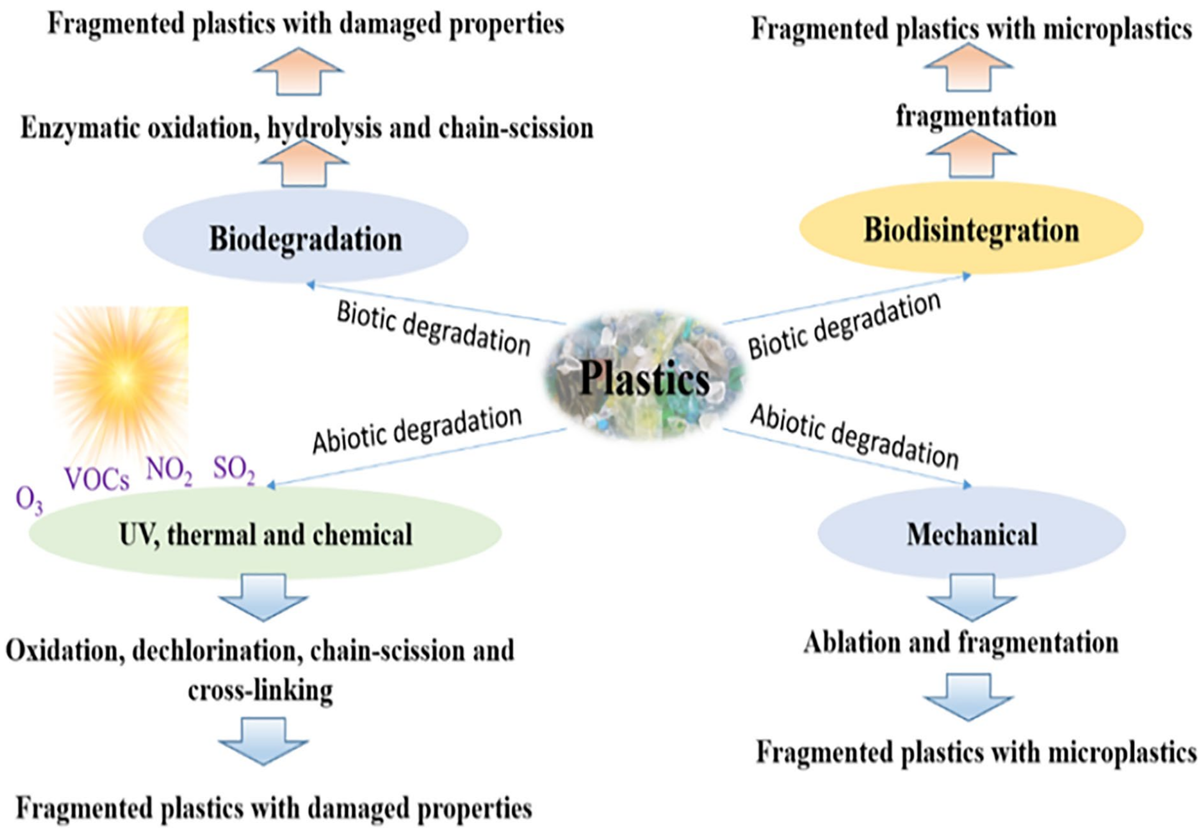


Fig. 3 An illustration of the mechanisms behind plastic deterioration (modified from Zhang et al., 2021)

4.1 Abiotic Degradation of Plastics

In this type of plastic degradation, the abiotic factors like water, temperature, light, air and other forces (mechanical) bring physicochemical changes in the plastics (Zhang et al., 2021). Due to plastics' limited bioavailability, abiotic breakdown is typically anticipated to occur before biodegradation (Andrady, 2015). The abiotic degradation of plastics can occur generally via photo-degradation, thermal, chemical or mechanical (Zhang et al., 2021).

4.1.1 Photodegradation of Plastics

One of the most significant environmental factors that triggers plastic breakdown is photodegradation. Plastics often undergo photodegradation through the use of free radical-mediated processes brought on by solar radiation, mainly due to ultraviolet (UV) radiation, the UV-A (315–400 nm) and UV-B (290–315 nm) irradiation (Liu et al., 2019; Zhang et al., 2021). In general, plastics such as PE resists photodegradation due to absence of chromophores, but impurities or structural changes in the plastic act as chromophores like the carbonyl groups within the PE backbone which undergoes Norrish Type I and Type II reactions forming ketones, radicals and endvinlys resulting in a main-chain scission (Zhang et al., 2021). The free radicals generally react with oxygen forming peroxy radicals that are further converted to peroxide moiety and finally dissociated into macroalkoxy and hydroxyl radicals that catalyze the subsequent reactions (Torikai et al., 1986). Similar to PE, impurities in PP helps in forming radicals in presence of UV radiation and subsequent reactions lead to random cross-linking and chain scissions, with formation of low molecular weight degraded products (Su et al., 2019; Zhang et al., 2021). Likewise, in PVC, impurities act as chromophores which absorb UV radiations and forms free radicals which can further generate hydroperoxides that break the double bonds of the backbone chain resulting in small fragmented products (Law, 2017; Yang et al., 2018).

4.1.2 *Thermal Degradation of Plastics*

The term "thermal degradation" describes the degradation of polymers as a result of energy input at high temperatures. At high temperatures, plastics can experience thermo-oxidative reactions. Long polymer chains can be disrupted, creating radicals, when the polymer absorbs enough heat to break over the energy barrier (Peterson et al., 2001; Pirsaheb et al., 2020). Both molecule reduction and expansion may occur during heated degradation as an outcome of cross-linking and chain scission. The temperature required for thermal deterioration is determined by the thermal characteristics of the plastic polymers and the availability of oxygen (Crawford & Quinn, 2017). Additionally, the deterioration of plastics may be accelerated by temperature and UV light, and the rate of oxidative processes also speeds up in response to temperature (Andrady et al., 2003; Zhang et al., 2021).

4.1.3 *Chemical Degradation of Plastics*

Pollutants including ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and volatile organic compounds (VOCs) in the environment can either directly damage plastics or stimulate the creation of radicals through photochemical reactions, which may additionally cause plastics to degrade (Crawford & Quinn, 2017). Chain scission on the polymer chain results from the interaction of O_3 with double bonds. O_3 can likewise react with saturated polymers; however it does so far more slowly (Cheremisinoff, 2001). Moreover, UV light has the ability to excite SO_2, resulting in a reactive singlet or triplet state that directly interacts with the unsaturated carbon-to-carbon double bond ($C=C$) or produces O_3 through a photochemical reaction with O_2. Furthermore, because of the odd electrons present in the molecule, NO_2 is highly reactive and may quickly react with the unsaturated $C=C$ in the polymer (McKeen, 2019). The pH and salinity of the water are the two chemical parameters that have the greatest impact on plastic decomposition in aquatic environments. Polyamides (PAs), a kind of plastic that is vulnerable to hydrolysis, may degrade when exposed to high concentrations of acidic or basic hydrogen ions (H^+) or hydroxide ions (OH^-) in an aqueous environment (Hocker et al., 2014).

4.1.4 *Mechanical Degradation of Plastics*

The term "mechanical deterioration" describes how polymers break down as a result of outside influences. Environmental external pressures might result from plastics rubbing up against sand and rocks due to waves and wind. The mechanical breakdown of polymers can also be brought on by the thawing and freezing of plastics in aquatic conditions (Pal et al., 2018). Lower elongation at break values increases the likelihood that plastics may shatter in the presence of external tensile forces. Plastics that are subjected to constant stress eventually experience polymer chain scission (Sohma, 1989). The mechanical characteristics of plastics, notably their tensile modulus and tensile elongation at break, will be impacted by chain scissions of polymers during thermal, photo, and chemical degradation (Andrady, 2017; Zhang et al., 2021). Mechanical degradation is mostly relevant to synthetic fibers, which undergo degradation forming MPs fibers via stresses, shear or abrasion during laundering (Cesa et al., 2020).

4.2 Biotic Degradation of Plastics

The term "biotic degradation of plastics" describes how microorganisms erode polymers. Microorganisms can breakdown plastics either physically by digesting, biting, or chewing fragmentation or biologically by biochemical processes (Danso et al., 2019). The biological breakdown of plastics may be primarily caused by microorganisms, such as bacteria, fungi, and insects (Crawford & Quinn, 2017). Due to their solid form and the fact that only a very tiny portion of the polymer is exposed to potential degraders, conventional plastics often have a very poor bioavailability (Battin et al., 2016). Additionally, because macromolecule polymers cannot be utilized directly by bacteria, extracellular enzymes must first break them down into smaller molecules before they can be absorbed by cells and used for further metabolization (Chen et al., 2019).

The bacteria *Azotobacter beijerinckii* was revealed to have "hydroquinone peroxidase" as the mechanism for polystyrene (PS) biodegradation (Nakamiya et al., 1997). Furthermore, it has been hypothesized

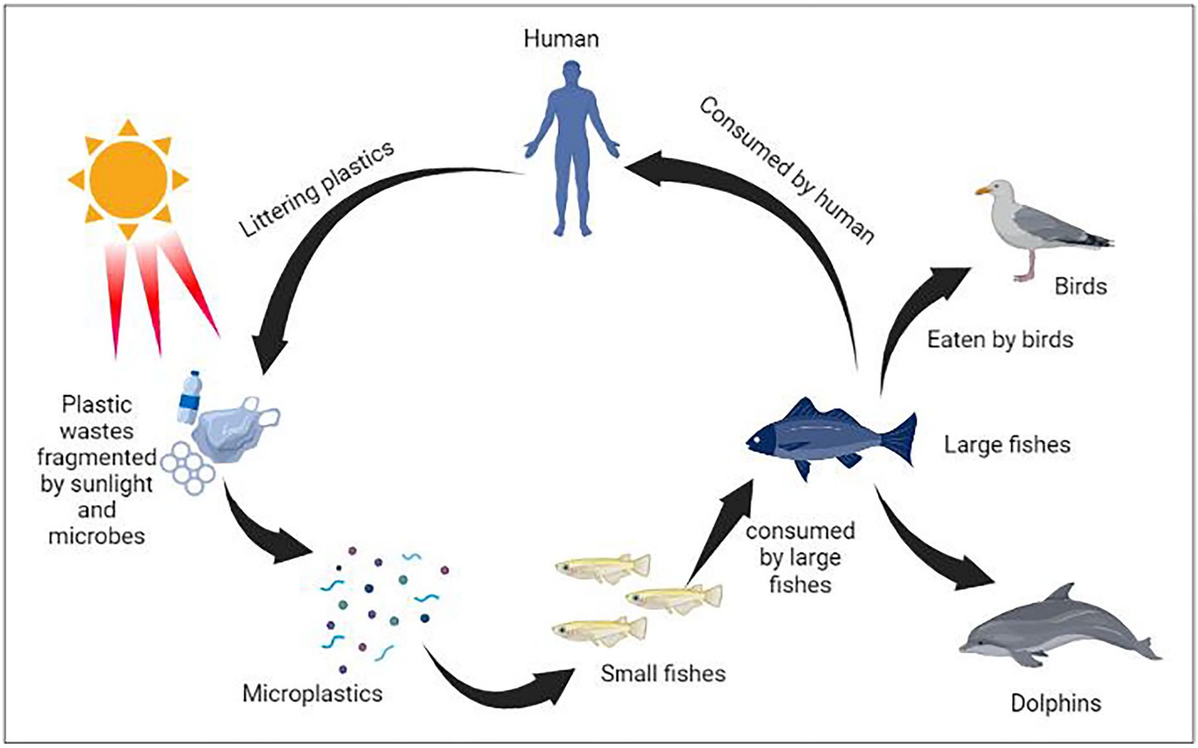


Fig. 4 Effect of microplastics in aquatic environment (modified from Issac and Kandasubramanian, 2021)

that a number of fungi-excreted enzymes can shorten PE polymer strands (Sánchez, 2020). The oxidative breakdown of hydrolysable polymers may also be aided by enzymatic oxidation in addition to hydrolysis (Magnin et al., 2020). Plastics eventually have the potential to mineralize into CO_2 and H_2O in aerobic environments and into CO_2, methane (CH_4), organic acids, H_2O, and ammonium (NH_4) in anaerobic environments, which promotes the formation of microbial biomass (Zhang et al., 2021).

5 Impact on Aquatic Ecosystem

Most of the plastic waste discovered in coastal waterways is assumed to have originated from poor land management mainly due to illegal dumping of wastes, storm water runoff, and activities like fishing, shipping, and aquaculture. The rivers, sewage systems, surface runoffs, wind, and shore trash all carry plastic debris from the terrestrial to the marine (Ory et al., 2020). The persistent, bioaccumulative, and toxic (PBT) compounds, which include organic pollutants and heavy metals, are also carried by MPs and are a source of multiple stresses for life (Manzoor et al., 2021). MPs litter in the ocean is a potential contributor to biodiversity loss and a health risk to humans. Plastics and their degraded by-products are consumed by a wide range of aquatic creatures, from invertebrates to fish, with varying effects (Li et al., 2020). MPs also serve as a carrier for chemical contaminants in aquatic ecosystems by transporting chemicals to other aquatic organisms or locations (Ha & Yeo, 2018). Due to their tiny size, which is similar to plankton, MPs pose a risk to the health of the organism by being easily consumed by fish and other aquatic animal, along with any toxins they may be linked to. Even at higher trophic levels, birds consume fish that has already ingested MPs and hence accumulating it in their body (Manzoor et al., 2021). The effect of MPs in aquatic environment is shown in Fig. 4.

Since MPs has been found in numerous biotas at various trophic levels, it is clear that MPs has moved through the food chain over time. After entering aquatic habitats, MPs can be transported throughout the food chain, for instance, from small to large plankton or from mussel (*Mytilus edulis*) to green crab (*Carcinus maenas*) (Zhang et al., 2019). According to Kühn et al. (2015), MPs accumulation has increased in numerous marine species from 1997 to 2015. The number of afflicted species has dramatically expanded as a result of MPs accumulation. Nelms et al. (2019) reported that MPs were discovered to be tropically transported from wild mackerel (*Scomber scombrus*) to gray seals (*Halichoerus grypus*). Numerous fish species and other animals that are higher up the food chain have been found to exhibit biomagnification (Bhuyan, 2022). One of the most important components of the marine ecosystem, plankton, is also negatively impacted by MPs. Chlorophyll absorption is decreasing as a result of MPs entering phytoplankton cell walls. When exposed to MPs, heterotrophic plankton that goes through the phagocytosis process keeps these minute plastic pieces in their tissues (Chatterjee & Sharma, 2019). The occurrence of MPs in the digestive tracts of wild gudgeons (*Gobio gobio*) from French rivers showed that continental fish consumed MPs, with MPs contamination found in 12% of collected fish (Sanchez et al., 2014). More, the presence of mesoplastics and MPs in freshwater fish from China showed that all 21 sea species and 6 freshwater species of fish contained plastics (Jabeen et al., 2017). Traces or residues of consumption of foamed PS was also found in the stomach contents or feces of a variety of aquatic creatures, such as fish, crustaceans, turtles, birds, and mammals. As floating fragments are quite identical in size and color to conventional food items like fish eggs, larvae, and fish, foamed PS is frequently found in seabird's stomach too (Laist, 1987; Turner, 2020).

