



Current trends in microplastic removal using biodegradation approaches and advancement – A review

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ABSTRACT

Due to improper disposal and mismanagement of plastic waste, plastic converted into microplastic when exposed to the environment causes tremendous burdens to nature. It becomes the most persistent pollutant in air, water, and land environments due to the inert property of plastic. It enters the environment from various sources, such as industrial, household, and agricultural waste, affecting the lives of humans, other living beings, and the entire ecosystem. Much research and experimentation have been conducted to eliminate microplastics from the environment with the help of conventional methods, such as physical, chemical, and biological, which remove microplastics but are inefficient in eliminating them from the environment. Some processes are good for nature and the environment, as they can cause secondary pollution. Therefore, there is a need for some scientifically proven new methods to achieve the required level of results and be environmentally friendly. Bioremediation is a sound technique used to degrade plastic with the help of bacteria, fungi, algae, and insects. However, some studies reveal that the pretreatment (UV, thermal, chemical, and physical) can change the inert property of plastic, making it more available to the microbes and increasing the biodegradation process without affecting the microbes' life. Such a treatment gives hope for removing plastic from the environment in an efficient way.

Introduction

Throughout the world, plastics have been the most widely used artificial, synthetic material. Humans have learned how to fabricate and manipulate various plastics by changing their strength, durability, and lightness compared to the former plastic material. Plastic is a synthetic polymer that uses fossil fuels or natural substances like cellulose [1]. Plastics' inertness and recalcitrant properties make them biodegradable-resistant and accumulate in aquatic and terrestrial environments [2]. Plastics are placed in two different categories: thermosetting plastic and thermoplastic. Thermoplastics are heat-sensitive plastics that can change their shape upon heating, such as polypropene (PP), Polystyrene (PS), polyethylene (PE), poly(vinyl chloride) (PVC), polycarbonate (PC), polytetrafluoroethylene (PTFE) [3–7]. Thermosetting plastics such as organosilicon, phenolic resin, urea–formaldehyde resin, and epoxy resin are heat-resistant plastics and do not change their shape upon heating, but decompose when the temperature rises between 250 and 300 °C [3,8]. First, plastic pollution was reported in the 1970s and continues to grow [9]. In 2016, 335 million tons of plastic were produced [10]. In

2019, 370 million tons of plastic production reached worldwide, and by 2050, it will reach 1800 million tonnes [11]. European plastic contributed 58 million tons [12,13]. Plastic production by Asian countries is about 114.0 million tonnes [14]. In 2018–19, 3.3 million metric tons of plastic were produced by India, 60 % of the plastic produced is reused by recycling, and the remaining 40 % creates pollution [15,16]. Plastics like poly(vinyl chloride) (PVC), High-density polyethylene (HDPE), Low-density polyethylene (LDPE) poly(ethene terephthalate) (PET), polypropene (PP), polyethylene (PE), and polystyrene (PS) are the most frequently used, which are fossil fuel oriented [17]. Fossil fuel-based plastic contributes to 90 % of the world's plastic production and is also responsible for microplastic pollution [18]. Single-use plastic items cause 50 % of plastic pollution, like plastic disposable items, agricultural films, packaging films, and plastic bottles [19]. It is assumed that 10 % of the plastic produced reaches the ocean and persists for a long time, but the more interesting thing is that 95 % of the waste that contaminates the sea contains plastics [20]. Apart from that, elastomer and rubber are widely used materials in insulation, automotive parts, coating, and sealing rings, gloves, the tyre industry, and rubber flooring [21]. This

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wide range of applications contributes 5–10 % pollution in the ocean, such as abraded rubber tyres. 2.4 kg per capita of tyre wear particles are emitted into the soil, air, and water system and cause serious damage to the environment. Still, according to ISO 472, 2013, elastomer-based materials are not considered plastic, and their related pollution is controversial in the scientific community [22].

Microplastic (MPs) is similar to bulky plastic waste but categorized based on its size of less than 5 mm in any dimension from degraded larger plastic products, either consumer or industrial wastes, which cannot be detected by the unaided eye [23–26]. Human activities like using personal care products and clothes rinsing cause environmental microplastic contamination [27,28]. Such microplastic accumulation in the environment causes threats to living beings by entering the food chain [29,30]. Recent research shows that microplastics emerging from teabags and glitter products act as an emerging source of microplastics [31]. Microplastic waste enters the soil system and blocks the plant's roots [32]. It is estimated that soil holds 4 to 23 times more microplastics than the ocean, and is a severe threat to the terrestrial habitat [33]. Microplastic reaches the water system through anthropogenic activities like tourism, marine industries, and commercial fishing, harming the aquatic ecosystem [34]. Microplastic in the aquatic environment harms fish, reptiles, and vertebrates by ingestion, clogging, and trapping them [35]. Microplastic acts as a potent sorbent that accumulates harmful substances (pesticide DDT, phthalate, PCBs (polychlorinated biphenyls), DDE (dichloro-diphenyl-dichloro-ethylene), and other toxic substances, due to weathering and surface area volume [36,37] and act as a vector for such toxic chemicals and risk the lives of plants, vertebrates, and humans [38,39].

Various methods are used to remove microplastics from the environment, such as filtration, chemical treatment, sorption, ingestion, and biological techniques. These methods are used for certain samples and broad applications, but are not efficient in eliminating microplastics up to the required level. Additionally, some are not environmentally friendly and have high operational costs [40,41]. Biodegradation can be a sound method of microplastic elimination from the environment, in which microbes such as bacteria, algae, fungi, and micro-fauna like insects are used to degrade the microplastic or plastic waste to make it free from plastic, in which microorganisms produce enzymes and degrade the plastic polymers into monomers or smaller molecules [42,43]. The biodegradation of plastic occurs by biofilm formation on a plastic surface and the production of extracellular enzymes to disintegrate plastic into monomers, which are ingested by the microbes for carbon sources

and release water and CO₂ [44]. However, various studies on microbial degradation of plastic waste show positive results, but the degradation percentage is not high enough, and the time duration is also long [42,43]. Novel microbes can be used to degrade synthetic polymers, and plastic-degrading enzymes (Ceres and Demetra) are used to degrade the polyethylene extracted from gut bacteria of *Galleria mellonella* waxworms [45]. New biodegradation methods should be used, such as the pre-treatment of plastic waste. Pre-treatment, such as chemical, UV, plasma, and gamma treatment of plastic, can alter the morphology and properties, and then further pretreated plastic samples subjected to the microbes can ease the biodegradation process [44]. Several studies show promising results in which plastic samples are treated with heat, short UV rays, and chemicals. Then microbes feed on it, and the process of biodegradation, like biofilm formation and microbial enzyme action, increases the biodegradation percentage and reduces the time of the process as depicted in Fig. 1. This review provides a new source of microplastics and a new biodegradation approach to plastic waste.

Source of microplastic

Microplastics are smaller plastic fragments less than 5 mm in size. They came into existence through anthropogenic activity and ended up in the ocean through the river system [46]. Microplastics can be found in fibers, fragments, and spheres ranging from 1 to 5000 µm [47]. Weathering and physical abrasion cause the formation of micro- and nano-plastics. Microplastic is categorized into primary and secondary microplastics [48,49], as depicted in Fig. 2. In contrast, nanoplastics are much smaller plastic fragments <100 nm in dimension; they breach the cell of the living organism and cause problems, and are considered by the scientific community. The washing process of plastic objects and synthetic fibers causes them to break down and produce nanoplastic [50]. Primary microplastics are those produced intentionally in the industry for domestic use, such as toothpaste, facial cleansers, shaving creams, makeup foundation, sunscreens, repellents, blush powder, baby products, and resin pellets [51,52]. Microplastics used in the cosmetic industry are mainly polyolefin particles (74–240 µm), PS balls (<2 mm), and PP and PE particles (<5 µm). They are released into the environment after consumers use them [53]. Around 1000–19,000 microplastic particles per ml were found in the facial scrubs [54]. Plastic pellet losses were reported during plastic products' production and threatened the nearby water system [55,56]. Air blasting technology like boating, aircraft, automobiles, manufacturing, and the telecommunication

