Asian Journal of Chemistry; Vol. 35, No. 2 (2023), 289-300

ASIAN JOURNAL OF CHEMISTRY

https://doi.org/10.14233/ajchem.2023.26928

REVIEW

Microbial Approaches for the Plastic Bioremediation and Ecofriendly Environmental Sustainability

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Received: 9 November 2022; *Accepted*: 12 December 2022; *Published online*: 30 January 2023; AJC-21108

The world's first "infinite" plastic waste is a major issue existing in both developed and developing countries. Synthetic plastics are correlated to the current lifestyle in packing of food, detergents, cosmetics, plastic bottles, sanitary wares, household utensils, artificial leather and pharmaceutical products. These synthetic plastics include polyurethane, polystyrene, polypropylene, low-density polyethylene, polyvinyl chloride, high-density polyethylene and polyethylene terephthalate in the descending order of recycling codes. Extensive use of these synthetic polymer materials paves way for accumulation in the ecosystem. Improper handling of this plastic wastes by traditional disposal methods like landfill and incineration in open fields leads to the release of toxic chemicals in the environment. The recent advancement in the degradation of synthetic plastics is concentrated on the use of microorganisms and their enzymes as biological treatment. The interaction between microbes and the plastic polymer is needed to understand for quenching the thirst for microbial bioremediation approach to overcome plastic pollution. However, knowledge of scientific evidence for plastic degradation by microbes is paucity. This review highlighted insight gist about the effective microbial technology applied in bioremediation techniques like *in situ* and *ex situ* strategies. Further exploration of the vast diversity of plastic-eating microorganisms and their enzymes involved in the mechanism results in a valuable end product. This literature represents the green route to the bio-recycling of harmful plastic material from the ecosystem.

Keywords: Microbial bioremediation, Plastic pollution, Ecofriendly, Biological treatment.

INTRODUCTION

The 1950s mark the beginning of the era of commercial production of plastics. Plastic is a key source of increasing the economy in major fields like health, construction, agriculture and consumer goods [1] (Table-1). From the long chain of petroleum and hydrocarbon derivatives, the organic synthetic polymer is synthesized. The synthesized polymers are called plastics. The rigidity of plastic is obtained by the mixture of both natural and synthetically produced polymers. In the packaging sector, the ideal characteristics of plastics is shape, mechanical tensile strength and low cost. Its extensive application in various sector led to increase in production and distribution. To meet the demand for plastic increase in a large quantity of production and peak level in the generation of plastic waste. Plastic waste is a major issue in this present 21st century, which leads to environmental pollution, due to long-lasting accumulation in the environment. Over 10 years ago, increased use of plastic led to the accumulation of plastic waste which is being landfilled, incinerated or disposed into the atmosphere. The Organization for Economic Co-operation and Development report says that only 9% of plastic waste is recycled [2]. Plastic waste generation in India has increased twice in the last decade with an annual increase of 21.8% in 2021. The Center for Science and Environment declared a report on the heading of "State of India's Environment 2022" which announces that humans produce 689.8 tons of plastic waste per day. Central Pollution control board also confirms that 25,940 tons of plastic waste are generated in Delhi and Chennai. The exacerbation effect of greenhouse gas emissions has increased due to the distribution and production of plastic waste presently. If this current status reveals at the end of 2050 total greenhouse gas emission of carbon content will reach a peak of 15% [3]. National Academy of Sciences (NAS) reports stated that accurately 4.5×10^4 metric tons of polythene waste were released into the sea annually. Bioremediation is a utilization of microorganism to degrade

TABLE-1
REPRESENTS THE DIFFERENT TYPES OF SYNTHETIC PLASTICS [Ref. 1]