6 Impact on Terrestrial Ecosystems

In aquatic ecosystems, MPs are already seen as a serious issue. However, when compared to effects on aquatic species, understanding of MP's effects on the terrestrial ecosystem is rather limited. The threat of MPs transmission from agricultural land to the human food chain has recently been studied and established. Therefore, MPs should be viewed as a potential danger to sustainable agriculture and food supply (Sarker et al., 2020). MPs in aquatic habitats have been thoroughly studied, but research in terrestrial habitats has just begun to pick up the pace (He et al., 2020). Continuous inputs and fragmentation of massive plastic litters, the most of which are thought to come from terrestrial sources, have contributed to the abundance of MPs in oceans. Terrestrial domain like land is more prone to plastic contamination than oceans. The annual intake of MPs from sewage sludge/biosolids applied to agricultural areas is estimated to surpass the total quantity of MPs now floating in the oceans (Wang et al., 2020). Since soil microbial communities are the primary drivers of carbon processing, nitrogen cycling, and other biogeochemical processes vital to human life, alteration in soil structures (water-holding capacity, water stable aggregates, bulk density, pore volume) linked to the presence of MPs may have a direct impact on these processes. These modifications in physicochemical characteristics rely on the polymer, concentration, and shape of the MPs (Baho et al., 2021). The potential for MPs to disrupt important soil–water connections and the effects on soil structure and microbial activity were studied and showed that MPs had an impact on the water holding capacity, bulk density, and a link between water stable aggregates and microbial activity. More, MPs were considered as significant anthropogenic stressors and key agents of climate change in terrestrial environment (de Souza Machado et al., 2018).

MPs are integrated into the soil by numerous physicochemical interactions, which impact growth of plants and soil bioactivity (Sarker et al., 2020). MPs pollution of soils may affect the biophysical and geochemical conditions as well as the characteristics of the soil. This may also have a significant impact on the structural and functional variety of soil microbial communities, perhaps leading to severe soil environmental issues (Khalid et al., 2020; Rillig & Bonkowski, 2018). When the Mung bean (*Vigna radiata*) was directly exhibited to soil polluted with nanoplastics, Chae and An (2020) noticed 83.3% decline in root development at a concentration of 100 mg kg^{-1} nanoplastics in the soil. Additionally, a buildup of micro plastic particles in Mung bean leaves was noted. The African giant snail (*Achatina fulica*), which consumed the tainted Mung bean plant, was thereafter adversely affected in terms of growth rate. MPs have the ability to alter soil structure and characteristics, as well as plant performance. Several studies have confirmed that MPs delay seed germination, limit plant development, and cause genetic

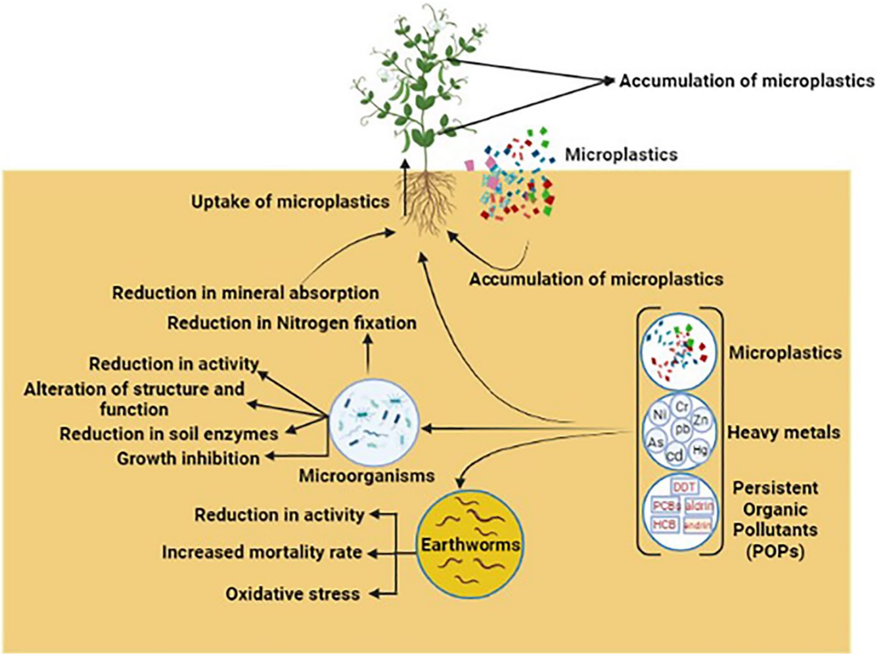


Fig. 5 Effect of microplastics to plants and organisms that live in soil (modified from Khalid et al., 2020)

toxicity and ecotoxicity in plants, among other things, depending on the kind and amount of MPs (Ge et al., 2021). Recently, a hydroponics experiment studied the aggregation and transfer of MPs in rice seedlings and showed that rice seedlings can aggregate MPs in their roots and relocate them to aerial parts, possibly transporting the amassed MPs to herbivores if feeds on such MPs loaded plant parts (Liu et al., 2022). Figure 5 shows the effect of microplastics to plants and organisms that live in soil.

7 Impact on Aerial Ecosystems

In addition to being found in water and soil, MPs have also been found in the air, which is often overlooked in many studies yet significant source of inhalation and oral exposure (Sridharan et al., 2021). MPs have been found in soils, densely inhabited areas, and many other locations all over the world, with the Antarctic and Arctic regions raising the most concern (Shao et al., 2022). Atmospheric transport may also play a crucial role in the spread of MPs to pristine habitats around the world (Sridharan et al., 2021). Furthermore, MPs were also discovered in Arctic snow, indicating considerable atmospheric contamination, showing that aerial transport plays a big part in the dispersal of MPs (Bergmann et al., 2019). Figure 6 schematizes the airborne MPs being deposited into global biosphere. In rainwater and air samples taken from 11 remote and protected sites in the Western US, the presence of MPs was also reported (Brahney et al., 2020). The data showed that more than 1000 tons of MPs enter these areas annually. However, compared to rainfall, snow MPs tend to be huge and more varied in their composition and shape. This may be because snowflakes are larger and have slower terminal velocities than raindrops. It is therefore imperative to pay more attention to the substantial role that snowfall plays in the transference of MPs from the atmosphere to the soil and surface water (Abbasi et al., 2022).

MPs were reported in Arctic polar waters for the first time by Lusher et al. (2015). Most of the MPs discovered were fibers. The sources and routes by which MPs entered the Arctic are still unknown. Although it is probable that the northeast Atlantic and Norway's prevailing winds and surface water transport have an impact on the amount of MPs that enter Arctic waters. More recently, the first evidence of MPs in Antarctic snow was documented by Aves et al. (2022). The most typical morphotype observed was a fiber, and PET was the most typical polymer discovered. The study also noted that MPs could also

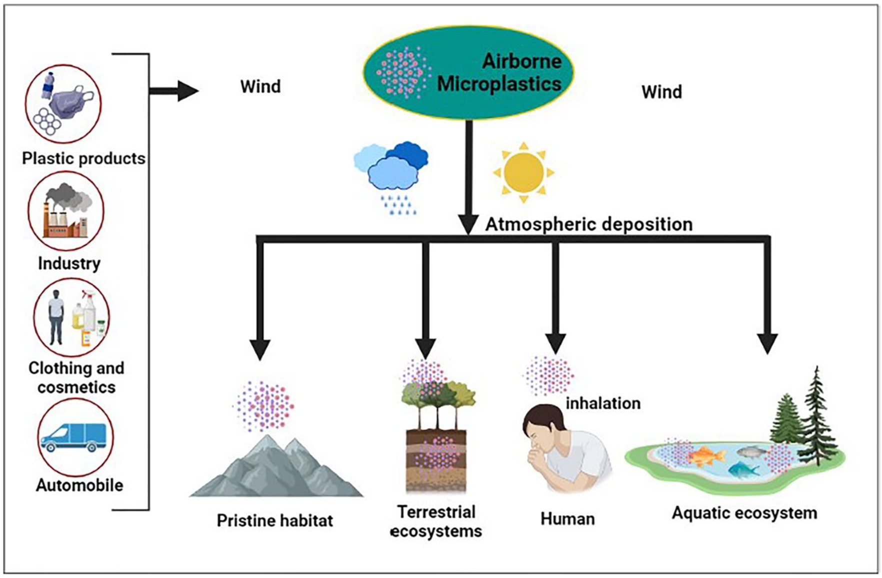


Fig. 6 Schematic representation of airborne microplastics being deposited into global biosphere (modified from Shao et al., 2022)

be transferred over extended distances by ocean currents, exchanged from the ocean to the atmosphere during evaporation, and transported over both short and long distances by the atmosphere. Airborne MPs are typically generated when bigger plastics are broken down by UV light, but they can also come from clothing and personal care items (Lett et al., 2021). Since they are microscopic and have a low density, these particles are easily swept into the atmosphere by air currents after degrading (Revell et al., 2021). The wind-driven dispersion of dried sludge byproducts applied to agricultural soils may also cause MPs to be released into the atmosphere. Synthetic fibers, microbeads, and particles have been identified in the wastewater treatment facilities' sludge and became airborne (Amato-Lourenco et al., 2020). Abrasions of car tyres are a main source of airborne MPs along with paint and abrasive cleaning agents (Verschoor, 2018). An important way that humans are susceptible to aerial MPs is by inhalation, and dust is a key inhalation medium. When inhaled, aerial MPs have the potential to cause a variety of ailments in the human cardiovascular and respiratory systems, as well as cancer (Sridharan et al., 2021). The immediate bronchial reactions (asthma-like) that occur when particles are inhaled are the first signs of toxicity, and the detrimental impacts of particle toxicity are primarily associated to inflammation caused by particle localization and immune cells that produce proteases, reactive oxygen species, and cytokines to fight the foreign substance. In addition, persistent inflammation may result in cancer (Enyoh et al., 2019). Prata (2018) has discussed occupational diseases in workers from a variety of industries that is caused by airborne MPs. Chronic bronchitis, extrinsic allergic alveolitis, chronic pneumonia, pneumothorax, dyspnea, and cancer are among these illnesses. However, a need for additional research is deemed necessary to completely comprehend the above mentioned occupational diseases and establish safe exposure limits.

8 Impact on Human Biological System

There are significant environmental issues as an outcome of the massive quantities of waste plastic that have accumulated in the environment. Studies have revealed that these plastic wastes continue to harm wild animals' health and may be a concern to people's health as they are potential pathogen carriers (Sang et al., 2021). The size of plastic waste is a significant consideration not only for ingestion by organisms but also primarily for its ability to pass through biological barriers, which has an array of impacts at the cellular level (Binelli et al., 2020). MPs penetrate the human body by the intake of food containing them, inhalation of airborne MPs, and skin contact with these particles found in goods, fabrics, or dust. Microorganisms like *Vibrio* spp. may also colonize the surface of MPs. MPs might serve as vectors

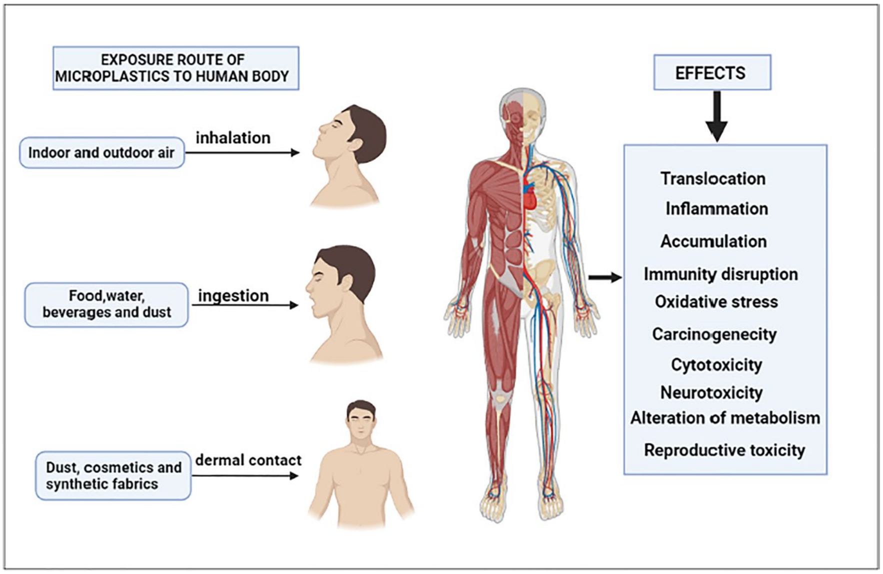


Fig. 7 Exposure route of microplastics to human body and its associated effects (modified from Ageel et al., 2022; Bhuyan, 2022)

in this situation, bringing pathogens to the tissues, shielding them from the immune system, and inducing tissue injury that might encourage infection (Prata et al., 2020). Figure 7 shows a schematic diagram of exposure route of MPs to human body and its associated effects.

MPs may be absorbed and consumed by species at the primary trophic level, such as zooplankton and phytoplankton, providing a possible route into the food chain (Lusher, 2015). The marine food web diversity in aquatic animals, such as turtles, seabirds, fish, crabs, and worms, have been documented for the ingestion of MPs. Several studies have shown that MPs accumulate in the guts of organisms, which are usually not directly ingested by humans. However, humans do eat shellfish, including clams, mussels, and some shrimps, along with their gut as a whole (Galloway, 2015). Thus, significant threat to human health is posed by MPs in seafood. There is a great possibility that intestinal MPs contamination will spread throughout the body. The different effects associated with MPs exposure to the body are oxidative stress, cytotoxicity, neurotoxicity, carcinogenicity, reproductive toxicity, immunity disruption, alteration of metabolism, translocation of cells, and inflammation (Bhuyan, 2022). The combined effects of plastics and their composites, often known as endocrine-disrupting compounds (EDCs), are harmful to both human and marine species health. All recent human study subjects had high concentrations of these metabolites in their urine. Despite detoxifying, minute quantities of EDCs produced from plastic tend to bio-accumulate in bodily tissues (Biamis et al., 2021). MPs in human feces were first discovered by Harvey and Watts (2018). The most prevalent polymers were PP and PET and more than half of the global population is estimated to bear MPs in their feces. In addition, the occurrence of MPs in human placenta was first evidenced by Ragusa et al. (2021). Using Raman microspectroscopy, 12 MPs fragments (varying in size from 5 to 10 μm) with irregular shape were discovered in the placentas of four women with physiological pregnancies. More recently, Leslie et al. (2022) discovered and quantified MPs in human blood for the first-time. Baeza-Martínez et al. (2022) also reported the discovery of the first MPs evidence in human lower airways, in the form of microfibers. This discovery has enormous significance as it demonstrates that MPs can move throughout the body and could be lodged in organs.

9 Challenges Associated with the Strategies to Mitigate Plastic Pollution

9.1 Landfilling

Landfills are one of the simplest and cheapest ways to dispose polymers; however, there is a major issue due to the limited availability of landfill space. This works well with biodegradable polymers (Roohi et al., 2018). Due to the linear rather than cyclical nature of the material flow, landfills have a considerable negative effect from sustainability perspective, where none of the material resources used to make plastics is recovered (Hopewell et al., 2009).