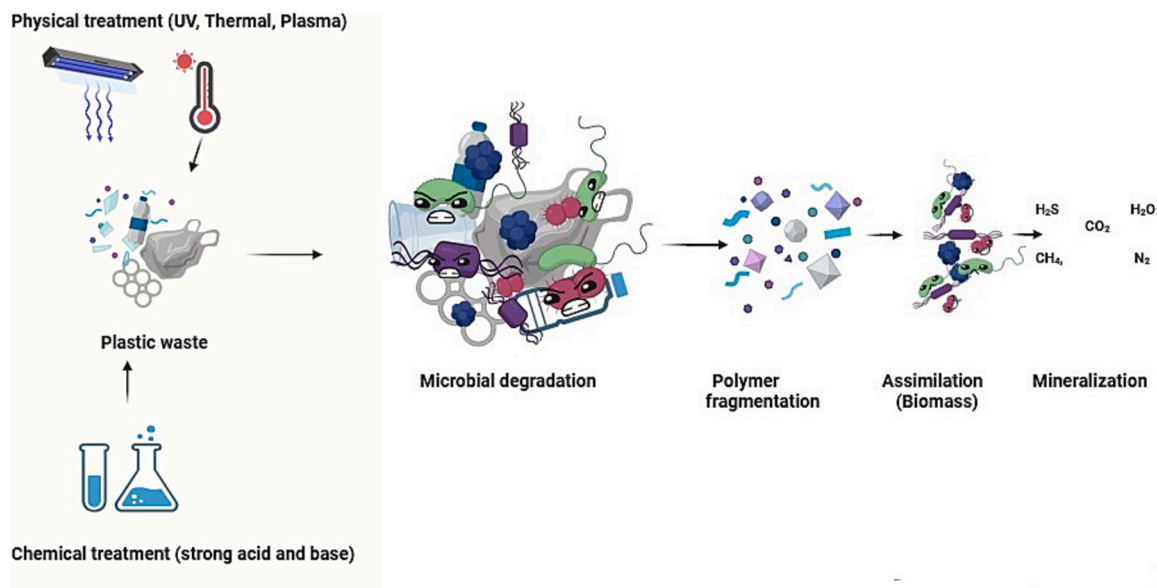


Fig. 1. Pretreatment-based plastic biodegradation

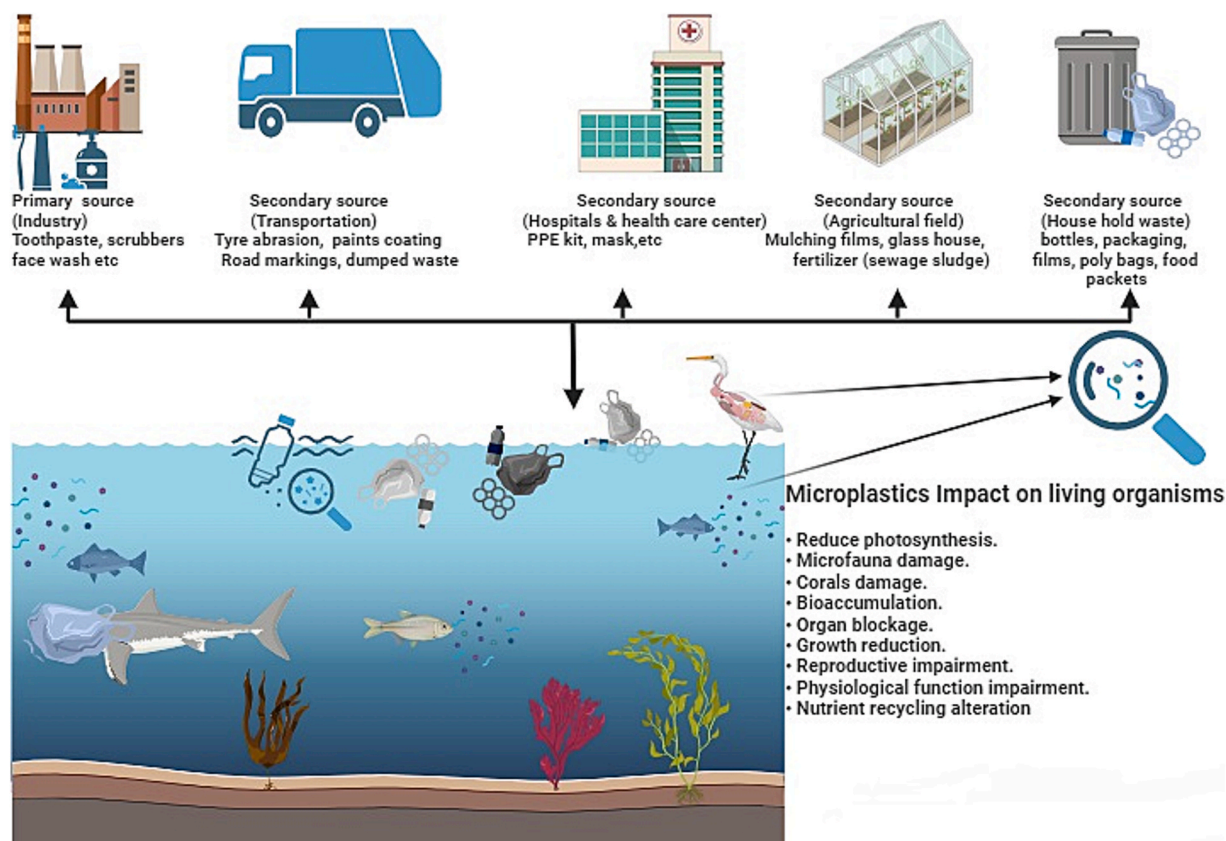


Fig. 2. Microplastic sources and impact.

industry are the popular areas that contribute to the primary source of microplastic pollution while removing color, coating, rust, and other contaminants from the surface of the metal body [48,57]. Which releases untreated wastewater directly into the water system [58].

Secondary microplastics are unintentionally generated from larger plastic waste that is exposed to an environmental factor, causing degradation of the plastic waste. The degradation can be chemical, physical, or biological, changing and reducing the integrity of larger plastic waste [59,60]. Environmental factors like temperature, sunlight, water pH, salinity, and chemical, biological, and physical tension cause environmental cracks in plastic and release smaller fragments [59]. Exposure to sunlight and chemicals of biological origin or other waste causes chemo-photodegradation [23]. The disintegration of plastic into microplastic occurs more frequently on beaches due to the intense UV from the sun, physical abrasion by sand, waves, and wind, and oxygen [59]. Irrespective of the primary or secondary source of microplastic, the ocean holds the world's 92 % of oceanic plastic debris [61]. Around 102,000 microplastic particles per cubic meter are present in the ocean water [62].

Microplastics in the terrestrial environment (Terrestrial-originated microplastic)

Reports estimated that soil holds 4 to 23 times more microplastics than the ocean, and terrestrial-based microplastics are responsible for 80 to 90 % of MP pollution in water bodies and pose a significant threat to the environment [13,63]. Various activities cause microplastic pollution on land, but primarily improper disposal of plastic waste, use of plastic in agriculture, and runoff largely cause the microplastic in soil [33]. Various other sources contribute to the microplastics in soil, like ash from plastic incinerators, plastic packaging material, plastic bottles, and urban runoff [33,63,64]. The textile industry releases microplastics as synthetic, regenerated, and natural fibers during the washing process in

textile sewage; 42 million tonnes of synthetic fiber are released annually. Per liter of effluent holds more than 100 fibers, and >1900 fibers could be generated in a single wash of garments [65]. Rubber tires are classified as plastic and produce 26 to 74 % microplastics. Globally, they contribute to 5 to 10 % of the plastics that reach the ocean. Yearly, per capita tire-based microplastic emissions globally, in India, and the United States, are 0.81 kg, 0.23 kg, and 4.7 kg, respectively [65]. Personal care products such as paste, scrubs, makeup, shampoo, skin creams, shower gel, and soap hold microplastic in the form of microbeads in various shapes and sizes. They are released into domestic sewage and challenge wastewater treatment plants by escaping into it. It is estimated that 0.199 trillion microbeads are unintentionally released yearly [65]. Current agricultural practices like mulching and greenhouse shedding contribute to the micro- to nano-plastics in soil [66]. The packaging and construction industry, landfill sites, and littering contribute to the presence of microplastics in the environment. Alone, landfills hold 21 to 42 % of plastic waste globally, while leachate holds 0.42 to 24,358 particles per liter. Consumer and packaging are the sources of MPs in the water system; 93 % of bottled water shows MPs. Plastic pipes, insulating material, electronic goods, and cladding contribute to the microplastic [65].