Synthetic plastics	Abbreviation	Structure	Key ingredients	Reaction	Melting temperature	Glass transition temperature	Crystallinity	Recycling codes	Uses
Polyethylene terephthalate	PET	$(C_{10}H_8O_4)_n$	Terephthalic acid and ethylene glycol	Polymerization	260	80	40-60	1 PET	Textile fibers, bottles, containers
High-density polyethylene	HDPE	$(C_2H_4)_n$	Ethylene, benzene	Polymerization	200-300	-120	80-90	2 HDPE	Plastic bottles, cutting boards, recycle bin
Polyvinyl Chloride	PVC	$(H_2C–CHCl)_n$	Chlorine, ethylene	Electrolysis, polymerization	100-260	60-70	–	3 PVC	Piping, cable insulation
Low-density polyethylene	LDPE	$(C_2H_4)_n$	Ethylene gas	Chain-growth polymerization.	160-260	-120	45-65	4 LDPE	Single use covers, agricultural mulches.
Polypropylene	PP	$(C_3H_6)_n$	Propene, ethylene, and hydrogen	Metallocene catalyst, chain-growth polymerization.	130	63-112	–	5 PP	Tote bags, twine, tape, ropes
Polystyrene	PS	$(C_8H_8)_n$	Ethylene, benzene, benzoyl peroxide	Suspension polymerization	240	63-112	60-70	6 PS	Disposable cups, plates, dishwares, package material for foods.
Polyester polyurethane	Polyester PUR	$C_3H_7NO_2$	Toluene diisocyanates, polyols, hydroxybenzotriazole	Polymerization	-95 (soft) 100 (hard)	-10 to 45 (soft) 190-205 (hard)	40-50	7 OTHER	Printer rollers, ticket dispensing roller.
Polyether polyurethane	Polyether PUR	$C_{17}H_{16}N_2O_4$	Toluene diisocyanates, polyols, hydroxybenzotriazole	Polymerization	8-20 (soft)	-75 to -50 (soft) 185-205 (hard)	40-50	7 OTHER	Materials used in adhesive applicant and sealant.

toxic chemical substance present in the ecosystem. To get the better bioremediation, potential microorganism is optimized to stimulate the degradation process [4]. The advantages of bioremediation [5] has been used in multiple application in the cleanup of the oil spill [6], groundwater, lagoons, process waste stream and sludges [5] contaminated plastic pollutants either by *in situ* or *ex situ* techniques. In *in situ* techniques involve the remediation of the contaminated site directly *e.g.* cleanup of the oil spill. *Ex situ* techniques involve the collection of pollutants from contaminated sites and degradation takes place in the optimized chamber in the laboratory [5] *e.g.* treatment of PET bottle waste, *etc*.

Microbial and enzymatic bioremediation is the potential biological treatment tool for degrading plastic waste. Naturally microorganism have a capability to utilize the petrochemical as their energy and carbon source, thereby they help to minimize jeopardy of plastic waste and balance the change in climate and environment. The naturally plastic eating microorganism can be bioengineered to enhance its potential. Microorganisms degrade the plastic material by the following mechanism of biodeterioration, bio-fragmentation, mineralization and assimilation. The biodeterioration and bio-fragmentation can be done by physical and chemical treatment for stimulation microorganism to degrade completely. Mineralization and assimilation are done by biological treatment using potential plastic eating microorganism in optimized condition to give the end product of carbon dioxide, water or methane. The green environmental sustainability depends on the microorganism because they have capability to degrade plastic pollutant in air, land and water. Kenny *et al.* [7] reported the optimized factors for the plastic eating microorganism are (i) they should alive in pollutant area till its completion of degradation; (ii) combination of different microorganism can be used for the successful degradation; and (iii) pollutant and enzyme produced by microorganisms should adhere to each other for effective cleavage of the petrochemical polymer. An optimized condition is needed for the microorganism for its reproduction, which is applied for bioremediation. The long chain of hydrocarbon and petrochemical derivatives are disintegrated into various oligomers, which is further mineralized into water, methane or water and carbon dioxide [8-11].

The main drawback of plastic is that posses long chain polymers, which cannot be easily degraded by the environment and remain in the ecosystem as deposits leads to environmental pollution. The environmental deposited plastic wastes lead to chemical pollution in various ways. The compounds present in the plastics are chemically transferred to the living organisms during their ingestion process for degradation. Some molecules present in the plastic debris are toxic and get deposits in the living body. Soil pollution caused by hydrocarbons like petroleum products is the major problem world is facing nowadays. The soil is also highly contaminated by oil which leads to losing the soil properties like prolificacy, water-absorption capacity, porosity and binding capacity [12]. Accumulation of plastic in agricultural fields will affect the crops growth and crops yields by inhibiting the photosynthesis and causing severe issue as soil pollution. The solution for soil pollution in recent years is the development of technologies to treat contaminated soils and microbial bioremediation based on their metabolic activities [13]. In plastic degradation, the microbes play a major role in the mechanism of microbial conversion of organic compounds as byproducts by the sole source plastic. This review explains the vast phylum of microbes and its enzyme associated with microbial bioremediation. Further, the mechanism and acceleration of microbial degradation by its valuable end product were also discussed.