9.2 Incineration

When disposed plastics are burned in an incinerator, it leads to the generation of secondary toxic air pollutants, which is known to have detrimental impacts on the environment and human health (Roohi et al., 2018). Hazardous compounds may be emitted into the atmosphere during the process of incineration. For instance, the presence of PVC and halogenated compounds in mixed plastic trash incineration raises the possibility of releasing dioxins, polychlorinated biphenyls and furans into the environment. Moreover, after these hazardous compounds are released, it binds with dust particles and can be transported over great distances by the wind. Therefore, incineration of plastic in context of solid waste-management is preferred lesser than landfilling and mechanical recycling, primarily due to the detrimental effect on the various components of the environment (Hopewell et al., 2009). Moreover, strict pollution control guidelines imposed by the regulatory authorities have further restricted its wide scale operations, and only plastic incinerating plants for recovering energy are allowed to operate (Raubenheimer & McIlgorm, 2017).

9.3 Challenges in recycling processes

Recycling is a significant method found to be effective in reducing plastic waste, but it is projected that approximately 12% (800 Mt) of plastics were incinerated and only 9% (600 Mt) of the total (6300 Mt) amount of plastics produced have been recycled in the year between 1950 and 2015. The remaining 79% (4900 Mt) of plastics has either been dumped in landfills or is still lying in the nature (Geyer et al., 2017). In addition, every recycling cycle includes degradation, due to exposure to hot processing temperatures that cause a breakdown of molecules into monomers and oligomers, which may migrate to packaged food products (Dey et al., 2021).

9.4 Clean-up activities

In addition to being tools for awareness-raising and citizen science, cleanup initiatives have been suggested as mitigation techniques. However, the pervasive pollution of the environment with plastic particles of all sizes makes it appear difficult to completely eradicate plastic pollution (Prata et al., 2019).

9.5 Reducing Plastics Consumption

Food safety has become a growing concern among the people throughout the globe. It has been estimated that approximately 450 people died in UK in the year 2006 because of foodborne diseases. The most convenient way to enhance food safety is through appropriate packaging, which minimizes food contamination. The majority of such food packaging industry depends entirely on single use plastics. Although the strategy of reducing the plastics consumption is beneficial, it is occasionally challenging because of food safety concerns and inconvenience (Beitzen-Heineke et al., 2017).

9.6 Using Paper Bags and Jute Bags

Although paper bags have been proposed as plastic bag substitutes, paper bag manufacture uses 40% more energy than plastic bag production (Schnurr et al., 2018). Paper bags are reusable and recyclable, but they use more fossil fuels to generate and manufacture than plastic bags because they are made from wood fiber pulp or recycled fibers. Jute bags are well recognized for their resilience and are created from renewable vegetable fibers. Jute bags, however, can pose a greater risk of microbial contamination due to cleaning difficulties, and when combined with chemicals to increase durability, they might raise the danger of environmental contamination when compost (Nwafor & Walker, 2020).

9.7 Ban on Single-Use Plastics

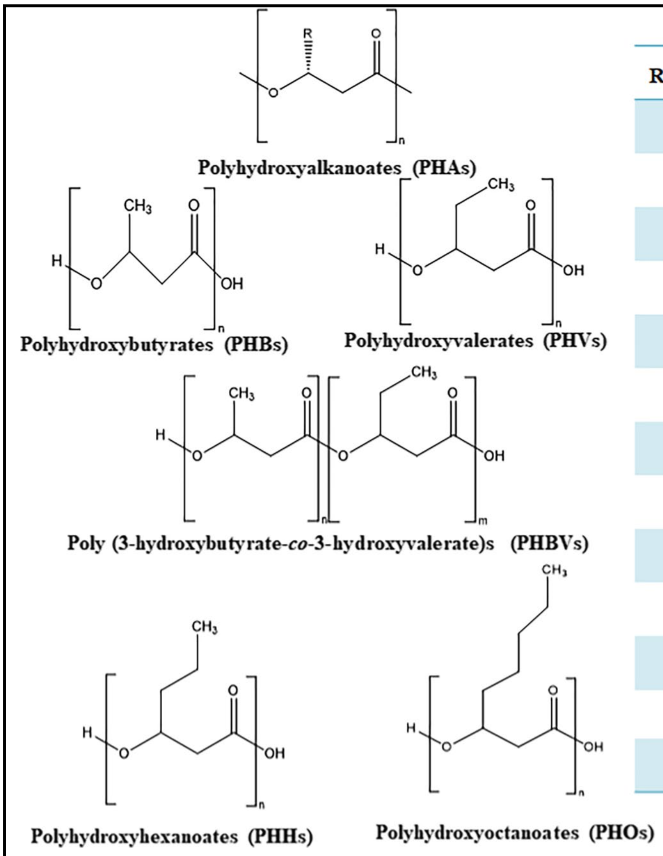
One of the typical measures recently implemented by governments of several nations all over the world to reduce the predicament of plastic pollution is to enforce a ban on shopping bags made of single-use plastic (SUP) (Dey et al., 2021). However, an outright ban on plastic bags won't do much to address the fact that a particular nation lacks an efficient environmental management strategy. Such measures, however judicious they may be, will not protect the environment from the negative consequences of a "throw-away" mentality of the people that need to be more environmentally educated to become better aware of the extent of the problem and the collective efforts to be undertaken to solve this problem for their own salvation and benefit. Instead, better management rather than a constraint on the usage of thin plastic bags would probably be a better option and a possible solution to the issues they cause (Casanova, 2012). Planning and implementing sustainable low-cost solid waste management strategies is crucial for emerging countries like India. The lack of effective sanitation techniques is mostly caused by lack of awareness, inappropriate technical knowledge, a lack of funding, irresponsibility at all levels of the society, and the implementation and enforcement of law and policy (Rajmohan et al., 2019).

10 A Possible Approach to Mitigate Plastic Pollution

A multimodal approach involving prevention, reuse, recycling, recovery, and disposal is necessary to address the world's plastic problem and biodegradable plastics are a crucial and integral part of this strategy (Flury & Narayan, 2021). Single-use plastic will be banned by 2030, according to the European Union's plastic strategy. Therefore, the packaging and distribution sectors were compelled to pioneer the usage of biodegradable polymers as an alternate to traditional plastics (Loh & Chew, 2021). Polyhydroxyalkanoates (PHAs) are seen as potential substitutes for conventional petrochemical plastics because of their robust mechanical qualities that are comparable to those of thermoplastics derived from petroleum and their high level of biodegradability (Khatami et al., 2021). Additionally, PHAs generation by microbes has drawn some interest in past few years in the field of medical science due to its biocompatibility properties where it can be implanted in living tissues of human without triggering any immunological responses. Other properties like non-toxicity, insolubility in water, as well as its thermo-plasticity, make it an excellent alternative to conventional plastics (Loh & Chew, 2021).

10.1 Polyhydroxyalkanoates

PHAs are a type of biopolyester and the most well-known are polyhydroxybutyrates (PHBs) and a copolymer of poly (3-hydroxybutyrate-*co*-3-hydroxyvalerate)s (PHBVs). PHAs, including PHBs, polyhydroxyvalerates (PHVs), poly-4-hydroxybutyrates (P4HBs), as well as polyhydroxyhexanoates (PHHs) and polyhydroxyoctanoates (PHOs) (Ansari & Fatma, 2014) are biodegradable, environmentally benign, and non-toxic (Muneer et al., 2022). General structure of PHAs and some of its polymers is presented in Fig. 8. PHAs are made from lignocellulosic biomass and can be thermoformed into a variety of bio-based products (Reshmy et al., 2021). Both gram-negative and gram-positive microorganisms (George et al., 2021) produce granules of PHAs, which are used as water-insoluble storage compounds when the environment is stressful. They are produced by biosynthesis, which occurs when there is a surplus of carbon and a limited supply of vital growth nutrients like nitrogen or phosphate (Możejko-Ciesielska & Kiewisz, 2016). According to their structural characteristics, these bacterial polyesters can be broadly separated into two groups: short-chain-length PHAs (scl-PHAs), which have 3–5 carbon atoms, and medium-chain-length PHAs (mcl-PHAs), which have 6–14 carbon atoms (Kim, 2002). However, compared to scl-PHAs production, the process development for mcl-PHAs production has been significantly less extensive (Sun et al., 2007). A few bacteria can collect PHAs up to 90% of the dry cell weight (George et al., 2021). Olive oil, fermented molasses, date syrup, pomace, effluents from paper mill and palm oil mill are just a few of the wastes that have been used as carbon source and have accumulated between 40 and 70% biodegradable PHAs (Abd El-malek et al., 2020). PHAs are a type of biopolymers that are not only ecologically friendly, but it also has a variety of material qualities that can be adjusted. The current market cost of PHAs is roughly €5 per kg, which is over 6 times more expensive than the cost of traditional plastics (€0.8–1.5 per kg). This is primarily due to the high cost of biodegradable polymers, as most techniques are still in the research and development stages (Khatami et al., 2021). In spite of its



R (alkyl) group	Carbon no.	PHAs polymers
Methyl	C_4	Polyhydroxybutyrates
Ethyl	C_5	Polyhydroxyvalerates
Propyl	C_6	Polyhydroxyhexanoates
Butyl	C_7	Polyhydroxyheptanoates
Pentyl	C_8	Polyhydroxyoctanoates
Hexyl	C_9	Polyhydroxynonanoates
Heptyl	C_{10}	Polyhydroxydecanoates
Octyl	C_{11}	Polyhydroxyundecanoates
Nonyl	C_{12}	Polyhydroxydodecanoates
Decyl	C_{13}	Polyhydroxytridecanoates
Undecyl	C_{14}	Polyhydroxytetradecanoates
Dodecyl	C_{15}	Polyhydroxypentadecanoates
tridecyl	C_{16}	Polyhydroxyhexadecanoates

Fig. 8 General structure of PHAs and some of its polymers (modified from Akinmulewo & Nwinyi, 2019)

high manufacture cost, the production capacity of PHAs was 2.11 million tons globally in 2018 and is projected to surpass 2.6 million tons in 2023. With additional cost reductions and the increase in highly improved utilization, it is expected to evolve into a valuable material that is marketable (Sun et al., 2018).

11 Polyhydroxybutyrates

In 1925, Lemoigne made the first discovery of the linear polyester poly-3-hydroxybutyrates (PHBs) in bacteria. The biological synthesis of PHBs from non-replenishing sources taking place in both gram-negative and gram-positive bacteria under the circumstance of nutritional imbalance is the most significant factor in its production (Rajan et al., 2019). PHBs have a linear chain structure and both crystalline and amorphous phases, which results in its high degree of crystallinity. It is available either as a pure polymer or as a component of copolymers and blends. In a varied range of bacterial strains, it is produced as a carbon reserve and is then manufactured industrially through bacterial fermentation (McAdam et al., 2020). In their cells, bacterial species collect intracellular PHBs granules as a source of carbon and energy. The role of carbon-rich culture media in PHBs synthesis is crucial. Carbon is used by micro-organisms for both energy production and biosynthesis. For microbial growth and the production of PHBs, an appropriate carbon supply is essential. Simple sugars like glucose, fructose, mannose, galactose, sucrose, and xylose, as well as polysaccharides like starch and lipids like oleates and glycerides, are examples of sources of defined carbon. Nitrogen is also a key component in fermentation media as a vital component of proteins, nucleic acids, and co-enzymes like vitamins (Allikian et al., 2019). Among the inexpensive carbon sources

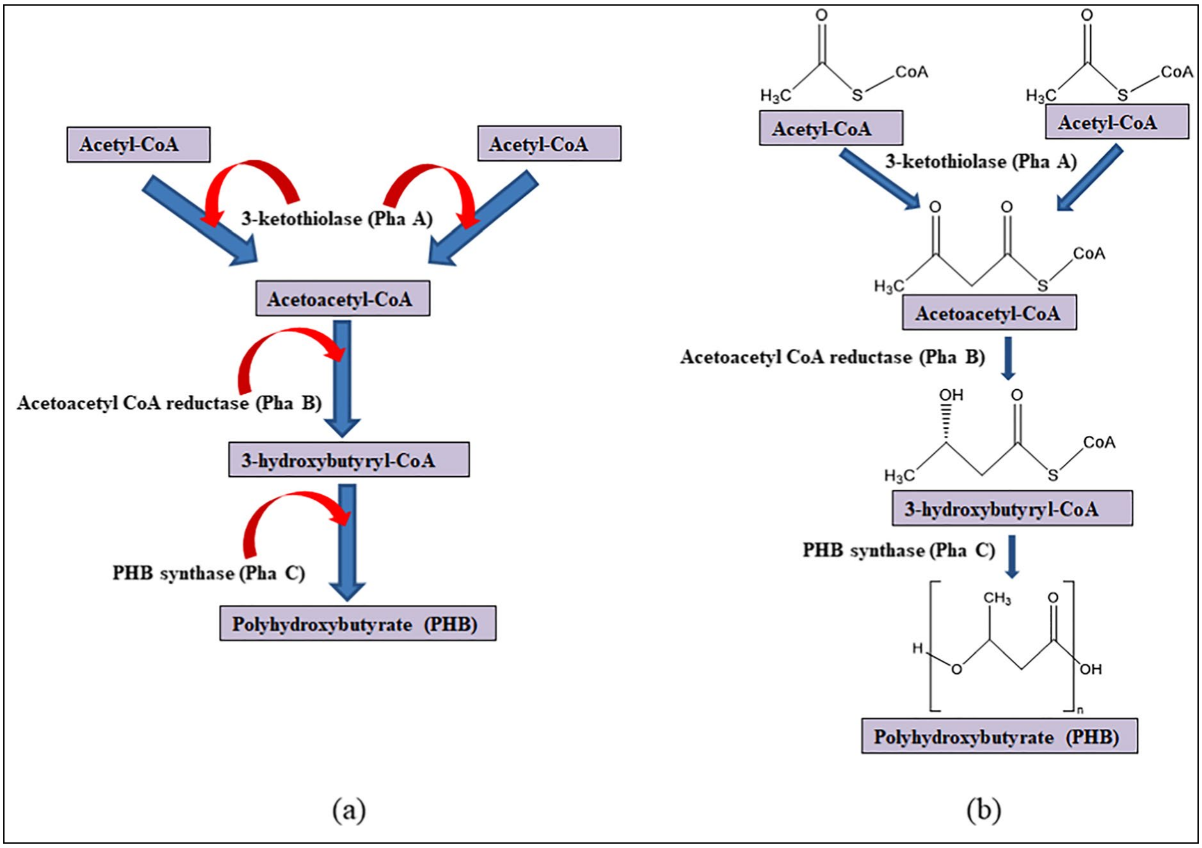


Fig. 9 Biochemical mechanism for PHB production. **a** Schematic diagram showing metabolic pathway of PHB production. **b** Schematic diagram showing metabolic pathway of PHB production along with its chemical structure (modified from Ross et al., 2017)

are molasses, maize steep liquor, starch, wheat bran, among others (Verlinden et al., 2007).