Microplastics in the aquatic environment (Aquatic-originated microplastic)

Microplastic in the ocean was first observed in the 1970 s, but did not receive as much consideration in the scientific community. Its continuous accumulation and impact on the ecosystem hikes in the following decades, attracting the interest of researchers [13]. Ocean-based sources are responsible for 10 to 20 % of microplastics in the water environment, which includes commercial fishing, tourism, offshore industries, and marine vessels [67]. 600,000 tons of Fishing nets and gear are dumped in the ocean each year, causing problems to aquatic life, and are responsible for microplastics in the water [68]. The coastal ecosystem of India

holds 258 to 438.8 particles/kg of soil, and surface and groundwater hold 19 particles per liter; in other countries like China, 27.5 particles/L, Malaysia has 0.25 to 0.88 particles/individual, and Spain has 1567 particles/L [69–73]. Globally, 14 million metric tons reach the ocean, and India contributes 8.33 million metric tons annually. Major cities of India, like Mumbai, release 2200 million liters per day in the coastal waters; other cities like Chennai, Kolkata, Gopalpur, and Visakhapatnam are also facing the same situation [74]. More than 80 % of oceanic plastic pollution is associated with land-based sources.

Some emerging sources of microplastics

Other than personal care products, fishing activity, washing, and the clothing industry, various sources act as emerging sources of microplastic pollution. Glitter products are used in other materials like clothes, shoes, toys, cosmetics, and bags. They are smaller <5 mm, easily spill and reach the sewage system by washing them, and are much more dangerous than microbeads. A study of WWTPs in Norway found that 1.7 % of glitter microplastic, with a total microplastic of 6077 particles/kg, and the usage of glitter is continuously growing. The plastic recycling facility unintentionally produces microplastics of PC, PET, PP, and HDPE sizes ranging from 0.212 to 1.18 mm, which are found in the sludge and wastewater of the factory [75]. Tea bags and cups are the sources of microplastic; minor cracks in their structure release around 11.6 billion and 102 million microplastics, respectively [23]. Honey is a source of microplastic; in a study, researchers found that honey bees were entangled in unwoven microfiber wipes and chewed, leading to microfiber plastic in the honey [76]. PPE (personal protective kit) is a new microplastic microfiber source that enters the water and disrupts the aquatic ecosystem [77]. Stormwater is a significant source of microplastics and leads to MP pollution in the surface water. The water gathered the microplastic from tire and road wear particles, road dust, and littering. The average MP in stormwater is 0.38 to 197,000 pieces/L [78]. The research finds new routes of microplastic entering the soil, such as solid waste, sludge used as compost, and runoff of tires, paint, and mulch. Sludge and compost amendment to the soil put 0.016–1.2 kg hm^{-1} microplastics in it by applying 7 t hm^{-1} of sludge. Untreated sewage irrigation pollutes the soil by adding microplastics because such water holds lots of microplastic, which emerges from cloth washing, soaps, toothpaste, and scrubs. In Spain, sewage-irrigated farmland holds 5190 pieces of kg^{-1} [79]. Studies have found that continuous use of plastic film in mulching increases the microplastic concentration, ranging from 80.3 to 346.8 pieces/Kg [80]. Microplastic is found in the air, which is an important concern. Air is dominated by microplastic fibers whose size ranges from 100–300 μm , which can be 366 particles/ m^2/day [46]. Atmospheric microplastic not only pollutes the air but also pollute the water and soil. Published reports show that the suspended air holds 0 to 4.18 pieces per cubic meter (n/m^3) [81]. The outdoor microplastic dust varied from 7 to 431 particles/mg [82]. Such a polluted outdoor environment occurs due to high industrial activity near residential areas and affects urban life. Indoor microplastic concentration dust fall ranges from 0.4 to 59.4 fibers/ m^3 , while settled dust shows 6–184 pieces/mg [82,83]. Activities such as furniture, cleaning habits, and household activities pollute the indoor environment [83]. The atmospheric fallout of microplastics pollutes the area where they land, either in water, soil, or in an outdoor or indoor environment. Research considers the urban and suburban areas, and observation concludes that atmospheric fallout occurs between 2 and 355 pieces/ m^2 / day. The urban area shows higher fallout than the suburban area [84]. Microplastics act as a source and sink of other hazardous pollutants, such as polyaromatic hydrocarbon (PAH), which is attached to the polystyrene that emerges from the firewood and falls in an indoor environment, other micropollutant mono butyl phthalate (MBP), diethyl hexyl phthalate (DEHP), Benzisothiazolone (BIT) and 1,2-dihydro-2,2,4-triethyl quinoline were detected in MPs and dust which settled down in indoor environment which required further research [85]. Such

emerging sources of microplastics are a growing concern for human and environmental health, and more research is needed to win the battle against microplastics and their consequences.

Microplastic nuisance to living beings

As mismanaged plastic is exposed to the environment, it causes plastic pollution and directly increases the microplastic pollution that enters our environment. It acts omnipresent and is found in soil, water (fresh or marine), air, and sediments. It directly or indirectly influences all living organisms and humans by exerting a toxic effect on them.

Nowadays, microplastics are omnipresent, and avoiding exposure to humans is almost impossible. Reports found microplastics in human placentas and feces. Such microplastics enter from various sources, consuming contaminated water, food, and dust particles [86,87]. Reports show that bottled water is the most common source of microplastics that enter the human body [88]. In a simulated perfusion model, researchers demonstrated that the smallest microplastic, 240 nm, can pass the human placenta barrier and enter the bloodstream [62]. The finding of medical studies conducted on rats and humans proves that PVS and PS size <150 μm can move from the intestine to the circulatory system after consumption of contaminated seafood [89]. On average, humans consume 0.1–5 g of microplastic via various routes [90]. The entry of microplastics into the human body can cause disastrous problems like disruption in the immune system, changes in metabolic activity, lung disease, oxidative stress, neurotoxicity, bioaccumulation, reproduction impairment, carcinogenicity, and cytotoxicity [91]. Microplastic significantly impacts the health of living organisms like plants, animals, and microbes, which unintentionally ingest them, whether they belong to terrestrial or aquatic environments. Entry of microplastics into living organisms leads to bioaccumulation through the food chain and reaches all living organisms [92]. Aquatic organisms of various trophic levels easily consume these due to their size differences, reach the human dining table, and threaten their health. The harm that could be seen in aquatic organisms is histopathological and behavioral disturbances, embryotoxicity, neurotoxicity, and hematological and metabolic changes [93]. Several studies have given results about microplastics ingested by marine living beings (mammals, vertebrates, invertebrates, and sea birds) [92,94]. A study confirms that the accumulation of microplastics in different species of aquatic animals is around 8 % in mammals, 10 % in zooplankton, 18 % in mollusks, and 38 % in fish [95]. Microplastics act as carriers of environmental pollutants like heavy metals like chromium that interact with polyethylene, which is uptake by common goby fish, and it reduces the enzyme acetylcholinesterase and causes acute toxicity [96]. Microplastics also affect seabirds when they unintentionally ingest them, causing problems like blockage, damage to the digestive system and multiple organs, and decreased nutrient absorption [97]. In a case study, 10 different species of 110 sea birds were studied, and it was found out 64.54 % of the birds' guts had plastic pieces, the GI tract carried 890 pieces of plastic, of which 35.95 % were pellets, and 65.92 % were plastic users [98].

Not only aquatic life but also terrestrial life is affected by microplastics; organisms like songthrushes and blackbirds typically act as indicators of microplastics. In an investigation, the researchers found that the GI tract contained microplastics, of which 84 % are fibers, and film <1 mm in size constituted 10 % of the objects. Such a report suggests that microplastic also affects terrestrial life [99]. Microplastics alter the physiological condition and behavior of animals; in a study, chickens were taken as test subjects for checking the microplastic effect, and they observed that microplastic exposure reduces the antioxidant ability and growth, interrupts the gut microbiome of chickens, and leads to a reduction in nutrient absorption [100]. A report was published that was done on domesticated pigs to check the presence of microplastics in pigs; the specimens from the lungs were collected and examined, and it found that the average 12 μP piece/g and dead fetal pigs contained 6 μP pieces/g and the size of microplastic varied from 115.14 μm to 1370.40

mm and most common type of plastic is polyamide [101].