Bioremediation strategies: Bioremediation strategies help in remediation of the contaminated site of location. The different bioremediation technique helps in depending on the site's saturation degree and the unwanted compound can be eliminated. The bioremediation of contaminated sites depends on the soil conditions like biotic and abiotic materials, porosity, water tables and outpouring characteristics are seen to evaluate whether the contaminated material needs to eliminate by either *in situ* nor *ex situ* method. There are three major applications of bioprocesses strategies:

In situ bioremediation techniques

Bioventing: This method is one of the common bioremediation approaches, which involve the drilling holes in the surface of soil. After drilling holes they pass air intrusion and aeration, which supports the growth of microbes and starts a degradation reaction. This bioventing method can be used for the application of bioremediation of soil and water table problems by the release of oxygen and nutrients at a controlled venting rate.

Biosparging: This method is also one of the *in situ* bioremediation approaches in which high pressure air is injected into the soil of ground water table. This stimulates microbial action for the degradation by enhancement of oxygen level concentration and biological artificially supply of air. This approach is effective and low cost when compared to gouging and tilling contaminated soil or pumping the water and filter tanks, which is costly and high usage of manpower.

Bioaugmentation: This biological method is applied for decontaminating soil and water. In this method, inoculation of effective microbial strain into contaminated site soil, which is responsible for biodegradation. Bioaugmentation is done with a combination of bioventing and biosparging. This combinational method effectively works for the bioremediation of the contaminated site.

Genetically engineered microbial community: Recent advancement in synthetic biology leads to the synthesis of genetically modified microorganism, which is used for the bioremediation of xenobiotics and plastic wastes. The genetic engineering in the microbial consortia [14] has been reported by altering the environmental ambience, *i.e.* mutation of a specific gene, knocking gene out to enhance the bioremediation [15]. Other than altering the ecosystem setting another method followed by studying interaction patterns of engineered microbial species in the synthetic community have been analyzed. This GMO bioremediation strategy is highly recommendable [16] for a safe environment.

***Ex situ* bioremediation techniques:** In *ex situ* bioremediation is carried out by treatment of plastic waste in its geographical location of polluted site.

- Biopile is a solid phase treatment used for the removal of the environmental pollutants into usable byproducts in controlled pH, temperature and moisture. It is mixed with certain agro wastes, saw dust, hay with microbial inoculation and used for the landfarming or composting.
- Bioreactor is a slurry phase treatment used for bioremediation of plastic, which is carried out in the closed vessel of biological reaction. Bioreactor based bioremediation is carried out in the controlled condition pH, temperature, agitation, aeration to enhance bioremediation more effectively with minimum loss of abiotic factor.

Microbial biodegradation: Microorganisms and its extracellular enzymes play important part in the plastic bioremediation of certain types of plastics based on polymer structure. The plastic polymer chemical bond is broken into monomers by the microbial enzyme degradation [6]. The microorganism which has the ability to degrade the polythene film will get colonize on its surface forming a biofilm [17]. After colonization on its polythene film, microorganism consumes it as of carbon nutrient supplement [18]. Starting stage of the degradation is microorganisms utilize the polythene as sole carbon and energy source [2]. Various types of the natural and synthetic plastics are degraded by the microorganism like bacteria and fungi [19] as the polymer substance are potential source for reproduce and survival of selected microbes [20]. After the degradation gets over the end byproducts released by the microorganism is utilization of polyethylene. After the byproducts has utilized, mineralization is carried out to get the CO_2, H_2O (aerobic) and CH_4 (anaerobic) [21] as end product [22]. The microbial degradation of the synthetic polymers is not 100% possible as low level of polymers are combined with biomass and natural products [23]. The degradation of polymer is determined by the bond scission, structural and chemical transformations and adding new functional group formation [24]. In bacteria taxonomy, *Pseudomonas* species have highly potential in degradation of plastic material. The percentage of degradation is 20.54% of polythene and 8.16% of plastics whereas *Aspergillus glaucus* degraded 28.80% of polythene and 7.26% of plastics in one-month [25]. Microbial bioremediation of polyethylene plastic wastes is quite emerging idea of research work nowadays [26] (Table-2).