PHBs are a member of the PHAs family and are distinguished by an ester linkage group (−COOR) and methyl functional group ($-CH_3$); these functional groups are also responsible for the material's hydrophobic, high crystallinity, thermoplastic, and brittle properties. PHBs and its byproducts, for example, have two major temperatures that define their thermal properties: a melting temperature (T_m) for their crystalline phase and a glass transition temperature (T_g) for their amorphous phase (Grigore et al., 2019). PHBs are an excellent alternative for synthetic polymers and have mechanical qualities similar to polypropylene (Verlinden et al., 2007). The biochemical mechanism by which PHBs are produced has three phases. Firstly, to form acetoacetyl-coenzyme A (CoA), two molecules of acetyl-CoA are linked utilizing 3-ketothiolase (PhaA). Secondly, utilizing the enzyme acetoacetyl-CoA reductase, 3-hydroxybutyryl-CoA is generated by reducing acetoacetyl-CoA by nicotinamide adenine dinucleotide (PhaB). Finally, employing PHB synthase (PhaC), PHBs is polymerized from 3-hydroxybutyryl-CoA, releasing CoA (Ross et al., 2017). The biochemical mechanism for PHB production is displayed in Fig. 9.

A wide range of bacteria are the most researched, accepted, and renowned species in the bioplastics manufacturing process. PHAs granules are used by many bacterial species as a source of carbon stores and energy in their cells (Thiruchelvi et al., 2020). The microorganisms such as *Bacillus cereus* (Narayanan et al., 2020a), *Cupriavidus necator* (Aramvash et al., 2015), *Pseudomonas aeruginosa* (Javed & Jamil, 2015), *Azospirillum rubrum* (Jin & Nikolau, 2014), *Brevundimonas* spp., and *Enterococcus* spp. from cardboard industry waste water (Bhuwal et al., 2013), *Burkholderia cepacia* from biodiesel-glycerol

(Zhu et al., 2010), *Pseudomonas putida* from vegetable oil wastes (Gatea et al., 2018), *Bacillus megaterium* (Joyline & Aruna, 2019), *Bacillus siamensis*, *Bacillus subtilis*, *Staphylococcus aureus* (Vijay & Tarika, 2019), *Paraburkholderia* spp. (Sriyapai et al., 2022), *Methylocystis* spp. *and Rhizobium* spp. (Abd El-malek et al., 2020; Snell & Peoples, 2009), *Aeromonas hydrophila*, *Burkholderia sacchari*, *Acinetobacter* spp., *Halomonas boliviensis*, *Sphingobacterium* spp., *Caulobacter* spp., *Brochothrix* spp., *Ralstonia* spp., and *Yokenella* spp. (Mascarenhas & Aruna, 2017) are capable of producing PHBs. These microorganisms utilize various substrates for the production of PHAs. For instance, different forms of PHAs can be created from a wide range of sustainable sources, comprising fatty acids, agricultural wastes, and by-products from industries. Furthermore, the market price of commonly utilized substrates, namely oils, pure sugars and fatty acids, accounts for half of the entire cost of PHAs production. Therefore, a number of research works has been done in order to incorporate low-cost carbon-rich substrates like agro-industrial wastes (sugarcane bagasse, rice bran, wheat bran, wheat straw, and corn cob) for the production of PHAs (Abd El-malek et al., 2020). Tsang et al. (2019) reviewed on current technology for the synthesis of PHA-based bioplastics from food waste (FW). When FW is landfilled, it causes harmful effects such as groundwater contamination and emission of greenhouse gases. Therefore, production of PHA-based bioplastics seems to be an ideal method for FW disposal, and its production from FW is a renewable and sustainable method that uses resources that are carbon neutral.

Nevertheless, only a few bacterial strains have so far been employed effectively on an industrial scale to produce PHAs due to high production cost (Możejko-Ciesielska & Kiewisz, 2016). To determine the efficacy of PHAs production, Mohapatra et al. (2017) have isolated and screened different *Bacillus* species. They found that under optimized condition (glucose concentration of 10 g/L, temperature 37 °C for 48 h, C:N ratio 6:1, pH 7) for microbial growth, the *Bacillus* species produced 3.09 g/L of PHAs, which was believed to be a greater yield than *Paenibacillus durus* (Hungund et al., 2013) that accumulated 0.9 g/L of PHAs using fructose as carbon source. To produce an eco-friendly biodegradable polymer of PHAs, Tanamool et al. (2013) used sweet Sorghum juice as carbon source. The study revealed that *Bacillus aryabhattai* had the highest PHAs accumulation of 1.74 g/L with 57.62% of DCW. A study was conducted by Narayanan et al. (2020a) to identify the most common bacteria that produce PHBs in polluted lake soil samples and found that *Bacillus cereus* strain NDRMN001 has the ability to produce 91.54% of PHBs from 36.26 g/L culture biomass.

12 Properties of PHBs

12.1 Physico-Mechanical Properties

PHBs are a homopolymer with highly crystalline, rigid, but brittle material. It performs as a hard-elastic substance when spun into fibers. Copolymers with the majority of PHBs' other mechanical qualities, like PHBVs or mcl-PHAs, are less brittle and stiff than PHBs. The crystalline helical structure of homopolymer PHBs appears to be shared by a number of different copolymers (Verlinden et al., 2007). Along with molecular weight, the length of the side chain, the kind of monomer, and the separation between the ester bond and the functional group all affect the mechanical properties of PHAs. The interaction of these variables can alter the glass transition (T_g) and melting (T_m) temperatures of polymers as well as their crystallinity (stiffness/flexibility) (Guimarães et al., 2022). PHAs with medium chain lengths are elastic and flexible; they have high elongation at break ratios, moderate tensile strength, and low crystallinity. mcl-PHAs polymers exhibit higher elongation-to-break ratios, lower glass transition temperatures, and lower melting temperatures than scl-PHAs polymers (Sharma et al., 2017).

PHBs material's mechanical characteristics, such as its tensile strength (43 MPa) and Young's modulus (3.5 GPa), are comparable to those of isotactic polypropylene's tensile strength (38 MPa) and Young's modulus (1.7 GPa). Nevertheless, PHBs' extension to break (5%) is significantly lesser than polypropylene's (400%). In comparison to polypropylene, PHBs looks to be a harder and more brittle material (Sudesh et al., 2000). PHBs grow into incredibly thin lamellar crystals that are arranged as spherulites when it is produced from the melt or oblong lath-like single crystals in dilute solution. Lamellar thicknesses in PHBs spherulites are normally in the range of 5 nm, though they can be noticeably smaller in crystals produced from solutions (Barham et al., 1984; Van der Walle et al., 2001).

12.2 Thermal Properties

At temperatures near its melting point, which is 160–180 °C, PHBs exhibits severe instability. It is a thermoplastic polymer having a T_m in the range of 160–180 °C and a T_g of 0–5 °C. Around its T_m, it starts to degrade thermally. The melting points of PHBs vary based on the carbon source. Due to its semi-crystalline nature, PHBs exhibits a melting behavior between crystalline and pure amorphous materials (Sreedevi et al., 2015). At temperatures exceeding 170 °C, there are reports of alterations in molecular weight and the generation of crotonic acid (Van der Walle et al., 2001). After being held at 190 °C for 1 h, a sample of PHBs was found to lose nearly half of its initial molecular weight (Barham et al., 1984).

13 Applications of Polyhydroxyalkanoates

Biopolymers such as polyhydroxyalkanoates (PHAs) are biodegradable and can be made without fossil fuels because they are mostly made from biomass, implying possible carbon neutrality. As a result, there has been a surge in the use of these materials in the form of blends or composites with degradable or non-degradable synthetic polymers (Nandakumar et al., 2021). PHAs are an essential source of packaging material because of qualities including thermoplasticity, hydrophobicity, insulation, and vapor barrier. PHA-derived jars, disposable cups, trays, containers, and foam-based packaging utensils are already available in the food industry (Rekhi et al., 2022). PHAs have various medical utilizations such as drug carrier, tissue engineering, heart valves, surgical sutures, medical implants, artificial skin, artificial organ reconstruction, chemotherapeutics, antibacterial, anti-cancer agents, memory boosters, and biocontrol agents in aquaculture. PHAs have been presented as a possible medical device material since it is biocompatible with human bones and tissues, biodegradable, and has high mechanical properties. Articular cartilage restoration, cardiac patch fabrication, meniscal repair devices, adhesions barriers, repair patches, orthopedic pins, tacks and rivets, screws and staples, stents, suture fastener, surgical mesh and other devices are among the most potential devices (Kalia et al., 2021; Ray & Kalia, 2017). Furthermore, when utilized in vivo, PHAs have no acute or long-term negative impacts on health (Raza et al., 2018).

PHAs are also employed in agriculture for a variety of purposes, including seed and fertilizer encapsulation, crop protection films, and biodegradable pesticide and insecticide carriers (George et al., 2021). Shade nets, clips, geotextiles, wires, and pheromone dispensers are examples of products used in agriculture to protect plants from severe environmental conditions (Kalia et al., 2021). Many farmers cover their fields with plastic blankets to boost product production. Traditional polymers leave traces, whereas biodegradable plastic made from natural materials degrades completely. Biodegradable mulch film can be ploughed back into the field after its use, reducing labor and disposal cost (Rujnić-Sokele & Pilipović, 2017; Venkatachalam & Palaniswamy, 2020).

The automotive sector is pursuing sustainability efforts, such as the use of biopolymers. Toyota claims to be the first to utilize sugarcane-based PET in car liners as well as some interior surfaces. In one model, Mazda motors claims an interior fittings content of more than 80% plant-derived content, as well as seat covers made entirely of plant-derived biofabric (Lackner, 2000). PHBs, one of the PHAs, may prove to be a highly environment-friendly material for the automotives interior components (Mostafa et al., 2020). Furthermore, technological advancements have assured that the spectrum of biopolymers applications continues to expand, currently including keyboard parts, mobile phone coverings, microchips and ultracapacitors (Rekhi et al., 2022), and automobile components (Industry Experts, 2012). The applications of PHAs biopolymers are presented in Fig. 10.

14 Advantages of Polyhydroxybutyrates

In comparison to conventional plastics made from petrochemicals, polyhydroxybutyrates (PHBs) have various benefits. PHBs are completely biodegradable and are made from renewable resources. It is entirely

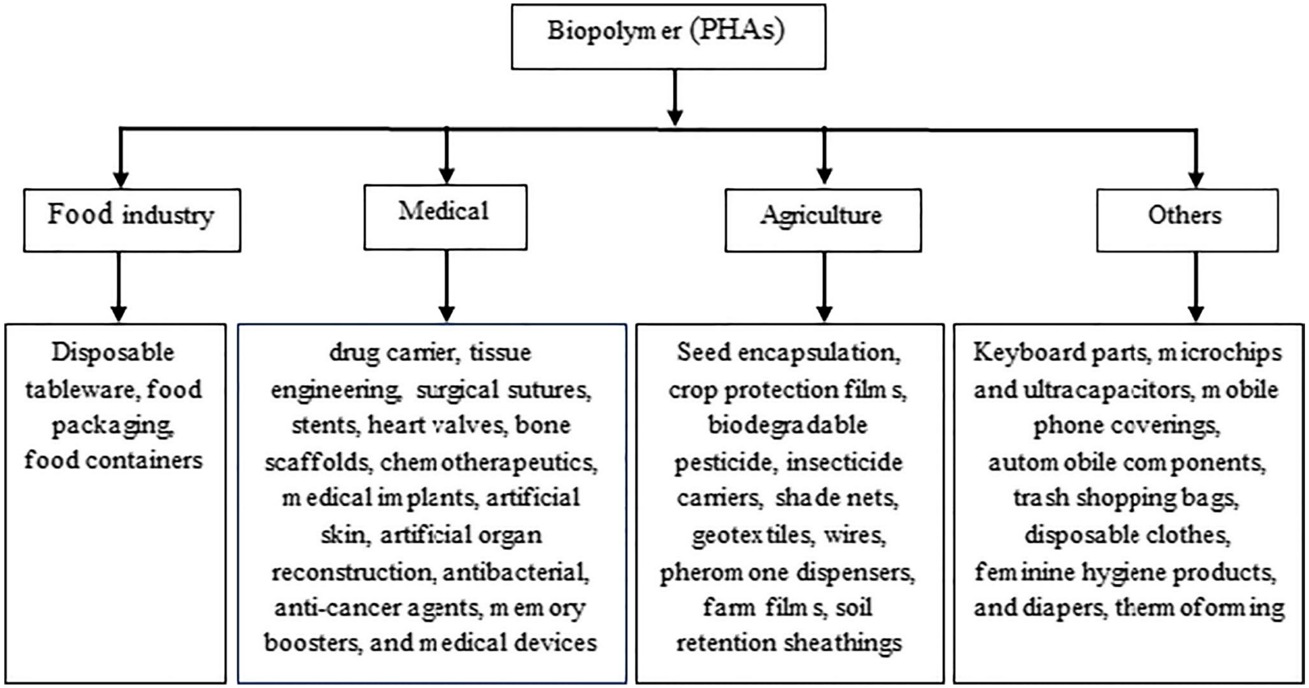


Fig. 10 Applications of PHAs Biopolymers (modified from Abd El-malek et al., 2020)

nontoxic and has better physical qualities for food packaging applications than polypropylene (Ansari & Fatma, 2014). Green plastics provide a number of advantages over petroleum-based plastics, including non-toxic chemicals, ease of recycling, reduced use of fossil fuels, lower energy requirements, and are renewable and environmentally safe (Thiruchelvi et al., 2020). Another advantage of bioplastics' biodegradability is that the end products can be recycled as raw materials, removing the requirement for virgin raw materials and providing the product with several end-of-life alternatives (Nandakumar et al., 2021). The various advantages of PHBs are discussed below.

14.1 Biodegradability

PHAs are considered to be the most important biopolymers because of their high biodegradation efficiency, which is essential for their replacement of traditional plastics (Robledo-Ortíz et al., 2021). Biodegradation can take place in both anaerobic and aerobic environments when microorganisms like bacteria, fungus, or actinomycetes are present (Lammi et al., 2019). The final products under aerobic conditions are biomass, carbon dioxide (CO_2), and water, whereas the final products under anaerobic conditions are biomass, CO_2, methane (CH_4), and water (Gu, 2003). These products are not hazardous to the environment, and CO_2 and CH_4 in particular could be employed in power plants to produce electricity (Kuciel et al., 2019). During photosynthesis, the byproducts are further reabsorbed by microorganisms and plants, serving as a feedstock for the subsequent synthesis of PHAs. PHAs are a component of the biosphere's nutrient cycle as a result of this property (Bhola et al., 2021). The rate and time of biodegradation can be influenced by the polymer's crystallinity, surface morphology, side-chain length, and shape, as well as environmental factors like temperature, UV exposure, nutrition levels, mechanical force strength, types of bacteria present, pH, and oxygen levels. The average rate of PHAs biodegradation in the marine environment was found to be 0.04–0.09 mg/day/cm^2, indicating that it would take between 1.5 and 3.5 years for a PHAs water bottle to entirely decompose (Dilkes-Hoffman et al., 2019). In contrast, a conventional plastic takes about 500 to 1000 years to degrade in marine environment (Whiting, 2018). However, they do not decompose completely; instead, they photo-degrade and turn into tiny microplastics, polluting the marine environment (Zhang et al., 2021).

14.2 Biocompatibility

PHBs are biocompatible with human bones and tissues; therefore, it can be inserted into the human body without triggering an inflammatory reaction. It can be employed as a carrier for the gradual release of drugs since it degrades gradually within the human body (Nair & Laurencin, 2007). The biocompatibility of PHBs is also possible to assess in the context of tissue engineering, and this quality can be improved by sodium hydroxide and lipase treatment (Zhao et al., 2002). By amalgamation with other polymers, altering the surface, or integrating PHAs with different inorganic materials, PHAs can further improve their mechanical and biocompatibility qualities, making them acceptable for a broader range of applications (Sreedevi et al., 2015).