Microplastics can alter or impair soil health and nutrients like C, N, and P; in a study, 28 % w/w of PP-microplastic increases SOM concentration and the leaching of soil nutrients like DON, DOS, and DOP. While in low concentrations, 7 %w/w, such changes are not reported [102]. Microplastic interferes with soil enzymes, which manage the nutrient cycle, and such interruption leads to changes in soil enzyme activity, such as reducing the activity of urease, FDAse, and dehydrogenase [103,104]. Microplastics influence the soil microbial community by changing the microenvironment of the soil. Different microplastics influence soil microbes in different ways, such as PVC and PE microplastics, which decrease the diversity and abundance of the microbiome [105]. Microplastics can enhance some specific microbial communities and influence the interaction of microbes and plants [106]. Microplastic enhances the microbial community and induces self-degradation [107]. Soil fauna (Flagellates, amoebae, springtails, ciliates, and earthworms) are essential in maintaining soil quality; they are affected by soil microplastics because they reduce their growth, damage their intestines, cause oxidative stress, induce immune disorders, gene abnormalities, and cause neurotoxicity [108]. Changes in soil properties and nutrient cycle by entering microplastics in agricultural ecosystems lead to changes in greenhouse gas emissions. Studies claim that microplastics decrease the decomposition and mineralization of SO₂ and reduce N₂O and CO₂ liberation [109].

Remediation strategies for microplastics

Microplastics emerged as a persistent contaminant in our environment (air, water, soil). However, it ultimately reaches the aquatic system and causes a severe nuisance by making it into the food chain and accumulating in food [110]. Different management strategies, reduction in sources, scientific research, public awareness, policymakers, and upgradation of technology are required to remove microplastics from the environment [111]. The existing microplastic removal from water systems is a crucial and challenging task; complete removal of microplastics from vast water systems is most likely not possible, but regional remediation practices can reduce the concentration. For example, sediment dredging is one of the techniques used to remove sediments and microplastics from the water system. This can be employed in polluted areas like industrial areas and a marine Harbor [112]. Currently, several techniques are used to eliminate microplastics from water, including physical, chemical, and biological, as listed in Table 1.

Physical method

Adsorption

Adsorption is a physical process in which adsorbents accumulate contaminants on their surface. Like graphene oxide, chitin is a good adsorbent and adsorbs significantly different microplastics [134]. Biochar is also a good adsorbent, porous, and hydrophobic, which can engage with microplastics and adsorb them [135–137]. Different studies use different absorbent materials, like Biochar, which can remove 90 microplastics of 10 µm size, granular activated charcoal, able to remove microplastics of size 1–5 µm, while aluminosilicate modified zeolite is also able to remove microplastics [138]. In a study, the researcher prepared a magnetic polyoxometalate-supported ionic liquid phase that can remove PS microplastics of size 1 to 10 µm and concentration of 1 g/l with 100 % efficiency. In another study, magnetic carbon nanotubes can eliminate the PA, PET, and PE microplastics 5 g/l within 5 h [139]. Several other adsorbents, like cellulose fiber, magnetic sepiolite, magnetic magnesium hydroxide, and polyacrylamide, magnetic nano-ferric oxide, can remove microplastics with the efficacy of 98 %, 90 %, 92 %, >80 %, respectively [138].

Table 1

Different removal methods of microplastics.

Method	Medium	Type of plastic	% of removal	Reference Studies
Filtration	Treated wastewater	MPs	89.7 %	[113]
Filtration	Sea water	MPs	95.5 ± 12 %	[114]
Ultrafiltration	Landfill leachate	MPs	75 %	[115]
Disc filter			40–98.5 %, 95 %, 97 %	[116]
Dissolve air flotation,	Wastewater	MPs		
Rapid sand filter				
Sedimentation	Wastewater	MPs	40.7 %	[117]
Sedimentation	Wastewater	MPs	91.7 %	[118]
Sedimentation	Wastewater	MPs	58.8 ± 8.1 %	[119]
Adsorption	Wastewater and Ultrapure water	PA, PET, and PE	100 %	[120]
Adsorption	Water	PS	100 %	[121]
Film of TiO ₂ nanoparticle	Aqueous phase or solid phase	PE	95.30 % for 700 nm PS, 98.40 % for 400 nm PE	[122]
		PS	100 % PVC in 90 h, 100 % PE in 40 h, 100 % PE in 60 h.	[123]
Atomic layer of Nb ₂ O ₅	Aqueous medium	PVC, PP, PE		
C, N-TiO ₂	Aqueous medium	HDPE	71.77 %	[124]
TiO ₂ /Ag/reduced graphene oxide (rGO)	Aqueous medium	PE	76 %	[125]
Magnetism adsorption by Magnetic CNTs,	—	PET, PE	100 %	[126]
Magnetic adsorption by Fe-HDTMS	—	PS, PET	92 %	
Agglomeration	Distilled water	PE, PP	13.3 to 99.1 % 7.0 to 99.0 %	[127]
Agglomeration	Demineralized water	PVC, PA, PESPP/PE	30.3 to 80.7 % 65.3 to 93.5 % 40.4 to 76.7 % 1.8 to 98.3 %	[128]
Chlorination	Wastewater	MPs	7.7 %	[117]
Coagulation/flocculation	Surface water	PES, PE, PS	99 % 82 % 84 %	[129]
			98.2 % by poly aluminum chloride and 99.4 % by ferric chloride	[130]
Coagulation/flocculation	Wastewater	PS		
Coagulation	Drinking water	PE	Almost 90.9 %	[131]
Biofilter	Wastewater	MPs	79 %	[132]
Active sludge	Wastewater	MPs	16.6 %	[117]
Active ingestion	Aqueous phase	PE	1.5	[133]

Filtration

Membrane filtration is a sound filtration technique that removes microplastics through membrane separation. Such a technique, like membrane bioreactors and dynamic membranes, appeared simple, with low operational cost and energy consumption. Integration of membrane techniques with advanced methods like pervaporation or reverse

osmosis intensifies the efficiency of microplastic removal [111]. Among all the filtration techniques, ultrafiltration is the most promising and cost-effective; in a case study, it can remove 86 % of microplastics from conventional wastewater treatment plants [140]. Other filters like disc filter, rapid sand filter, and Holey $\text{Ti}_3\text{C}_2\text{Tx}$ membrane can remove microplastics with the efficiency of 89.7 %, 75.4 %, and 99.3 %, respectively [138].

Flotation

It is a similar process to flocculation; in flotation, bubbles are introduced to the aqueous media in the mixture, which causes pollutants to attach to the bubbles. It is successfully applied to separate the microplastic from the liquid medium. In an experiment, four mechanisms of bubble efficiency and the difficulty of removing $<100\ \mu\text{m}$ plastic are discussed. (i) The microplastic size and the number of bubbles ascending influence the solution. (ii) The effective calculation of the collided microplastic that is not attached to the bubbles, with inter-particle forces and trajectory confirmed by hydrodynamics. (iii) ratio of collision of bubbles with microplastics and adherence to the bubbles after the collision. (iv) The ratio of detached microplastics from early adhesion is influenced by collision, inertia, gravity, and turbulent conditions [141]. One of the studies claims that adherence to bubbles is better for hydrophobic, virgin plastic than for weathered hydrophilic plastic [142].

Magnetic separation

Extraction and recovery of Microplastic <150 is more complicated and more challenging; techniques like magnetic separation help extract plastic like PE, PS, PU, and PVC, PET from various water matrices like freshwater, seawater, and sediments. This technique involves two basic steps: microplastic pieces hetero-agglomerate with magnetic nano seeds, and finally, the agglomeration is separated through a magnetic field or force. This method has advantages like no size limit for microplastics, fewer pressure drops, and differences in microplastics can be removed. Heavy metal and organic dye removal are also addressed in the literature [143–146]. In a study, an iron nanoparticle is coated with the hydrophobic agent (Hexadecyl tri methoxy silane) and used to extract microplastics, about 92 %, with a size of $20\ \mu\text{m}$ of PE, PS beads. This method removes $200\text{--}1\ \mu\text{m}$ of microplastic from sediments and freshwater with outputs of 84 and 78 % efficiency, respectively [147].