14.3 Natural Feedstock

Biopolymers are made from substances that are naturally occurring and can be produced by a variety of metabolic processes in living cells, including microbes and plants, that involve chemical and thermo-chemical polymerization (Haddadi et al., 2019). Currently, using inexpensive raw materials are given some thought to reduce PHBs cost. Biomasses from maintaining green spaces, wastes, and byproducts of industry, including glycerol, sugarcane bagasses, and lignocellulosic biomass from agricultural or forest residues, and dairy wastes and food industry waste (Sirohi et al., 2020) are some of these potential substrates. This method's main benefit is that it turns these wastes into products with added value (Angelini et al., 2015).

14.4 Sustainable Bioeconomy

If sustainability requirements are incorporated into the process and product design, PHAs can be desirable substance for a sustainable bioeconomy. The utilization of lignocellulosic biomass as a feedstock has potential for sustainable PHAs production because it naturally occurs as waste and can therefore reduce feedstock greenhouse gas emissions, land use, and other feedstock-associated effects like water use and fertilizer (Dietrich et al., 2017).

15 Limitations of Biodegradable Plastics

PHBs are a unique type of hydrophobic polymer with a high melting point and crystallinity that is genuinely biocompatible and biodegradable. However, for some applications, its strength and a few additional qualities, like thermal stability, solvent resistance, gas permeability, and flame retardance, are insufficient for end use (Maiti et al., 2007). The thermal instability of PHBs, which causes its molecular weight to fall at 170–185 °C by a random scission mechanism, is one of its most significant drawbacks. It has a relatively small processing window because its melting point, which is about 175 °C, is just a little below its degradation temperature, which starts at 185 °C (Robledo-Ortíz et al., 2021). Moreover, PHBs has very poor mechanical qualities with a low elongation at break as a result of its high crystallinity, which restricts the variety of its applications (Ansari & Fatma, 2014). Therefore, to enhance the thermal, physical, and mechanical properties of these materials, it is crucial to produce blends of components from natural sources, synthetic biodegradable polymers, and/or non-biodegradable polymers (Moreira et al., 2022). Blending, coating, adding nanoparticles, adding cellulose, chemical/physical alteration, are some of the options (Jabeen et al., 2015). PHAs are substantially more costly than conventional polymers and other bio-based biodegradable plastics, despite the fact that some PHAs improve ductility as their chain length rises (Meereboer et al., 2020). Furthermore, maintaining best bacterial growth conditions is one of the main hindrances to the industrial output of PHAs. At the completion of the cultivation of bacteria, the majority of fermentation techniques do not provide the maximum synthesis of PHAs granules (Sharma et al., 2021). Due to limitations in production techniques, the cost of bio-based polymers has historically been a significant barrier in commercial use. The emergence of microbial synthesis pathways and the accessibility of inexpensive carbon-rich precursors have made it easier to produce PHAs at a reasonable price for usage in medical and other commercial applications. However, the drawback of mixed cultures is that they are less expensive but produce poor yields and productivity in terms of volume. Moreover, consumer purchasing habits and attitudes toward sustainable products also have an impact on the cost and competition issues (Maraveas, 2020). Due to the fact that consumers focus their purchasing decisions on a product's value in relation to its price, bio-based polymers are still currently unable to compete with traditional plastics on the commercial market (Kapferer & Laurent, 2016; Maraveas, 2020).

16 Conclusion and Future Perspectives

The current predicament created by huge quantity of non-biodegradable wastes in the environment has led to spurring research into novel biodegradable materials build from natural resources like biomass, plants, and microorganisms. MPs being an emerging pollutant in both marine and terrestrial environment, it is necessary to reduce its application and opt for an eco-friendly plastic such as bioplastics. The process of landfills needs a lot of space, an uninterrupted energy supply, and billions of dollars to continue operating in order to fix an issue that shouldn't have existed in the first place. The marine environment has already been irreparably damaged by ocean dumping (Bhola et al., 2021). A new plastic economy paradigm is required to reduce plastic waste from packaging. This idea of a circular economy includes bio-based and biodegradable polymers (Flury & Narayan, 2021). Bioplastics can help solve environmental issues such as unregulated garbage dumping on land and disposal into the sea, as well as the hazardous compounds released as a result. However, to maximize the benefits of bioplastics, appropriate collection, sorting, and recycling processes, as well as public awareness, are required (Venkatachalam & Palaniswamy, 2020). This study gives a brief overview of PHAs, which have now gained interest for being prospective substitutes for traditional plastics because of their biological origin, biodegradability, and biocompatibility, and subsequently mitigating MPs pollution. Although bioplastic production would reduce fossil fuel consumption, CO_2 emissions, and plastic waste generation, the high cost of producing bioplastic from bacteria remains a key restriction when compared to the cost of producing petroleum-derived polymers (Ali et al., 2017). However, as bio-engineering techniques are progressively improving, they have the ability to manufacture effective, high-performance high-yield PHBs, even from wastestream resources, lowering costs and producing PHBs materials at competitive prices with the necessary mechanical qualities to open up a wide range of advanced applications and market prospects (McAdam et al., 2020). Their range of applications will expand as production costs are brought reduced, culminating in a competitive pricing for these biodegradable polymers (Kavitha et al., 2018). Petroleum-derived plastic is expected to be completely substituted once PHAs is more economically viable. This will give an opportunity for technological advancement without worrying too much about dumping and will benefit the economy in the sectors where petroleum-derived plastic is currently used (Bhola et al., 2021). In this regard, research on manufacturing of PHAs from low-cost raw materials, such as waste and by-products, is ongoing. To lower synthesis costs and create efficient recovery and downstream processing techniques for PHAs, as well as to increase their commercialization, significant research and development is still required (Keshavarz & Roy, 2010). The use of biodegradable plastics to reduce pollution is a discussed benefit; nevertheless, substituting conventional plastics with bioplastics is not the most efficient solution; rather, the problem still resides in throw-away attitude. To solve the problem, eco-friendly mentality, strict rules, and an awareness programme must be carefully designed and implemented, and sustainable resources must be used. As the bioplastics area develops, much more emphasis should be paid on both production and disposal processes. This review may help trigger further scientific interest to thoroughly research on PHAs as a sustainable option to green plastic.

Declarations

Conflict of Interest The authors declare no conflict of interest.

References

Abbasi, S., Alirezazadeh, M., Razeghi, N., Rezaei, M., Pourmahmood, H., Dehbandi, R., Mehr, M. R., Ashayeri, S. Y., Oleszczuk, P., & Turner, A. (2022). Microplastics captured by snowfall: A study in Northern Iran. *Science of the Total Environment, 822*, 1–7. https://doi.org/10.1016/j.scitotenv.2022.153451

Abd El-malek, F., Khairy, H., Farag, A., & Omar, S. (2020). The sustainability of microbial bioplastics, production and applications. *International Journal of Biological Macromolecules, 157*, 319–328. https://doi.org/10.1016/j.ijbiomac.2020.04.076

Ageel, H. K., Harrad, S., & Abdallah, M. A. E. (2022). Occurrence, human exposure, and risk of microplastics in the indoor environment. *Environmental Science: Processes & Impacts, 24*(1), 17–31.

Akinmulewo, A. B., & Nwinyi, O. C. (2019). Polyhydroxyalkanoate: A biodegradable polymer (a mini review). In *Journal of physics: Conference series* (1378, 4, 042007). IOP Publishing. https://doi.org/10.1088/1742-6596/1378/4/042007

Ali, W. S., Zaki, N. H., & Obiad, S. Y. N. (2017). Production of bioplastic by bacteria isolated from local soil and organic wastes. *Current Research in Microbiology and Biotechnology*, *5*(2), 1012–1017. Retrieved August 11, 2022, from https://www.researchgate.net/publication/315375411_Production_of_bioplastic_by_bacteria_isolated_from_local_soil_and_organic_wastes

Allikian, K., Edgar, R., Syed, R., & Zhang, S. (2019). Fundamentals of fermentation media. In *Essentials in Fermentation Technology* (pp. 41–84). Springer, Cham. https://doi.org/10.1007/978-3-030-16230-6_2

Amato-Lourenço, L. F., dos Santos Galvão, L., de Weger, L. A., Hiemstra, P. S., Vijver, M. G., & Mauad, T. (2020). An emerging class of air pollutants: Potential effects of microplastics to respiratory human health? *Science of the Total Environment, 749*, 1–27. https://doi.org/10.1016/j.scitotenv.2020.141676

Andrady, A. L. (2015). Persistence of plastic litter in the oceans. In M. Bergmann, L. Gutow, & M. Klages (Eds.), *Marine anthropogenic litter* (pp. 57–72). Springer.

Andrady, A. L. (2017). The plastic in microplastics: A review. *Marine Pollution Bulletin, 119*(1), 12–22. https://doi.org/10.1016/j.marpolbul.2017.01.082

Andrady, A. L., Hamid, H. S., & Torikai, A. (2003). Effects of climate change and UV-B on materials. *Photochemical & Photobiological Sciences, 2*(1), 68–72. https://doi.org/10.1039/b211085g

Angelini, S., Cerruti, P., Immirzi, B., Poskovic, M., Santagata, G., Scarinzi, G., & Malinconico, M. (2015). From microbial biopolymers to bioplastics: sustainable additives for PHB processing and stabilization. In V.C. Kalia (Eds.), *Microbial factories* (pp. 139–160). Springer, New Delhi. https://doi.org/10.1007/978-81-322-2595-9_10

Ansari, S., & Fatma, T. (2014). Polyhydroxybutyrate-a biodegradable plastic and its various formulations. *International Journal of Innovative Research in Science, Engineering and Technology, 3*(2), 9598–9602. https://doi.org/10.1371/journal.pone.0158168

Aramvash, A., Akbari Shahabi, Z., Dashti Aghjeh, S., & Ghafari, M. D. (2015). Statistical physical and nutrient optimization of bioplastic polyhydroxybutyrate production by Cupriavidus necator. *International Journal of Environmental Science and Technology, 12*(7), 2307–2316. https://doi.org/10.1007/s13762-015-0768-3

Arikan, E. B., & Ozsoy, H. D. (2015). A review Investigation of bioplastics. *Journal of Civil Engineering and*

Architecture, 9(2), 188–192. https://doi.org/10.17265/1934-7359/2015.02.007

Aves, A. R., Revell, L. E., Gaw, S., Ruffell, H., Schuddeboom, A., Wotherspoon, N. E., LaRue, M., & McDonald, A. J. (2022). First evidence of microplastics in Antarctic snow. *The Cryosphere, 16*(6), 2127–2145. https://doi.org/10.5194/tc-16-2127-2022

Awasthi, A. K., Tan, Q., & Li, J. (2020). Biotechnological potential for microplastic waste. *Trends in Biotechnology, 38*(11), 1196–1199. https://doi.org/10.1016/j.tibtech.2020.03.002

Baeza-Martínez, C., Olmos, S., González-Pleiter, M., López-Castellanos, J., García-Pachón, E., Masiá-Canuto, M., Hernández-Blasco, L., & Bayo, J. (2022). First evidence of microplastics isolated in European citizens' lower airway. *Journal of Hazardous Materials*, 1-12https://doi.org/10.1016/j.jhazmat.2022.129439

Baho, D. L., Bundschuh, M., & Futter, M. N. (2021). Microplastics in terrestrial ecosystems: Moving beyond the state of the art to minimize the risk of ecological surprise. *Global Change Biology, 27*(17), 3969–3986. https://doi.org/10.1111/gcb.15724

Barham, P. J., Keller, A., Otun, E. L., & Holmes, P. A. (1984). Crystallization and morphology of a bacterial thermoplastic: Poly-3-hydroxybutyrate. *Journal of Materials Science, 19*(9), 2781–2794. https://doi.org/10.1007/BF01026954

Battin, T. J., Besemer, K., Bengtsson, M. M., Romani, A. M., & Packmann, A. I. (2016). The ecology and biogeochemistry of stream biofilms. *Nature Reviews Microbiology, 14*(4), 251–263. https://doi.org/10.1038/nrmicro.2016.15

Beitzen-Heineke, E. F., Balta-Ozkan, N., & Reefke, H. (2017). The prospects of zero-packaging grocery stores to improve the social and environmental impacts of the food supply chain. *Journal of Cleaner Production, 140*, 1528–1541. https://doi.org/10.1016/j.jclepro.2016.09.227

Bergmann, M., Mützel, S., Primpke, S., Tekman, M. B., Trachsel, J., & Gerdts, G. (2019). White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. *Science Advances, 5*(8), 1–10. https://doi.org/10.1126/sciadv.aax1157

Bhola, S., Arora, K., Kulshrestha, S., Mehariya, S., Bhatia, R. K., Kaur, P., & Kumar, P. (2021). Established and emerging producers of PHA: Redefining the possibility. *Applied Biochemistry and Biotechnology, 193*(11), 3812–3854. https://doi.org/10.1007/s12010-021-03626-5

Bhuwal, A. K., Singh, G., Aggarwal, N. K., Goyal, V., & Yadav, A. (2013). Isolation and screening of polyhydroxyalkanoates producing bacteria from pulp, paper, and cardboard industry wastes. *International Journal of Biomaterials, 2013*, 1–10. https://doi.org/10.1155/2013/752821

Bhuwal, A. K., Singh, G., Aggarwal, N. K., Goyal, V., & Yadav, A. (2014). Poly-β-hydroxybutyrate production and management of cardboard industry effluent by new Bacillus sp. NA10. *Bioresources and Bioprocessing, 1*(1), 1–11.

Bhuyan, M. (2022). Effects of microplastics on fish and in human health. *Frontiers in Environmental Science, 10*, 1–17. https://doi.org/10.3389/fenvs.2022.827289

Biamis, C., O'Driscoll, K., & Hardiman, G. (2021). Microplastic toxicity: A review of the role of marine sentinel species in assessing the environmental and public health impacts. *Case Studies in Chemical and Environmental Engineering, 3*, 1–7. https://doi.org/10.1016/j.cscee.2020.100073

Binelli, A., Pietrelli, L., Di Vito, S., Coscia, L., Sighicelli, M., Della Torre, C., Parenti, C. C., & Magni, S. (2020). Hazard evaluation of plastic mixtures from four Italian subalpine great lakes on the basis of laboratory exposures of zebra mussels. *Science of the Total Environment, 699*, 1–31. https://doi.org/10.1016/j.scitotenv.2019.134366

Blight, L. K., & Burger, A. E. (1997). Occurrence of plastic particles in seabirds from the eastern North Pacific. *Marine Pollution Bulletin, 34*(5), 323–325. https://doi.org/10.1016/S0025-326X(96)00095-1

Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M., & Sukumaran, S. (2020). Plastic rain in protected areas of the United States. *Science, 368*(6496), 1257–1260. https://doi.org/10.1126/science.aaz5819

Bucci, K., Tulio, M., & Rochman, C. M. (2020). What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review. *Ecological Applications, 30*(2), 1–16. https://doi.org/10.1002/eap.2044

Cai, L., Wang, J., Peng, J., Wu, Z., & Tan, X. (2018). Observation of the degradation of three types of plastic pellets exposed to UV irradiation in three different environments. *Science of the Total Environment, 628*, 740–747. https://doi.org/10.1016/j.scitotenv.2018.02.079

Calero, M., Godoy, V., Quesada, L., & Martín-Lara, M. Á. (2021). Green strategies for microplastics reduction. *Current Opinion in Green and Sustainable Chemistry, 28*, 1–6. https://doi.org/10.1016/j.cogsc.2020.100442

Casanova, L. (2012, May 17). *Plastic bags should be managed, not banned.* Sci Dev Net. Retrieved August 11, 2022 from https://www.scidev.net/asia-pacific/opinions/plastic-bags-should-be-managed-not-banned/

Cesa, F. S., Turra, A., Checon, H. H., Leonardi, B., & Baruque-Ramos, J. (2020). Laundering and textile parameters influence fibers release in household washings. *Environmental Pollution, 257*, 113553. https://doi.org/10.1016/j.envpol.2019.113553

Chae, Y., & An, Y. J. (2020). Nanoplastic ingestion induces behavioral disorders in terrestrial snails: Trophic transfer effects via vascular plants. *Environmental Science: Nano, 7*(3), 975–983. https://doi.org/10.1039/C9EN01335K

Chalmin, P. (2019). The history of plastics: from the Capitol to the Tarpeian Rock. *Field Actions Science Reports. The Journal of Field Actions*, (Special Issue 19), 6–11.