Chemical method

Coagulation and flocculation

Coagulation-flocculation-sedimentation techniques are used to eliminate the microplastic; it is a sound chemical method, most studied for microplastic removal [148]. It mainly involves flocculation and sedimentation, which is referred to as coagulation-flocculation-sedimentation (CFS). In this process, a chemical coagulant is added to the aqueous media, and the coagulant interacts with the pollutants and creates agglomeration and sedimentation [136,141]. In a study, nano plastic settling is 80 % by using calcium-aluminum ion composite as a flocculant; an increase in pH caused the firm to attach the NP to the surface of the aluminum and calcium ions and ease the coagulation process [149]. In another study, sodium alginate, Polyacrylamide (PAM), and activated silicic acid(ASA) were used to remove PET microplastic with PAC, and the findings of the study show that a high dosage of PAM was able to remove 91.45 %; the standard dosage of ASA able to remove 54.70 % of Microplastic [150]. In the electrocoagulation process, the coagulation is assisted with electricity, in which coagulants are continuously generated through electrodes. This process decreases the COD and increases the efficiency. In a study, the researchers examine the correlation between electrocoagulation efficiency and thermoplastic characteristics (PET, PP, LDPE, PA) from primary and secondary sources. Amorphous and hydrophilic microplastics were also found to have the lowest removal efficiency [151]. However, using a different

coagulant like Fe-Al can change the efficiency and remove PA around 96.82 % in 120 min [152].

Advanced oxidation process

This is an integration of several chemical processes that involve producing highly reactive species to disintegrate microplastics. A typical frequently used AOP process is Fenton, a process that involves an iron catalyst and hydrogen peroxide. In this process, highly reactive Hydroxyl radical-OH is produced, which degrades the microplastic [153]. In an experiment under UV light, a TiO_2 photocatalyst was used to disintegrate the polystyrene nanoplastic in water. The process reduces the 23.5 % concentration of nanoplastic pieces [154]. Another study shows that 50 % of polymethylmethacrylate (PMMA) nanobeads are disintegrated under the influence of $112\ \text{W/m}^2$ UV-A with catalyst $\text{TiO}_2\text{-P25}/\beta\text{-SiC}$ foams, flow rate $10\ \text{mL/min}$, in 7 h [155]. To decrease the harmful impact of polymer waste, it can be changed to low molecular weight molecules through photocatalysis. In my experiment, a 30-minute ozonation reaction to polymer caused a decrease of 96.3 % in molecular weight, with 30 % mineralization [156]. A thermal Fenton process is used to mineralize the LDPE, HDPE, PS, PVC, and PP, in which pH varies from 0.7 to 0.3, and the temperature is $25\text{--}160$ degrees Celsius. The output after 4 h, 75.6 % mineralization of microplastic and 95.9 % WL at 1-pH was achieved [157]. Apart from the above-discussed Fenton-AOP, Photo-Fenton, and electro-Fenton are other types of Fenton process that give fair results, but due to the stability of the catalyst in AOP, they hinder the continuous production of free radicals, and microplastic hydrophobicity reduces the activity of generated free radicals [158].

Photocatalysis

This chemical process is one of the effective and eco-friendly remediation methods. ZnO , WO_3 , BiOCl , $\text{g-C}_3\text{N}_4$, and TiO_2 are the typical photocatalysts that can be used against the microplastic degradation presence of light. The principle of this method is to generate electrons and holes under the influence of light by the photocatalyst, and the generated species interact with H_2O , O_2 , and OH to produce active oxygen species, which further react with organic molecules and mineralize them completely and produce H_2O , CO_2 , salt, and mineral acids [158]. In an experiment of photocatalysis, a CBBO- core shell structure $\text{BiO}_2\text{-x}/\text{CuBi}_2\text{O}_4$ p-n heterojunction photocatalyst was created to effectively photodegrade the PS microplastic in 15 days when the plastic is irradiated with the full spectrum of light. Significant changes in chemical and morphological structure are confirmed through FTIR and GC-MS [159]. In another study, PET is degraded by the Fe-doped $\text{BiO}_2\text{-x}/\text{BiOI}$ (FBI) heterojunction Z-scheme under light irradiation for 10 h. The characterization, such as FTIR, shows the presence of increased $-\text{CH}$ stretching, $\text{C}=\text{O}$ group, $-\text{OH}$, and $\text{C}-\text{O}$ group under the degradation process [160]. Not only microplastic, a photo catalyst used to remove the phenolic group organic pollutants such as Bisphenol-A (BPA). In a study, a semiconductor photo catalyst called Cu-doped $\text{BiO}_2\text{-x}$ (CBO) was designed, which uses solar light to eliminate the BPA 2.91 and 2.23 times higher as compared to $\text{BiO}_2\text{-x}$ catalyst [161].

Biological method

Bio-based removal of plastic is an approach to eliminating microplastics with the help of microbes. It is a simple, greener, energy-efficient process, but less effective in degrading synthetic polymers like plastic. In this process, a biofilm is created on the surface of the polymer. It produces extracellular enzymes over the polymer by microbes that disintegrate the larger polymer into smaller monomers, which are further consumed by microbes and release water and CO_2 [43]. Several techniques use bio-based removals, such as Biofilm-based Microplastic remediation, organosilane-based technique, membrane bioreactor (MBR), Bio-flocculation adsorption, and many more [126,136].

Biofilm-mediated microplastic treatment

In this, biofilm is created over the surface of plastic by microbes in an aquatic medium, and the interaction between Microplastic and biofilm introduces changes in physical and chemical properties on the surface of the polymer and causes biodegradation. A study demonstrated that biofilm is produced by *Rhodococcus ruber* on the surface of PE and colonizes it. Subsequently, there is a reduction in the molecular weight of PE by around 14 % to 21 % [162]. Many factors, such as pH, temperature, salinity, and UV radiation, influence the growth of biofilm. The major factor in its occurrence is the time period of microbes that change the properties of microplastics. Biofilm has the potential to degrade the polymer, but the current approach is not enough. Also, biofilm-producing microbes cannot utilize macromolecules or macropolymers directly. In forming biofilm on polymers, various other extracellular enzymes like hydrolase and oxidase convert the larger molecule into smaller chains or monomers, which are utilized by microbes and converted into CO₂ and Water [126]. A study was conducted in which the periphytic biofilm approach was used to biodegrade the microplastic, in which nutrients like glucose and peptones, and their combination, are applied, which act as carbon sources and increase the speed of degradation. They examined the experiment and found that adding glucose increases the biodegradation process of microplastic by a biofilm of periphyton from 5.95–14.02 % PE, 9.52–18.025 % PP, and 13.24–19.72 % PET in 60 days of the experiment as compared to peptone and glucose peptone combination. Weight loss analysis and FTIR, SEM, and GPC analysis confirmed microplastic degradation by observing the microplastic's morphology change. MiSeq sequencing confirms the dominant phyla *Deinococcus-thermus*, *Proteobacteria*, and *Cyanobacteria* in periphytic biofilm [163].

Membrane bioreactor

MBR is an integrated system comprising biocatalysts such as enzymes or bacteria, partitions, and works via a film-based mechanism [136,164]. It is an amalgamated process of physical and biological processes [136]. This technology demonstrates its efficiency in removing 90 % of microplastics from wastewater compared to conventional techniques. Its efficiency is strictly altered by feeding rate, concentration, hydraulic retention period, and physicochemical parameters of pollutants. A bacterium, *Ideonella sakaiensis*, effectively mineralizes the PET into ethyl glycol and terephthalate. The implications of such bacteria and other enzymes in MBR technology can enhance the potential of MBR technology in the future. Certain issues also arose that

limit this technology, such as membrane fouling and limitations in aeration [138].

Bio flocculant adsorption

This method uses bio-decomposable material, bio-flocculant substances produced by microbes that help in the flocculation process. Bioflocculant contains lipids and carbohydrates in its cells. Cellulose and lignin act as bio-flocculants, which show a range of applications and potential in removing microplastics. Bio-flocculants carry negative charged amino acids, which make them bind to metal ions. The bio-flocculant molecular arrangement favors adhesion and cohesion by ion interaction, electrostatic bonding, and London bonding. A study found that blue-green algae produce bio-flocculant that effectively removes microplastics from the waste systems. In an experiment, *Scenedesmus abundans* microalgae removed 84 % of polymethacrylate microplastic [138].