Chatterjee, S., & Sharma, S. (2019). Microplastics in our oceans and marine health. *Field Actions Science Reports. The Journal of Field Actions*, (Special Issue 19), 54–61.

Chen, X., Xiong, X., Jiang, X., Shi, H., & Wu, C. (2019). Sinking of floating plastic debris caused by biofilm development in a freshwater lake. *Chemosphere, 222*, 856–864. https://doi.org/10.1016/j.chemosphere.2019.02.015

Cheremisinoff, N. P. (2001). *Condensed encyclopedia of polymer engineering terms*. Butterworth-Heinemann.

Crawford, C.B., & Quinn, B. (2017). In C.B. Crawford, B. Quinn (Eds.), *Microplastic Pollutants*. (pp. 57–100).

Elsevier. https://doi.org/10.1016/B978-0-12-809406-8.00004-9

Danso, D., Chow, J., & Streit, W. R. (2019). Plastics: Environmental and biotechnological perspectives on microbial degradation. *Applied and Environmental Microbiology, 85*(19), 1–14. https://doi.org/10.1128/AEM.01095-19

de Souza Machado, A. A., Lau, C. W., Till, J., Kloas, W., Lehmann, A., Becker, R., & Rillig, M. C. (2018). Impacts of microplastics on the soil biophysical environment. *Environmental Science & Technology, 52*(17), 9656–9665. https://doi.org/10.1021/acs.est.8b02212

Dey, A., Dhumal, C. V., Sengupta, P., Kumar, A., Pramanik, N. K., & Alam, T. (2021). Challenges and possible solutions to mitigate the problems of single-use plastics used for packaging food items: A review. *Journal of Food Science and Technology, 58*(9), 3251–3269. https://doi.org/10.1007/s13197-020-04885-6

Dietrich, K., Dumont, M. J., Del Rio, L. F., & Orsat, V. (2017). Producing PHAs in the bioeconomy—Towards a sustainable bioplastic. *Sustainable Production and Consumption, 9*, 58–70. https://doi.org/10.1016/j.spc.2016.09.001

Dilkes-Hoffman, L. S., Lant, P. A., Laycock, B., & Pratt, S. (2019). The rate of biodegradation of PHA bioplastics in the marine environment: A meta-study. *Marine Pollution Bulletin, 142*, 15–24. https://doi.org/10.1016/j.marpolbul.2019.03.020

do Sul, J. A. I., & Costa, M. F. (2014). The present and future of microplastic pollution in the marine environment. *Environmental pollution*, *185*, 352-364. https://doi.org/10.1016/j.envpol.2013.10.036

Enyoh, C. E., Verla, A. W., Verla, E. N., Ibe, F. C., & Amaobi, C. E. (2019). Airborne microplastics: A review study on method for analysis, occurrence, movement and risks. *Environmental Monitoring and Assessment, 191*(11), 1–17. https://doi.org/10.1007/s10661-019-7842-0

Experts, I. (2012). Bioplastics—A global market overview. *Industrial Biotechnology, 8*(2), 62–65. https://doi.org/10.1089/ind.2012.1516

Fazey, F. M., & Ryan, P. G. (2016). Biofouling on buoyant marine plastics: An experimental study into the effect of size on surface longevity. *Environmental Pollution, 210*, 354–360. https://doi.org/10.1016/j.envpol.2016.01.026

Flury, M., & Narayan, R. (2021). Biodegradable plastic as an integral part of the solution to plastic waste pollution of the environment. *Current Opinion in Green and Sustainable Chemistry, 30*, 1–7. https://doi.org/10.1016/j.cogsc.2021.100490

Frias, J. P., & Nash, R. (2019). Microplastics: Finding a consensus on the definition. *Marine Pollution Bulletin, 138*, 145–147. https://doi.org/10.1016/j.marpolbul.2018.11.022

Galloway, T. S. (2015). Micro-and nano-plastics and human health. In M. Bergmann, L. Gutow, & M. Klages (Eds.), *Marine anthropogenic litter* (pp. 343–366). Springer.

Gatea, I. H., Abbas, A. S., Abid, A. G., Halob, A. A., Maied, S. K., & Abidali, A. S. (2018). Isolation and Characterization of *Pseudomonas putida* Producing Bioplastic. *Pakistan Journal of Biotechnology, 15*(2), 469.

Ge, J., Li, H., Liu, P., Zhang, Z., Ouyang, Z., & Guo, X. (2021). Review of the toxic effect of microplastics on terrestrial and aquatic plants. *Science of the Total Environment, 791*, 1–9. https://doi.org/10.1016/j.scitotenv.2021.148333

George, N., Debroy, A., Bhat, S., Singh, S., & Bindal, S. (2021). Biowaste to bioplastics An ecofriendly approach for a sustainable future. *Journal of Applied Biotechnology Reports, 8*(3), 221–233. https://doi.org/10.30491/JABR.2021.259403.1318

Getachew, A., & Woldesenbet, F. (2016). Production of biodegradable plastic by polyhydroxybutyrate (PHB) accumulating bacteria using low cost agricultural waste material. *BMC Research Notes, 9*(1), 1–9. https://doi.org/10.1186/s13104-016-2321-y

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances, 3*(7), 1–5. https://doi.org/10.1126/sciadv.1700782

Gowda, V., & Shivakumar, S. (2014). Agrowaste-based Polyhydroxyalkanoate (PHA) production using hydrolytic potential of *Bacillus thuringiensis* IAM 12077. *Brazilian Archives of Biology and Technology, 57*, 55–61.

Gregory, M. R., & Andrady, A. L. (2003). Plastics in the Marine Environment. In A.L. Andrady (Ed.), *Plastics and the Environment*, (pp. 379–401). John wiley & Sons. https://doi.org/10.1002/0471721557.ch10

Grigore, M. E., Grigorescu, R. M., Iancu, L., Ion, R. M., Zaharia, C., & Andrei, E. R. (2019). Methods of synthesis, properties and biomedical applications of polyhydroxyalkanoates: A review. *Journal of Biomaterials Science, Polymer Edition, 30*(9), 695–712. https://doi.org/10.1080/09205063.2019.1605866

Gu, J. D. (2003). Microbiological deterioration and degradation of synthetic polymeric materials: Recent research advances. *International Biodeterioration & Biodegradation, 52*(2), 69–91. https://doi.org/10.1016/S0964-8305(02)00177-4

Guimarães, T. C., Araújo, E. S., Hernández-Macedo, M. L., & López, J. A. (2022). Polyhydroxyalkanoates: biosynthesis from alternative carbon sources and analytic methods: A short review. *Journal of Polymers and the Environment*, 1-16. https://doi.org/10.1007/s10924-022-02403-7

Ha, J., & Yeo, M. K. (2018). The environmental effects of microplastics on aquatic ecosystems. *Molecular & Cellular Toxicology, 14*(4), 353–359. https://doi.org/10.1007/s13273-018-0039-8\

Haddadi, M. H., Asadolahi, R., & Negahdari, B. (2019). The bioextraction of bioplastics with focus on polyhydroxybutyrate: A review. *International Journal of Environmental Science and Technology, 16*(7), 3935–3948. https://doi.org/10.1007/s13762-019-02352-0

Harvey, F., & Watts, J. (2018, October 22). *Microplastics found in human stools for the first time*. The Guardian. Retrieved August 12, 2022 from https://www.theguardian.com/environment/2018/oct/22/microplastics-found-in-human-stools-for-the-first-time

He, D., Bristow, K., Filipović, V., Lv, J., & He, H. (2020). Microplastics in terrestrial ecosystems: A scientometric analysis. *Sustainability, 12*(20), 1–15. https://doi.org/10.3390/su12208739

Hocker, S., Rhudy, A. K., Ginsburg, G., & Kranbuehl, D. E. (2014). Polyamide hydrolysis accelerated by small weak organic acids. *Polymer, 55*(20), 5057–5064. https://doi.org/10.1016/j.polymer.2014.08.010

Hopewell, J., Dvorak, R., & Kosior, E. (2009). Plastics recycling: Challenges and opportunities. *Philosophical Transactions of the Royal Society b: Biological Sciences, 364*(1526), 2115–2126. https://doi.org/10.1098/rstb.2008.0311

Hungund, B., Shyama, V. S., Patwardhan, P., & Saleh, A. M. (2013). Production of polyhydroxyalkanoate from *Paenibacillus durus* BV-1 isolated from oil mill soil. *Journal of Microbial and Biochemical Technology, 5*, 013–017. https://doi.org/10.4172/1948-5948.1000092

Indian Plastic Industry Report. (2019). Plastic Industry Status Report. Retrieved August 9, 2022, from https://www.plastindia.org/plastic-industry-status-report.php

Issac, M. N., & Kandasubramanian, B. (2021). Effect of microplastics in water and aquatic systems. *Environmental Science and Pollution Research, 28*(16), 19544–19562. https://doi.org/10.1007/s11356-021-13184-2

Jabeen, N., Majid, I., & Nayik, G. A. (2015). Bioplastics and food packaging: A review. *Cogent Food & Agriculture, 1*(1), 1–6. https://doi.org/10.1080/23311932.2015.1117749

Jabeen, K., Su, L., Li, J., Yang, D., Tong, C., Mu, J., & Shi, H. (2017). Microplastics and mesoplastics in fish from coastal and fresh waters of China. *Environmental Pollution, 221*, 141–149. https://doi.org/10.1016/j.envpol.2016.11.055

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science, 347*(6223), 768–771. https://doi.org/10.1126/science.1260352

Javed, H., & Jamil, N. (2015). Utilization of mustard oil for the production of Polyhydroxyalkanoates by *Pseudomonas aeruginosa*. *Journal of Microbiology, Biotechnology and Food Sciences, 2021*, 412–414. https://doi.org/10.15414/jmbfs.2015.4.5.412-414

Jin, H., & Nikolau, B. J. (2014). Evaluating PHA productivity of bioengineered *Rhodosprillum rubrum*. *PLoS ONE, 9*(5), 1–8. https://doi.org/10.1371/journal.pone.0096621

Joyline, M., & Aruna, K. (2019). Production and characterization of polyhydroxyalkanoates (PHA) by *Bacillus megaterium* strain JHA using inexpensive agro-industrial wastes. *International Journal of Recent Scientific Research, 10*(7), 33359–74. https://doi.org/10.24327/ijrsr.2019.1007.3656

Kalia, V. C., Patel, S. K. S., Shanmugam, R., & Lee, J. K. (2021). Polyhydroxyalkanoates: Trends and advances toward biotechnological applications. *Bioresource Technology, 326*, 1–12. https://doi.org/10.1016/j.biortech.2021.124737

Kapferer, J. N., & Laurent, G. (2016). Where do consumers think luxury begins? A study of perceived minimum price for 21 luxury goods in 7 countries. *Journal of Business Research, 69*(1), 332–340. https://doi.org/10.1016/j.jbusres.2015.08.005

Kavitha, G., Rengasamy, R., & Inbakandan, D. (2018). Polyhydroxybutyrate production from marine source and its application. *International Journal of Biological Macromolecules, 111*, 102–108. https://doi.org/10.1016/j.ijbiomac.2017.12.155

Keshavarz, T., & Roy, I. (2010). Polyhydroxyalkanoates: Bioplastics with a green agenda. *Current Opinion in Microbiology, 13*(3), 321–326. https://doi.org/10.1016/j.mib.2010.02.006

Khalid, N., Aqeel, M., & Noman, A. (2020). Microplastics could be a threat to plants in terrestrial systems directly or indirectly. *Environmental Pollution, 267*, 1–11. https://doi.org/10.1016/j.envpol.2020.115653

Khatami, K., Perez-Zabaleta, M., Owusu-Agyeman, I., & Cetecioglu, Z. (2021). Waste to bioplastics: How close are we to sustainable polyhydroxyalkanoates production? *Waste Management, 119*, 374–388. https://doi.org/10.1016/j.wasman.2020.10.008

Kim, B. S. (2002). Production of medium chain length polyhydroxyalkanoates by fed-batch culture of *Pseudomonas oleovorans*. *Biotechnology Letters, 24*(2), 125–130. https://doi.org/10.1023/A:1013898504895

Koelmans, A. A., Nor, N. H. M., Hermsen, E., Kooi, M., Mintenig, S. M., & De France, J. (2019). Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. *Water Research, 155*, 410–422. https://doi.org/10.1016/j.watres.2019.02.054

Kooi, M., Nes, E. H. V., Scheffer, M., & Koelmans, A. A. (2017). Ups and downs in the ocean: Effects of biofouling on vertical transport of microplastics. *Environmental Science & Technology, 51*(14), 7963–7971. https://doi.org/10.1021/acs.est.6b04702

Kuciel, S., Mazur, K., & Jakubowska, P. (2019). Novel biorenewable composites based on poly (3-hydroxybutyrate-co-3-hydroxyvalerate) with natural fillers. *Journal of Polymers and the Environment, 27*(4), 803–815. https://doi.org/10.1007/s10924-019-01392-4

Kühn, S., Bravo Rebolledo, E. L., & Franeker, J. A. V. (2015). Deleterious effects of litter on marine life. In M. Bergmann, L. Gutow, & M. Klages (Eds.), *Marine anthropogenic litter* (pp. 75–116). Springer.

Kurniawan, S. B., Said, N. S. M., Imron, M. F., & Abdullah, S. R. S. (2021). Microplastic pollution in the environment: Insights into emerging sources and potential threats. *Environmental Technology & Innovation, 23*, 1–14. https://doi.org/10.1016/j.eti.2021.101790

Lackner, M. (2000). Bioplastics. *Kirk-Othmer Encyclopedia of Chemical Technology*, 1-41. https://doi.org/10.1002/0471238961.koe00006

Laist, D. W. (1987). Overview of the biological effects of lost and discarded plastic debris in the marine environment. *Marine Pollution Bulletin, 18*(6), 319–326. https://doi.org/10.1016/S0025-326X(87)80019-X

Lammi, S., Gastaldi, E., Gaubiac, F., & Angellier-Coussy, H. (2019). How olive pomace can be valorized as fillers to tune the biodegradation of PHBV based composites. *Polymer Degradation and Stability, 166*, 325–333. https://doi.org/10.1016/j.polymdegradstab.2019.06.010

Law, K. L. (2017). Plastics in the marine environment. *Annual Review of Marine Science, 9*, 205–229. https://doi.org/10.1146/annurev-marine-010816-060409

Lee, Y. R., Fitriana, H. N., Lee, S. Y., Kim, M. S., Moon, M., Lee, W. H., Lee, J. S., & Lee, S. (2020). Molecular profiling and optimization studies for growth and PHB production conditions in *Rhodobacter sphaeroides*. *Energies, 13*(23), 6471. https://doi.org/10.3390/en13236471

Leslie, H. A., Van Velzen, M. J., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., & Lamoree, M. H. (2022).

Discovery and quantification of plastic particle pollution in human blood. *Environment International, 163*, 1–8. https://doi.org/10.1016/j.envint.2022.107199

Lett, Z., Hall, A., Skidmore, S., & Alves, N. J. (2021). Environmental microplastic and nanoplastic: Exposure routes and effects on coagulation and the cardiovascular system. *Environmental Pollution, 291*, 1–14. https://doi.org/10.1016/j.envpol.2021.118190

Li, C., Busquets, R., & Campos, L. C. (2020). Assessment of microplastics in freshwater systems: A review. *Science of the Total Environment, 707*, 135578. https://doi.org/10.1016/j.scitotenv.2019.135578

Liu, M., Lu, S., Song, Y., Lei, L., Hu, J., Lv, W., Zhou, W., Cao, C., Shi, H., Yang, X., & He, D. (2018). Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai, China. *Environmental Pollution, 242*, 855–862. https://doi.org/10.1016/j.envpol.2018.07.051

Liu, K., Wang, X., Wei, N., Song, Z., & Li, D. (2019). Accurate quantification and transport estimation of suspended atmospheric microplastics in megacities: Implications for human health. *Environment International, 132*, 1–10. https://doi.org/10.1016/j.envint.2019.105127

Liu, Y., Guo, R., Zhang, S., Sun, Y., & Wang, F. (2022). Uptake and translocation of nano/microplastics by rice seedlings: Evidence from a hydroponic experiment. *Journal of Hazardous Materials, 421*, 1–8. https://doi.org/10.1016/j.jhazmat.2021.126700

Loh, Y. Z., & Chew, I. M. L. (2021). Mitigating plastic pollution through better process design: an opportunity from biomass to bioplastic. *Biomass Conversion and Biorefinery*, 1-22. https://doi.org/10.1007/s13399-021-01959-z

Lusher, A. (2015). Microplastics in the marine environment: Distribution, interactions and effects. In M. Bergmann, L. Gutow, & M. Klages (Eds.), *Marine anthropogenic litter* (pp. 245–307). Springer.

Lusher, A. L., Tirelli, V., O'Connor, I., & Officer, R. (2015). Microplastics in Arctic polar waters: The first reported values of particles in surface and sub-surface samples. *Scientific Reports, 5*(1), 1–9. https://doi.org/10.1038/srep14947

Magnin, A., Pollet, E., Phalip, V., & Avérous, L. (2020). Evaluation of biological degradation of polyurethanes. *Biotechnology Advances, 39*, 1–24. https://doi.org/10.1016/j.biotechadv.2019.107457

Maiti, P., Batt, C. A., & Giannelis, E. P. (2007). New biodegradable polyhydroxybutyrate/layered silicate nanocomposites. *Biomacromolecules, 8*(11), 3393–3400. https://doi.org/10.1021/bm700500t

Manzoor, S., Naqash, N., Rashid, G., & Singh, R. (2021). Plastic material degradation and formation of microplastic in the environment: A review. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2021.09.379

Maraveas, C. (2020). Production of sustainable and biodegradable polymers from agricultural waste. *Polymers, 12*(5), 1–22.

Marjadi, D., & Dharaiya, N. (2010). Bioplastic : A better alternative for sustainable future. *Everyman's Science, 45*(2), 90–92.

Mascarenhas, J., & Aruna, K. (2017). Screening of Polyhydroxyalkonates (Pha) accumulating bacteria from diverse habitats. *Journal of Global Biosciences, 6*(3), 4835–4848. Retrieved August 11, 2022, from http://www.mutagens.co.in/jgb/vol.06/3/060304.pdf

Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C., & Kaminuma, T. (2001). Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environmental Science & Technology, 35*(2), 318–324. https://doi.org/10.1021/es0010498

McAdam, B., Brennan Fournet, M., McDonald, P., & Mojicevic, M. (2020). Production of polyhydroxybutyrate (PHB) and factors impacting its chemical and mechanical characteristics. *Polymers, 12*(12), 1–20. https://doi.org/10.3390/polym12122908

McKeen, L. W. (2019). *The effect of UV light and weather on plastics and elastomers*. William Andrew.

Meereboer, K. W., Misra, M., & Mohanty, A. K. (2020). Review of recent advances in the biodegradability of polyhydroxyalkanoate (PHA) bioplastics and their composites. *Green Chemistry, 22*(17), 5519–5558. https://doi.org/10.1039/D0GC01647K

Mohapatra, S., Mohanta, P. R., Sarkar, B., Daware, A., Kumar, C., & Samantaray, D. P. (2017). Production of polyhydroxyalkanoates (PHAs) by *Bacillus* strain isolated from waste water and its biochemical characterization. *Proceedings of the National Academy of Sciences, India Section b: Biological Sciences, 87*(2), 459–466. https://doi.org/10.1007/s40011-015-0626-6

Moreira, J. B., Kuntzler, S. G., da Silva Vaz, B., da Silva, C. K., Costa, J. A. V., & de Morais, M. G. (2022). Polyhydroxybutyrate (PHB)-based blends and composites. In S.M. Rangappa, J. Parameswaranpillai, S. Siengchin, & M. Ramesh (Eds.), *Biodegradable Polymers, Blends and Composites* (pp. 389–413). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-823791-5.00007-7

Moshood, T. D., Nawanir, G., Mahmud, F., Mohamad, F., Ahmad, M. H., & AbdulGhani, A. (2022). Sustainability of biodegradable plastics: New problem or solution to solve the global plastic pollution?. *Current Research in Green and Sustainable Chemistry*, 100273. https://doi.org/10.1016/j.crgsc.2022.100273

Mostafa, Y. S., Alrumman, S. A., Otaif, K. A., Alamri, S. A., Mostafa, M. S., & Sahlabji, T. (2020). Production and characterization of bioplastic by polyhydroxybutyrate accumulating *Erythrobacter aquimaris* isolated from mangrove rhizosphere. *Molecules, 25*(1), 1–20. https://doi.org/10.3390/molecules25010179

Możejko-Ciesielska, J., & Kiewisz, R. (2016). Bacterial polyhydroxyalkanoates: Still fabulous? *Microbiological Research, 192*, 271–282. https://doi.org/10.1016/j.micres.2016.07.010

Muneer, F., Rasul, I., Azeem, F., Siddique, M. H., Zubair, M., & Nadeem, H. (2020). Microbial polyhydroxyalkanoates (PHAs): Efficient replacement of synthetic polymers. *Journal of Polymers and the Environment, 28*(9), 2301–2323. https://doi.org/10.1007/s10924-020-01772-1

Muneer, F., Rasul, I., Qasim, M., Sajid, A., & Nadeem, H. (2022). Optimization, Production and Characterization of Polyhydroxyalkanoate (PHA) from Indigenously Isolated Novel Bacteria. *Journal of Polymers and the Environment*, 1-11. https://doi.org/10.1007/s10924-022-02444-y

Nair, L. S., & Laurencin, C. T. (2007). Biodegradable polymers as biomaterials. *Progress in Polymer Science, 32*(8–9), 762–798. https://doi.org/10.1016/j.progpolymsci.2007.05.017

Nakamiya, K., Sakasita, G., Ooi, T., & Kinoshita, S. (1997). Enzymatic degradation of polystyrene by hydroquinone peroxidase of *Azotobacter beijerinckii* HM121. *Journal of Fermentation and Bioengineering, 84*(5), 480–482. https://doi.org/10.1016/S0922-338X(97)82013-2

Nandakumar, A., Chuah, J. A., & Sudesh, K. (2021). Bioplastics: A boon or bane? *Renewable and Sustainable Energy Reviews, 147*, 1–15. https://doi.org/10.1016/j.rser.2021.111237

Narayanan, M., Kandasamy, S., Kumarasamy, S., Gnanavel, K., Ranganathan, M., & Kandasamy, G. (2020a). Screening of polyhydroxybutyrate producing indigenous bacteria from polluted lake soil. *Heliyon, 6*(10), 1–8. https://doi.org/10.1016/j.heliyon.2020.e05381

Narayanan, M., Kumarasamy, S., Ranganathan, M., Kandasamy, S., Kandasamy, G., Gnanavel, K., & Mamtha, K. (2020b). Production and characterization of polyhydroxyalkanoates synthesized by *E. coli* isolated from sludge soil. *Materials Today: Proceedings, 33*, 3646–3653. https://doi.org/10.1016/j.matpr.2020.05.725

Nelms, S. E., Barnett, J., Brownlow, A., Davison, N. J., Deaville, R., Galloway, T. S., Lindeque, P. K., Santillo, D., & Godley, B. J. (2019). Microplastics in marine mammals stranded around the British coast: Ubiquitous but transitory? *Scientific Reports, 9*(1), 1–8. https://doi.org/10.1038/s41598-018-37428-3

Nwafor, N., & Walker, T. R. (2020). Plastic bags prohibition bill: A developing story of crass legalism aiming to reduce plastic marine pollution in Nigeria. *Marine Policy, 120*, 1–9. https://doi.org/10.1016/j.marpol.2020.104160

O'Connor, D., Pan, S., Shen, Z., Song, Y., Jin, Y., Wu, W. M., & Hou, D. (2019). Microplastics undergo accelerated vertical migration in sand soil due to small size and wet-dry cycles. *Environmental Pollution, 249*, 527–534. https://doi.org/10.1016/j.envpol.2019.03.092

OECD. (2022). *Global plastics Outlook: Economic Drivers,nvironmental Impacts and Policy Options*. Retrieved August 9, 2022, from https://espas.secure.europarl.europa.eu/orbis/sites/default/files/generated/document/en/plastic.pdf

Ory, N. C., Lehmann, A., Javidpour, J., Stöhr, R., Walls, G. L., & Clemmesen, C. (2020). Factors influencing the spatial and temporal distribution of microplastics at the sea surface—A year-long monitoring case study from the urban Kiel Fjord, Southwest Baltic Sea. *Science of the Total Environment, 736*, 1–41. https://doi.org/10.1016/j.scitotenv.2020.139493

Pal, P., Pandey, J. P., & Sen, G. (2018). Synthesis and application as programmable water soluble adhesive of polyacrylamide grafted gum Tragacanth (GT-g-PAM). In *Biopolymer Grafting* (pp. 153–203). Elsevier. https://doi.org/10.1016/B978-0-12-810462-0.00005-3

Pellini, G., Gomiero, A., Fortibuoni, T., Ferrà, C., Grati, F., Tassetti, A. N., Polidori, P., Fabi, G., & Scarcella, G. (2018). Characterization of microplastic litter in the gastrointestinal tract of *Solea solea* from the Adriatic Sea. *Environmental Pollution, 234*, 943–952. https://doi.org/10.1016/j.envpol.2017.12.038

Peterson, J. D., Vyazovkin, S., & Wight, C. A. (2001). Kinetics of the thermal and thermo-oxidative degradation of polystyrene, polyethylene and poly (propylene). *Macromolecular Chemistry and Physics, 202*(6), 775–784. https://doi.org/10.1002/1521-3935(20010301)202:6%3c775::AID-MACP775%3e3.0.CO;2-G

Picó, Y., & Barceló, D. (2019). Analysis and prevention of microplastics pollution in water: Current perspectives and future directions. *ACS Omega, 4*(4), 6709–6719. https://doi.org/10.1021/acsomega.9b00222

Pirsaheb, M., Hossini, H., & Makhdoumi, P. (2020). Review of microplastic occurrence and toxicological effects in marine environment: Experimental evidence of inflammation. *Process Safety and Environmental Protection, 142*, 1–14. https://doi.org/10.1016/j.psep.2020.05.050

Plastics Europe. (2019). *Plastics—The Facts 2019. An Analysis of European Plastics Production, Demand and Waste Data*. Retrieved August 9, 2022, from https://plasticseurope.org/wp-content/uploads/2021/10/2019-Plastics-the-facts.pdf

Plastics Europe.(2021). *Plastics - the Facts 2021 An analysis of European plastics production, demand and waste data.* Retrieved August 9, 2022, from https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf

Prata, J. C. (2018). Airborne microplastics: Consequences to human health? *Environmental Pollution, 234*, 115–126. https://doi.org/10.1016/j.envpol.2017.11.043

Prata, J. C., Silva, A. L. P., Da Costa, J. P., Mouneyrac, C., Walker, T. R., Duarte, A. C., & Rocha-Santos, T. (2019). Solutions and integrated strategies for the control and mitigation of plastic and microplastic pollution. *International Journal of Environmental Research and Public Health, 16*(13), 1–19. https://doi.org/10.3390/ijerph16132411

Prata, J. C., da Costa, J. P., Lopes, I., Duarte, A. C., & Rocha-Santos, T. (2020). Environmental exposure to microplastics: An overview on possible human health effects. *Science of the Total Environment, 702*, 1–31. https://doi.org/10.1016/j.scitotenv.2019.134455

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M. C. A., Baiocco, F., Draghi, S., & D'Amore, E. (2021). Plasticenta: First evidence of microplastics in human placenta. *Environment International, 146*, 1–8. https://doi.org/10.1016/j.envint.2020.106274

Rajan, K. P., Thomas, S. P., Gopanna, A., & Chavali, M. (2019). Polyhydroxybutyrate (PHB): A standout biopolymer for environmental sustainability. *Handbook of ecomaterials*, 2803-2825. https://doi.org/10.1007/978-3-319-48281-1_92-1

Rajmohan, K. V. S., Ramya, C., Viswanathan, M. R., & Varjani, S. (2019). Plastic pollutants: Effective waste management for pollution control and abatement. *Current Opinion in Environmental Science & Health, 12*, 72–84. https://doi.org/10.1016/j.coesh.2019.08.006

Raubenheimer, K., & McIlgorm, A. (2017). Is the Montreal Protocol a model that can help solve the global marine plastic debris problem? *Marine Policy, 81*, 322–329.