Plastic-degrading organisms

Plastic is of two types: bio-based and fossil-based plastic. Fossil-based plastic is non-biodegradable plastic, while bio-based plastic is further divided into two types: biodegradable and non-biodegradable. Plastics hold different chemical bonds; nylon carries an amide bond (NH-CO), and PET has an ester bond (–COO), while propylene and polyethylene have a carbon backbone (C–C). Monomers of plastic are derived from fossil or petroleum and produce different plastics such as polystyrene, polypropylene, polyethylene, polyethylene terephthalate, polyurethane, polyvinyl chloride, and polyvinyl chloride, and they are all non-biodegradable. They are exposed to physicochemical conditions, leading to larger plastic disintegration into microplastic formation. The microbes use them as food sources to obtain energy and release water and CO₂ [126]. The biodegradation process is achieved by altering the molecular weight, tensile strength, functional group, and other properties [111]. The biodegradation of plastic includes different steps, such as biofilm formation on the surface of the polymer and the release of extracellular enzymes, which break them into poky compounds and are further utilized by microbes and utilized in the cellular processes [44,165] as depicted in Fig. 3. Biodegradation of plastic can be accomplished by fungi, bacteria, insects, enzymes, and algae. Several disadvantages also affect the biodegradation of plastic, such as plastic being hydrophobic, which makes it less available to the microbes and makes it biodegradation-resistant; the time period of biodegradation is

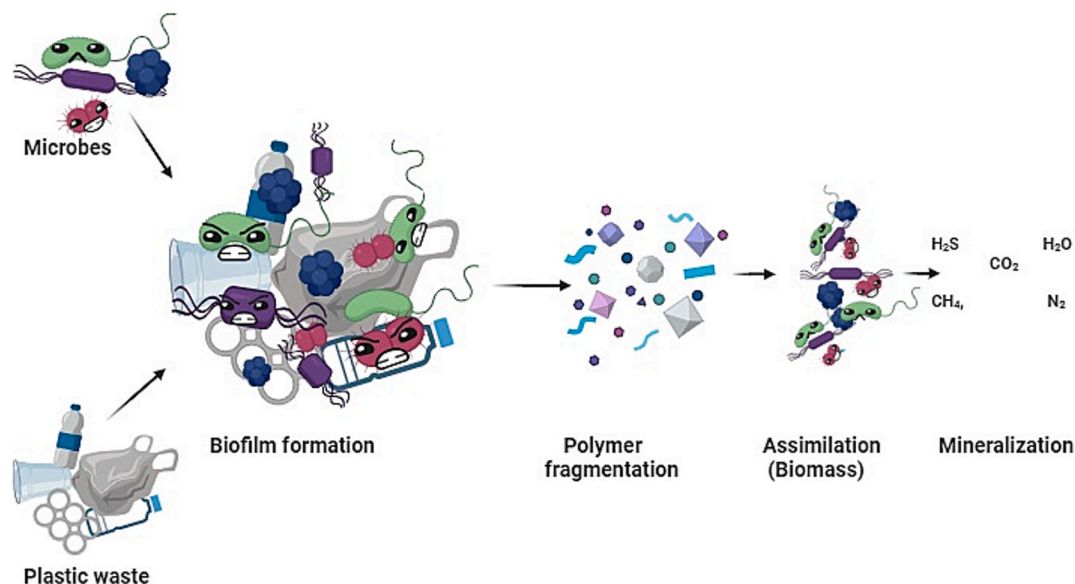


Fig. 3. Biodegradation pathway of microplastic.

long, and some experiments showed that maximum desired results are obtained in lab conditions. So, this way of remediation method is limited in real-world applications [141].

Bacteria

Various bacteria show their plastic degradation ability, like *Pseudomonas* (*P. fluorescens*), *Flavobacterium* (*F. lacus*, and *F. chungnamensis*), *Staphylococcus* (*Staphylococcus epidermis.*), *Bacillus* (*B. coagulans*, *B. neidei*, *B. smithii*, *B. megaterium*), *Enterobacter* (*Enterobacter cloacae*, *Enterobacter* sp., and *Pseudomonas arguina*) [166]. Bacteria can produce various catalytic enzymes and contribute to plastic degradation by adsorption, breakdown, and desorption. They used polymer as a carbon source and altered the integrity of the polymer [111]. Bacteria produce extracellular polysaccharides, create biofilm, colonize it, and degrade it [126]. Single enzymes cannot degrade plastic; multiple enzymes are responsible for the complete degradation of plastic [141]. Enzymes responsible for microplastic degradation are reported, such as protease, laccases, peroxidase, esterase, carboxylesterase, hydrolases, keratinases, lipases, oxidoreductases, and cutinases. In a study, researchers reported that the *Bacillus cereus* strain bio-degrades LDPE 43 % in 120 days [167]. In another experiment, strains of *Pseudomonas* degrade the 20 % HDPE in 120 days. In the biodegradation of PE plastic, the *Bacillus* sp. YP1 bacteria degrade 10.7 % of PE in 60 Days. Lab experiments reported that bacterial consortia are more efficient in the biodegradation of plastic in the symbiotic group of microbes [168]. In an experiment, *Bacillus* sp. strain bacteria colonize and change the microplastic surface structure [168]. A *pseudomonas* strain, *Pseudomonas aeruginosa* (E7), was isolated from oil spill beach soil and was able to degrade PE 40.8 % in 80 days [111].

Fungi

Fungi are eukaryotic, sporulating, non-autotrophic organisms that get their food or nutrients by employing endocytosis and exocytosis; they release enzymes that can degrade the microplastic [169–171]. As fungi hold considerable metabolic abilities, which makes them ideal organisms for degrading plastic, biofilm formed by plastic fragments is a sound source of fungi species that biodegrade plastic. Biofilm provides a different environment from the surroundings and microbes, including fungi, which thrive and are highly active, promote growth, and help in degradation [172]. Fungi show better degradation efficacy than bacteria and actinomycetes. Various strains of *Penicillium*, *Trichoderma*, and *Aspergillus* genera, including *P. frequentan*, *P. chrysogenum*, *P. oxalicum*, *Penicillium pinophilum*, *A. versicolor*, and *Aspergillus niger*, were biodegraded the PE. In a study, consortia of fungi such as *Aspergillus japonicus*, *Fusarium* sp., *Mucor* sp., and *Penicillium* sp. were identified out of 6 different fungal strains to degrade the LDPE polymer all fungi were incubated with LDPE and observed for 4 weeks, among all *Aspergillus japonicus* (36 %) *Fusarium* sp (32 %), and *Aspergillus flavus* (30 %), which reduce the maximum weight of LDPE by 30–36 % [173]. In another study, Fungi were extracted from the gut of the termites and identified as (*Sterigmatomyces halophiles*, *M. guilliermondii*, and *Meyerozyma Caribbean*), these isolated strains are incubated with the LDPE and used as the sole carbon source and found high-growth on the LDPE polymer and reduction in tensile strength around 63.4 % and mass reduction about 33.2 %, it further analyzed and detected production of variety of metabolites such as aldehydes, alkanes, and alcohols, and fatty acids [174].

Algae

Microalgae (phytoplankton) based plastic biodegradation research is scarce and needs more exploration to know their true potential [175,176]. This is a sound candidate due to its characteristics, such as photoautotrophic nutrition, compared to fungi and bacteria that produce endotoxins and are used for various applications [177]. Algae

collect microplastics and fix them using two methods: direct and indirect. In the case of a direct way, the microalgae surface directly adheres to the microplastic, while the nanoplastic is internalized in the cell and transferred to the other tissues. Larger pieces stick to the surface due to the cell walls and epidermis, which makes it hard to penetrate the tissue. The attachment of microplastics to the microalgae is due to the surface roughness of microplastics. Algae collect microplastics indirectly by secreting extracellular polymer substances and creating heterogeneous aggregates. Thus, hetero-aggregation promotes the self-precipitation of microplastics. This hetero-aggregation is repeatable and does not require energy like continuation and filtration, and large-scale applicability is simple [141,169]. Water turbulence disrupts adsorption and hetero-aggregation, a disadvantage of this process [171]. In a study, an LDPE sheet was degraded by algae called *Uronema africanum*. The LDPE sheet was incubated with algae for 30 days, covering the entire sheet and revealing a green, hairy structure on the LDPE sheet. Some analysis was done to determine whether any sign of degradation appeared or not, and it was found that through optical microscopy, some grooves, ridges, and abrasion appeared, which indicates that there is erosion on the LDPE sheet. Chromatography analysis was performed, which showed that there is a difference in the fatty acids of algae treated (Nonane, tetra-cosane, tricosane, octadecane) and the control (lack) LDPE sheet. Such analysis confirmed that *Uronema africanum* degrades the LDPE polymer [178]. In another study, microalgae were used to degrade the LDPE and HDPE, and three different strains of microalgae (*Scenedesmus dimorphus*, *Anabaena spiroides*, and *Navicula pupula*) were used to check the degradation of the polymer. The T.S. of the polymer sheet showed the proliferation of algae on both sides of the polymer and found degradation in the film. *Anabaena spiroides* algae showed a higher rate (8.18 %) of degradation of LDPE, which grows easily and feasibly [175]. In another experiment, the polymer is degraded with the help of algae, in which two different oxidized polymers, oxium and HDPE, are incubated with *D. salina* microalgae with different concentrations of 100, 200, and 300 mg in a 500 mL glass bioreactor for 15 days. The results are analyzed to check the degradation in the polymer. They found a reduction in the alkene functional group and the addition of primary alcohol, ether, and carbonyl. In the case of HPDE, interaction with algae reduces algae growth [179]. As algae-based biodegradation is not as good as other microbial degradation, there is a need for a lot of research to investigate algae-based biodegradation of plastic. (See Table 2.).

Insects

Recent studies believe some plastic PE and PS types can biodegrade more quickly in some invertebrates than in microbes in environmental conditions. Specifically, insects ingest the plastic, and their gut holds microbes and provides an environment that degrades plastic fast. The rate of degradation is based on the exposure time [187]. Larva of the insect *Tenebrio molitor* (mealworm) is a macro-invertebrate that shows its plastic (PVC, PLA, and PS) degradation power. In a study, *Tenebrio molitor* larvae were used to degrade the PVC microplastic (70–150 μ m), the ingestion rate of MP was 36.62 ± 6.79 mg 100 larvae⁻¹ in 16 days, and the larvae fecal had 34.6 % residue of PVC polymer and analysis showed that there is a reduction in weight, size, and size about 33.4 %, 36.4 % 32.8 % respectively, Larvae survived on a PVC diet for 5 weeks, but the life cycle wasn't complete with a survival rate of 39 % [188]. In another study, the same larvae were used to degrade the Styrofoam (PS), in which Styrofoam is fed with a normal diet for 1 month, and then larvae feces were analyzed by gel permeation chromatography, FTIR and found depolymerization and cleavages in the long chain of PS and some other metabolite in larval gut. Within 16 days, 47.7 % of ingested Styrofoam is converted into CO₂, and 49.2 % of the residue is expelled as fecal matter, while 0.5 % is converted into larval biomass. [189]. In another study, *Galleria mellonella* larvae were used to degrade the PE film, in which PE film was put in contact with 100 larvae for 12 h, and within 40 min, some holes appeared in the PE film, which is 2.2 ± 1.2

Table 2
Plastic-degrading organisms.

Technique	Medium	Species	Plastic	Percentage of degradation / Analysis	References
Biodegradation	Aqueous phase	<i>B. gottheilii</i>	PS,	3.0 %	[180]
			PE,	6.2 %	
			PET	5.8 %	
Biodegradation	Sludge	7.3 % in lab 43.7 % in situ	MPs		[181]
Biodegradation	—	<i>Gloeophyllum trabeum</i>	PS	50 %	[111]
Biodegradation by Fungi		<i>Aspergillus</i> sp. (VRKPT2) <i>P</i> <i>Aspergillus</i> sp. (VRKPT1)	PE	8.51 %	
Biodegradation by Fungi		<i>Aspergillus niger</i> , <i>Aspergillus fumigatus</i>	PE PP	6.02 77.1 %	[141]
Biodegradation by Algae	—	<i>Scenedesmus abundans</i> in 6 days	PS	53.1 %	
Biodegradation (biofloculation/heterogeneous aggregation) by Algae	—	After 14 days <i>Cyanothece</i> sp. Microalgae exhibit desired characteristics for flocculation and algae.	PS PLA PMMA	87.0 %, 98.0 %, 84.0 %	[141]
Biodegradation By Insect	—	<i>Tenebrio molitor</i> larvae (mealworms)	PLA PVC PS	85.2 ± 1.2 % 58.2 ± 1.5 % 67.7 ± 1.8 %	[141]
Biodegradation	—	<i>Pseudomonas aeruginosa</i> E7 (80 days)	LDPE	Test of CO ₂ evolution	[182]
Biodegradation	—	<i>Thermobifida alba</i> AHK119 (15 days)	Polyester	Zone of clearance	[183]
Biodegradation	—	<i>Streptomyces</i> sp. (18 days)	PET size 500, 420,300 and 212 µm and also film of PET, incubated with fungi at 28 °C at 120 rpm	49.2 %, 57.4 %, 62.4 %, and 68.8 %, GC-MS, SEM	[184]
Bacterial biodegradation Genetically engineered – Biodegradation	—	<i>Bacillus paralicheniformis</i> G1 (60 days) <i>Clostridium thermocellum</i> (14 days)	Polystyrene film PET Film	NMR, TG-DSC, FT-IR Weight loss, UV and SEM	[185] [186]

holes formed in one hour, a loss of 92 mg mass [190]. Plastic ingestion by macroinvertebrates causes physical damage and inflammatory response that change into nano plastic; for example, Antarctic krill ingest 31.5 µm virgin PE, and the diet of krill is low diet (80 % algae and 20 % PE fragments) and high diet (80 PE fragment and 20 % algae) and then expose to diet for four hours, this action is followed for 20 h in seawater and found that all are ingested. Fecal matter was analyzed, which showed that they reduced the size of PE fragments, which converted into <1 µm nano-plastic [191]. Earthworms cause the fragmentation of microplastic into nanoplastic after being exposed to microplastic. The *Eisenia andrei* earthworm was exposed to PE plastic ranging from 180–212 µm and 250–300 µm for 21 days, and results show that the microplastic converted into nanoplastic 180–364 nm in their gut and also affected the male earthworm reproductive organ, while the female was unaffected [192]. Such micro fauna studies induce new ways to eliminate microplastics from the environment quickly, but the chances of survival of the micro fauna decrease.

Pretreatment strategies to increase biodegradation of plastics

Pretreating the plastic causes modification and makes it more susceptible to microbial degradation [44]. Typically used pretreatments are chemical, thermal, and UV irradiation treatments; application of these techniques causes oxidation in hydrophobic, biodegradation-resistant polymers (LDPE, HDPE, and PP), thus creating a chain in polymer, surface roughness pit, and cracks [193], that is accessible to microbial action as depicted in Fig. 1 [44,194]. Polymers subjected to pretreatment cause more functional groups, such as ester, carboxyl, and carbonyl, which make polymers hydrophilic and increase microbial colonization [193].

Physical treatment

UV treatment

In this treatment method, the plastic sample experienced 225–212 nm range UV radiation. It caused photooxidation, thus forming active species like radicals on the polymer and other groups such as aldehyde, vinyl, and ketones in this process. Observation shows that PP, PE, and PET produce CO₂ and CO; PVC and PS produce yellowness [195,196]. In an experiment, PET, PS, and PE are treated with short UV with a dosage of $(7.02 \times 10^{12} \mu\text{W} \cdot \text{cm}^{-2} \cdot \text{s})$, which causes changes in polymer with hydrophilicity, roughness, surface degradation, viability to microbes, biofilm formation, and reduction in molecular weight. The highest biodegradation is in PE and PS, with 7.8 and 5.13 %, respectively, in 45 days [197]. In another study, plastic waste was exposed to UV treatment for 30 days and incubated with native bacteria for 24 weeks, and it found that there was significant weight loss, 52 % of polyethylene went to degradation when exposed to the peat moss and soil as compared to the garden soil which shows only 40–45 % PE film destroyed while PE film subject to husk shows 48 % to 53 % loss of weight [198]. An experimental study showed the opposite result: PET plastic film was exposed to UV radiation, and the exposure output was increased in the carboxyl group and crystallinity. Pretreated PET has a lower (8 %) biodegradation rate than the controlled study (no UV treatment) [199]. An optimum UV pretreatment parameter, specifically time duration, is required, which influences the photooxidation and biodegradation process [162]. In another study, a consortium of microbes composed of *Pseudomonas* sp, *Penicillium glaucoroseum*, *Penicillium raperi*, and *Aspergillus flavus*, used to degrade UV-pretreated mixed plastic (PS, PE, PET) in the presence of rhamnolipid biosurfactant, in which PS plastic weight loss of about 7.47 % compared to PET and PE in the same conditions. While PET and PE show higher biodegradation under biotreated and UV-pretreated conditions, the presence of rhamnolipid reduces

biodegradability [200]. An experiment is conducted in which LDPE is pretreated under Solar radiation and then fed to *Galleria mellonella*, and then the excreta residue of *Galleria mellonella* is analyzed using different techniques, HNMR, FTIR, GC–MS, and weight loss percentage. The results state that solar-pretreated LDPE holds the higher surface roughness that leads to an increase in the consumption of LDPE by *Galleria mellonella*, and the post-degradation of pretreated and Untreated LDPE is 55.8 % and 18.57 % by weight loss, respectively [201].