Ray, S., & Kalia, V. C. (2017). Biomedical Applications of Polyhydroxyalkanoates. *Indian Journal of*

Microbiology, 57(3), 261–269. https://doi.org/10.1007/s12088-017-0651-7

Raza, Z. A., Abid, S., & Banat, I. M. (2018). Polyhydroxyalkanoates: Characteristics, production, recent developments and applications. *International Biodeterioration & Biodegradation, 126*, 45–56. https://doi.org/10.1016/j.ibiod.2017.10.001

Rekhi, P., Goswami, M., Ramakrishna, S., & Debnath, M. (2022). Polyhydroxyalkanoates biopolymers toward decarbonizing economy and sustainable future. *Critical Reviews in Biotechnology, 42*(5), 668–692. https://doi.org/10.1080/07388551.2021.1960265

Reshmy, R., Thomas, D., Philip, E., Paul, S. A., Madhavan, A., Sindhu, R., Sirohi, R., Varjani, S., Pugazhendhi, A., Pandey, A., & Binod, P. (2021). Bioplastic production from renewable lignocellulosic feedstocks: A review. *Reviews in Environmental Science and Bio/technology, 20*(1), 167–187. https://doi.org/10.1007/s11157-021-09565-1

Revell, L. E., Kuma, P., Le Ru, E. C., Somerville, W. R., & Gaw, S. (2021). Direct radiative effects of airborne microplastics. *Nature, 598*(7881), 462–467. https://doi.org/10.1038/s41586-021-03864-x

Rillig, M. C., & Bonkowski, M. (2018). Microplastic and soil protists: A call for research. *Environmental Pollution, 241*, 1128–1131. https://doi.org/10.1016/j.envpol.2018.04.147

Robledo-Ortíz, J. R., González-López, M. E., Martín del Campo, A. S., & Pérez-Fonseca, A. A. (2021). Lignocellulosic materials as reinforcement of polyhydroxybutyrate and its copolymer with hydroxyvalerate: A review. *Journal of Polymers and the Environment, 29*(5), 1350–1364. https://doi.org/10.1007/s10924-020-01979-2

Roohi, Zaheer, M. R., & Kuddus, M. (2018). PHB (poly-β-hydroxybutyrate) and its enzymatic degradation. *Polymers for Advanced Technologies, 29*(1), 30–40. https://doi.org/10.1002/pat.4126

Ross, G., Ross, S., & Tighe, B. J. (2017). Bioplastics: New routes, new products. *Brydson's Plastics Materials*, 631-652. https://doi.org/10.1016/B978-0-323-35824-8.00023-2

Rujnić-Sokele, M., & Pilipović, A. (2017). Challenges and opportunities of biodegradable plastics: A mini review. *Waste Management & Research, 35*(2), 132–140. https://doi.org/10.1177/0734242X16683272

Sanchez, W., Bender, C., & Porcher, J. M. (2014). Wild gudgeons (*Gobio gobio*) from French rivers are contaminated by microplastics: Preliminary study and first evidence. *Environmental Research, 128*, 98–100. https://doi.org/10.1016/j.envres.2013.11.004

Sánchez, C. (2020). Fungal potential for the degradation of petroleum-based polymers: An overview of macro-and microplastics biodegradation. *Biotechnology Advances, 40*, 1–17. https://doi.org/10.1016/j.biotechadv.2019.107501

Sang, W., Chen, Z., Mei, L., Hao, S., Zhan, C., BinZhang, W., Li, M., & Liu, J. (2021). The abundance and characteristics of microplastics in rainwater pipelines in Wuhan, China. *Science of the Total Environment, 755*, 1–7. https://doi.org/10.1016/j.scitotenv.2020.142606

Sarker, A., Deepo, D. M., Nandi, R., Rana, J., Islam, S., Rahman, S., Hossain, M. N., Islam, M. S., Baroi, A., & Kim, J. E. (2020). A review of microplastics pollution in the soil and terrestrial ecosystems: A global and Bangladesh perspective. *Science of the Total Environment, 733*, 1–53. https://doi.org/10.1016/j.scitotenv.2020.139296

Schnurr, R. E., Alboiu, V., Chaudhary, M., Corbett, R. A., Quanz, M. E., Sankar, K., Srain, H. S., Thavarajah, V., Xanthos, D., & Walker, T. R. (2018). Reducing marine pollution from single-use plastics (SUPs): A review. *Marine Pollution Bulletin, 137*, 157–171. https://doi.org/10.1016/j.marpolbul.2018.10.001

Shah, M., Rajhans, S., Pandya, H. A., & Mankad, A. U. (2021). Bioplastic for future A review then and now. *World Journal of Advanced Research and Reviews, 9*(2), 056–067. https://doi.org/10.30574/wjarr.2021.9.2.0054

Shams, M., Alam, I., & Mahbub, M. S. (2021). Plastic pollution during COVID-19: Plastic waste directives and its long-term impact on the environment. *Environmental Advances, 5*, 100119. https://doi.org/10.1016/j.envadv.2021.100119

Shao, L., Li, Y., Jones, T., Santosh, M., Liu, P., Zhang, M., Xu, L., Li, W., Lu, J., Yang, C.X., Zhang, D., Feng, X., & BéruBé, K. (2022). Airborne microplastics: A review of current perspectives and environmental implications. *Journal of Cleaner Production*, 131048. https://doi.org/10.1016/j.jclepro.2022.131048

Sharma, S., & Chatterjee, S. (2017). Microplastic pollution, a threat to marine ecosystem and human health: A short review. *Environmental Science and Pollution Research, 24*(27), 21530–21547. https://doi.org/10.1007/s11356-017-9910-8

Sharma, P. K., Munir, R. I., Blunt, W., Dartiailh, C., Cheng, J., Charles, T. C., & Levin, D. B. (2017). Synthesis and physical properties of polyhydroxyalkanoate polymers with different monomer compositions by recombinant *Pseudomonas putida* LS46 expressing a novel PHA synthase (PhaC116) enzyme. *Applied Sciences, 7*(3), 1–20. https://doi.org/10.3390/app7030242

Sharma, V., Sehgal, R., & Gupta, R. (2021). Polyhydroxyalkanoate (PHA): Properties and modifications. *Polymer, 212*, 123161. https://doi.org/10.1016/j.polymer.2020.123161

Sirohi, R., Pandey, J. P., Gaur, V. K., Gnansounou, E., & Sindhu, R. (2020). Critical overview of biomass feedstocks as sustainable substrates for the production of polyhydroxybutyrate (PHB). *Bioresource Technology, 311*, 1–10. https://doi.org/10.1016/j.biortech.2020.123536

Snell, K. D., & Peoples, O. P. (2009). PHA bioplastic: A value-added coproduct for biomass biorefineries. *Biofuels, Bioproducts and Biorefining: Innovation for a Sustainable Economy, 3*(4), 456–467. https://doi.org/10.1002/bbb.161

Sohma, J. (1989). 23-Mechanochemical Degradation. *Comprehensive Polymer Science and Supplements*, 621-644. https://doi.org/10.1016/B978-0-08-096701-1.00203-2

Sorasan, C., Ortega-Ojeda, F. E., Rodríguez, A., & Rosal, R. (2022). Modelling the photodegradation of marine microplastics by means of infrared spectrometry and chemometric techniques. *Microplastics, 1*(1), 198–210. https://doi.org/10.3390/microplastics1010013

Sreedevi, S., Unni, K. N., Sajith, S., Priji, P., Josh, M. S., & Benjamin, S. (2015). Bioplastics: Advances in polyhydroxybutyrate research. *Advances in Polymer Science*. https://doi.org/10.1007/12_2014_297

Sridharan, S., Kumar, M., Singh, L., Bolan, N. S., & Saha, M. (2021). Microplastics as an emerging source of particulate air pollution: A critical review. *Journal of Hazardous Materials, 418*, 1–15. https://doi.org/10.1016/j.jhazmat.2021.126245

Sriyapai, T., Chuarung, T., Kimbara, K., Samosorn, S., & Sriyapai, P. (2022). Production and optimization of polyhydroxyalkanoates (PHAs) from Paraburkholderia sp. PFN 29 under submerged fermentation. *Electronic Journal of Biotechnology, 56*, 1–11. https://doi.org/10.1016/j.ejbt.2021.12.003

Statista.(2021). Distribution of plastic waste generation worldwide in 2018, by sector. Retrieved August 9, 2022, from https://www.statista.com/statistics/1166582/global-plastic-waste-generation-by-sector/

Su, Y., Zhang, Z., Wu, D., Zhan, L., Shi, H., & Xie, B. (2019). Occurrence of microplastics in landfill systems and their fate with landfill age. *Water Research, 164*, 1–23. https://doi.org/10.1016/j.watres.2019.114968

Sudesh, K., Abe, H., & Doi, Y. (2000). Synthesis, structure and properties of polyhydroxyalkanoates: Biological polyesters. *Progress in Polymer Science, 25*(10), 1503–1555. https://doi.org/10.1016/S0079-6700(00)00035-6

Sun, Z., Ramsay, J. A., Guay, M., & Ramsay, B. A. (2007). Fermentation process development for the production of medium-chain-length poly-3-hyroxyalkanoates. *Applied Microbiology and Biotechnology, 75*(3), 475–485. https://doi.org/10.1007/s00253-007-0857-4

Sun, J., Shen, J., Chen, S., Cooper, M. A., Fu, H., Wu, D., & Yang, Z. (2018). Nanofiller reinforced biodegradable PLA/PHA composites: Current status and future trends. *Polymers, 10*(5), 1–22. https://doi.org/10.3390/polym10050505

Tanamool, V., Imai, T., Danvirutai, P., & Kaewkannetra, P. (2013). Biopolymer generation from sweet sorghum juice: Screening, isolation, identification, and fermentative polyhydroxyalkanoate production by *Bacillus aryabhattai*. *Turkish Journal of Biology, 37*(3), 259–264. https://doi.org/10.3906/biy-1205-62

Thiruchelvi, R., Das, A., & Sikdar, E. (2020). Bioplastics as better alternative to petro plastic. *Materials Today: Proceedings, 37*(Part 2), 1634–1639. https://doi.org/10.1016/j.matpr.2020.07.176

Thompson, R. C., Swan, S. H., Moore, C. J., & Vom Saal, F. S. (2009). Our plastic age. *Philosophical Transactions of the Royal Society b: Biological Sciences, 364*(1526), 1973–1976. https://doi.org/10.1098/rstb.2009.0054

Torikai, A., Takeuchi, A., Nagaya, S., & Fueki, K. (1986). Photodegradation of polyethylene: Effect of crosslinking on the oxygenated products and mechanical properties. *Polymer Photochemistry, 7*(3), 199–211. https://doi.org/10.1016/0144-2880(86)90027-8

Tsang, Y. F., Kumar, V., Samadar, P., Yang, Y., Lee, J., Ok, Y. S., Song, H., Kim, K. H., Kwon, E. E., & Jeon, Y. J. (2019). Production of bioplastic through food waste valorization. *Environment International, 127*, 625–644. https://doi.org/10.1016/j.envint.2019.03.076

Turner, A. (2020). Foamed polystyrene in the marine environment: Sources, additives, transport, behavior, and impacts. *Environmental Science & Technology, 54*(17), 10411–10420. https://doi.org/10.1021/acs.est.0c03221

Venkatachalam, H., & Palaniswamy, R. (2020). Bioplastic world: A review. *Journal of Advanced Scientific Research, 11*(03), 43–53. http://sciensage.info/index.php/JASR/article/view/505.

Verlinden, R. A., Hill, D. J., Kenward, M. A., Williams, C. D., & Radecka, I. (2007). Bacterial synthesis of biodegradable polyhydroxyalkanoates. *Journal of Applied Microbiology, 102*(6), 1437–1449. https://doi.org/10.1111/j.1365-2672.2007.03335.x

Verschoor, A. J. (2018). Potential measures against microplastic emissions to water. Retrieved from http://hdl.handle.net/10029/622058

Vijay, R., & Tarika, K. (2019). Microbial production of polyhydroxyalkanoates (PHAs) using kitchen waste as an inexpensive carbon source. *Biosciences Biotechnology Research Asia, 16*(1), 155–166. https://doi.org/10.13005/bbra/2733

Waldschläger, K., Lechthaler, S., Stauch, G., & Schüttrumpf, H. (2020). The way of microplastic through the environment—Application of the source-pathway-receptor model. *Science of the Total Environment, 713*, 1–60. https://doi.org/10.1016/j.scitotenv.2020.136584

Van der Walle, G. V., De Koning, G. J. M., Weusthuis, R. A., & Eggink, G. (2001). Properties, modifications and applications of biopolyesters. *Biopolyesters*, 263-291. https://doi.org/10.1007/3-540-40021-4_9

Wang, J., Lv, S., Zhang, M., Chen, G., Zhu, T., Zhang, S., Teng, Y., Christie, P., & Luo, Y. (2016a). Effects of plastic film residues on occurrence of phthalates and microbial activity in soils. *Chemosphere, 151*, 171–177. https://doi.org/10.1016/j.chemosphere.2016.02.076

Wang, J., Tan, Z., Peng, J., Qiu, Q., & Li, M. (2016b). The behaviors of microplastics in the marine environment. *Marine Environmental Research, 113*, 7–17. https://doi.org/10.1016/j.marenvres.2015.10.014

Wang, W., Ge, J., Yu, X., & Li, H. (2020). Environmental fate and impacts of microplastics in soil ecosystems: Progress and perspective. *Science of the Total Environment, 708*, 134841. https://doi.org/10.1016/j.scitotenv.2019.134841

Wei, Y. H., Chen, W. C., Huang, C. K., Wu, H. S., Sun, Y. M., Lo, C. W., & Janarthanan, O. M. (2011). Screening and evaluation of polyhydroxybutyrate-producing strains from indigenous isolate *Cupriavidus taiwanensis* strains. *International Journal of Molecular Sciences, 12*(1), 252–265. https://doi.org/10.3390/ijms12010252

Whiting, K. (2018, November 2). *This is how long everyday plastic items last in the ocean. World Economic Forum.* Retrieved November 23 from https://www.weforum.org/agenda/2018/11/chart-of-the-day-this-is-how-long-everyday-plastic-items-last-in-the-ocean/

Wirtz, K. W. (2012). Who is eating whom? Morphology and feeding type determine the size relation between planktonic predators and their ideal prey. *Marine Ecology Progress Series, 445*, 1–12. https://doi.org/10.3354/meps09502

Yang, H., Ma, M., Thompson, J. R., & Flower, R. J. (2018). Waste management, informal recycling, environmental pollution and public health. *Journal of Epidemiology and*

Community Health, 72(3), 237–243. https://doi.org/10.1136/jech-2016-208597

Zhang, S., Wang, J., Liu, X., Qu, F., Wang, X., Wang, X., Li, Y., & Sun, Y. (2019). Microplastics in the environment: A review of analytical methods, distribution, and biological effects. *Trends in Analytical Chemistry, 111*, 62–72. https://doi.org/10.1016/j.trac.2018.12.002

Zhang, K., Hamidian, A. H., Tubić, A., Zhang, Y., Fang, J. K., Wu, C., & Lam, P. K. S. (2021). Understanding plastic degradation and microplastic formation in the environment: A review. *Environmental Pollution, 274*, 1–14. https://doi.org/10.1016/j.envpol.2021.116554

Zhao, K., Yang, X., Chen, G. Q., & Chen, J. C. (2002). Effect of lipase treatment on the biocompatibility of microbial polyhydroxyalkanoates. *Journal of Materials Science: Materials in Medicine, 13*(9), 849–854. https://doi.org/10.1023/A:1016596228316

Zhu, C., Nomura, C. T., Perrotta, J. A., Stipanovic, A. J., & Nakas, J. P. (2010). Production and characterization of poly-3-hydroxybutyrate from biodiesel-glycerol by *Burkholderia cepacia* ATCC 17759. *Biotechnology Progress, 26*(2), 424–430. https://doi.org/10.1002/btpr.355