Thermal treatment

In this pretreatment method, the plastic sample is subjected to heat in an oven, with temperature ranges from 70 to 150 °Celsius, causing a change in the properties of the polymer, and subsequently fed to the biodegradation process [202,203]. In a study, LDPE polymer is thermally treated at two different temperatures, 105 and 150 °C, and further, they are subjected to a feed consortium of 4 fungal strains for biodegradation for 9 months. Results showed that thermally treated (accelerated aging treatment-AAT) LDPE changes crystallinity and is easily targeted by fungus, and AAT increases the mineralization value by about 3.26 % [202]. In another study, LDPE film was thermally treated at 70 °C for 10 days in the preheated oven, and further, the film was fed to the fungal strain *Rhizopus oryzae* NS5 for 1 month. The film was analyzed to check the changes, and it was found that there was an 8.4 ± 3 % reduction in weight along with a 60 % decrease in tensile strength as compared to the control [203]. In another study, PP film was treated thermally at 100 degrees Celsius for 15 min, producing an uneven surface structure, which was fed to two *Actinomyces* sp. and *Pseudomonas* sp. Further analysis found a change in the morphology of the film and colonization of microbes on it, which indicates the modifications in the polymer [204].

Chemical treatment

In this pretreatment process, plastic samples are exposed to certain kinds of chemicals like acids or other oxidizing agents, which cause oxidation to plastic and increase surface roughness, cracks, and pits, which increase the functional groups [205]. In a study, PP is pretreated with a Fenton, short UV and thermally, which is exposed to microbes such as *Pseudomonas stutzeri*, *Pseudomonas azotoformans*, *Bacillus flexus*, and *Bacillus subtilis* separately for 12 months and found that *B. subtilis* and *P. azotoformans* produce high biosurfactant and biofilm on HDPE while short UV treated HDPE exposed with *B. flexus* increase the growth and density of organisms is higher than that of the control and degraded the 0.05 mm thick polypropylene film with 2.5 % weight loss [206]. In another study, HDPE was pretreated abiotically with 1 % manganese stearate prooxidant for 2 days and further exposed to 312 nm UV for 50 h and then subjected to *Aspergillus oryzae*, *Aspergillus flavus*, and *Aspergillus niger* microbe. The results show that the abiotically treated HDPE polymer has more significant changes, better microbe density, and *A. oryzae* has a higher biodegradation rate of about 72 % as compared to other strains, which is confirmed by FTIR analysis as a reduction in the carbonyl group of the polymer by *A. oryzae* [207]. In a study, HDPE was pretreated by UV for 60 h, thermal 50 degrees Celsius, and then (citric acid and KMnO_4/HCL) chemical treatment; the result shows a reduction in weight of about (9.4 ± 0.1) % by MF-12 (*A. terreus*) and surface modification than discrete pretreatment [208]. In this chemical pretreatment biodegradation, PET and PLA plastic are pretreated with Deep eutectic solvent, which is a mixture of glycerol and choline chloride, and then fed to the microbial consortium, which consists of *Nocardioidean zeae* EA12, *Chitinophaga Jiangningensis* EA02, *Gordonia desulfuricans* EA36, *Stenotrophomonas pavanii* EA33, *Mycolicibacterium parafortuitum* J101, and *Achromobacter xylosohdans* AP. The DES solvent increases the surface wettability and biofilm presence. This change states that DES raises the hydrophilicity of plastic, which increases degradation by making the plastic available to the microbes [209]. Such multiple pretreatments may not be possible on a large scale due to a lack of cost compatibility.

Other pretreatment methods

Several new pretreatment methods have been explored to increase the plastic biodegradation process, which has been explored less. Applying gamma rays (ionizing radiation) excites and ionizes the plastic to produce intermediate reactive species and causes modification in the plastic structure, inducing crosslinking and producing degraded products like the carbonyl group, carbon monoxide, and water vapor, loss of mechanical properties [210]. In a study of gamma radiation effect on the PP and LDPE films biodegradation with the help of *Lasiodiplodia theobromae*, in which PP and LDPE are irradiated with doses of 0–100 kGy and 0–1000 kGy, respectively, and incubated for 90 days, respectively. the result states a high weight loss of 0.3 mg from PP film with a large number of the carbonyl groups of the polymer compared to the control sample [211]. Plasma pretreatment of polymer causes structure modification and makes more functional groups available [212,213]. Polymer surfaces treated with plasma increase the radicals, roughness, and hydrophilicity. In a study, an LDPE sheet is treated with oxygen plasma for 6 min at 600 V, which reduces the 76.57 % contact angle of the surface, indicating hydrophilicity, increases the 99.81 % surface roughness, and increases fungi colonization by 88.72 % as compared to the untreated sample [214]. In an experiment, LDPE is pretreated with low plasma temperature in atmospheric conditions and inoculated with LDPE-degrading bacteria *Pseudomonas putida*. The plasma-treated LDPE biodegraded by 80 %, while the controlled LDPE biodegraded by about 50 %. Plasma treatment caused the oxidation of LDPE and induced more $-\text{C}-\text{O}-$ than $-\text{C}=\text{O}-$ bonds, and the degradation efficiency increased by 13–25.5 %. [215]. In another study, LDPE plastic film was used to degrade by bacteria consortium, in which LDPE is treated with UV and further subjected to the bacterial consortia composed of actinobacteria and proteobacteria, which degrade the film and measure through weight loss around 2.22–17 % in 120 days, while thermal and sunlight treated film only reduce 1.42–3.22 % and 1.67–4.57 wt respectively, whereas untreated Film only reduces 1.32–2.80 % weight [216].

Conclusion and future perspective

Resource consumption increases day by day as the human population grows, which ultimately creates huge stresses on the environment and natural resources; plastics are mostly made up of fossil fuels, which are cheap, durable, and readily available. Lacking sustainable plastic disposal and management causes it to be found in sediments, water, air, soil, glaciers, and the environment. It creates man-made harmful consequences for humans and environmental disasters like plastic pollution. That affects the entire ecosystem by affecting both living and nonliving things. Recently, several countries worldwide have implemented policies to curb plastic pollution and related problems; the Indian government has banned single-use plastic items and regulates the usage of plastic products, which affects the environment the most. Several techniques, such as magnetic separation, flotation, bioflocculation, and adsorption, are used to treat microplastics in water, which gives good results. Plastic pretreatment and further biodegradation of pretreated plastic give new hope to increase the biodegradation of plastic. Integrated treatment, such as chemical, biological, and physical-biological, discussed in pretreatment strategies, in which plastics are pretreated with UV, gamma rays, heat treatment, acid, and base treatment, damages the plastic structure and integrity that makes it vulnerable to microbial biodegradation. This advanced biodegradation approach, a synergetic method, disintegrates plastic efficiently without affecting the environment and gives direction for plastic biodegradation, and can possibly be applied in the real world. Apart from this, there is an alternate material that should be used, like bioplastic, which easily dissolves in nature. Bioplastic is not cost-competitive, which makes it less available in the market. There is a need for plastic transformation, which makes plastic less biodegradation resistant by adding less harsh chemicals and the addition of biodegradable substances in plastic,

making it prone to microbial action and dissolving it easily, so our environment becomes safer. This study aims to provide knowledge that conventional plastic remediation methods are not optimal and need a new, synergetic method of treatment for plastic that gives hope for a safer and ecologically sound way to eliminate plastic pollution from the environment.

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No data was used for the reason described in the article.

CRediT authorship contribution statement

Ashish Solanki: Writing – original draft, Visualization, Validation. **Vibhuti Sharma:** Writing – review & editing, Validation, Conceptualization. **Praveen Sharma:** Writing – review & editing, Supervision, Resources, Conceptualization. **Dushyant Kumar:** Writing – review & editing, Supervision, Resources, Conceptualization.

Declaration of competing interest

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

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