Sources of the microbial isolates: Microorganism has the ability to hydrolyze polyethylene (PE), which are generally

TABLE-2
REPRESENT THE MICROORGANISM CAPABLE TO DEGRADE DIFFERENT TYPES OF SYNTHETIC PLASTICS

Phylum	Plastic under examination	Organism	Ref
Bacteria	Polyethylene	*Pseudomonas putida* IRN22, *Micrococcus luteus* IRN20, *Acinetobacter pittii* IRN19	[27]
		Bacillus siamensis, *B. cereus*	[28]
		B. siamensis	[29]
		Pseudomonas, *Bacillus*	[30]
	Polyethylene terephthalate	*Ideonella sakaiensis*	[31]
		Rhizopus sp., *Pseudomonas* sp., *Pigmentiphaga* sp. and *Mycobacterium* sp.	[32]
	Polyvinyl chloride	*Spodoptera frugiperda* intestinal degrading strain *Klebsiella*	[33]
		Bacillus flexus and *Pseudomonas citronellolis*	[34]
	Polypropylene	*Lysinibacillus* sp.	[35]
		Staphylococcus sp	[36]
		Pseudomonas sp. ADL15	[37]
		Sporosarcina globispora, *Bacillus cereus*	[38]
	Polystyrene	*Acinetobacter johnsonii* JNU01 and *Pseudomonas lini* JNU01	[39]
		Snail- Achatina fulica	[40]
		Larvae- Galleria mellonella	[41]
		Larvae- Zophobas atratus, *Tenebrio molitor*, *Galleria mellonella*	[42]
	Polyurethane	*Pseudomonas capeferrum*	[43]
Fungi	Polyethylene	*Penicillium oxalicum* NS4 and *Penicillium chrysogenum* NS10 (KU559907)	[44]
		Aspergillus niger, *Aspergillus oryzae* and *Aspergillus flavus*	[45]
		Pleurotus ostreatus PLO6	[46]
		Arthrographis kalrae, *Candida rugosa*, *Lichtheimia sp.*, *Fusarium solanifrom*, *Acremonium flavum*, *Aspergillus fumigatus*, *Emericella nidulans*, *Aspergillus sp.* and *Aspergillus terreus*	[47]
		Aspergillus flavus, *Aspergillus oryzae*, *Rhizopus arrhizus*	[28]
	Polyethylene terephthalate	*C. antarctica*, *Penicillium citrinum* and *Aspergillus oryzae*	[47]
	Polyvinyl chloride	*Mucor* sp., *Penicillium expansum*	[48]
	Polypropylene	*Aspergillus fumigatus*	[36]
		Coriolus versicolor	[49]
	Polystyrene	*Geomyces*, *Mortierella*	[49]
	Polyurethane	*Penicillium griseofulvum*, *Xepiculopsis graminea*, *Cladosporium cladosporioides* and *Leptosphaeria sp. Agaricus bisporus*, wood saprotrophs *Phanerochaete sanguinea*, *Fomitopsis pinicola* tree pathogens *Heterobasidion parviporum* and ectomycorrhizal fungi *Suillus granulatus*	[50]
		Pestalotiopsis microspora	[51]
Actinomycetes	Polyethylene	*Streptomyces species*, *Pseudonocardia*, *Actinoplanes*, *Sporichthya*, *Streptomyces badicus* 252, *Streptomyces setoni* 75	[52]
		Rhodococcus ruber	[53]
	Polypropylene	*Rhodococcus* sp. ADL36	[37]

found around terrestrial or marine soil, ocean water, compost and activated sludge of waste treatment [54]. Even plastic-degrading microorganisms can be isolated from the gut of wax worm, *Galleria mellonella* has been found to have the ability to cleave polyethylene as reported by Yang *et al*. [55].

Bacterial biodegradation: Bacterial isolates like *Bacillus* spp. [56], *Rhodococcus* spp. [57] and *Pseudomonas* spp. [58] and fungi like *Aspergillus* and *Fusarium* [59,60], degrade polyethylene after the effective pretreatment of ultraviolet (UV) and heat treatment cleave the carbon atom chains of plastic and make sensitive and stimulate the microbial degradation [27]. *Pseudomonas putida* IRN22, *Micrococcus luteus* IRN20, *Acinetobacter pittii* IRN19 [27] and bacterial isolates from the genus *Delftia*, *Stenotrophomonas* and *Comamonas* [61] are used for the degradation of plastic material even without the pretreatment. *Pseudomonas, Klebsiella*, *Flavobacterium, Comamonas*, *Escherichia*, *Mycobacterium*, *Azotobacter*, *Alcaligenes*, *etc.* are the most common bacteria which participate in biodegradation of polymeric materials [62]. Similarly, some of the fungi for plastic degradation are *Aerobasidium*, *Candida*, *Chaetomium*, *Cladosporium*, *Ganoderma*, *Geotrichum*, *Phlebia*, *Paecilomyces*, *Penicillium*, *Phanerochaete*, *Sporotrichum*, *Thermoascus*, *Trametes*, *Thielavia*, *Talaromyces*, *etc.* [63]. *Sphinobacterium* sp., *Bacillus* sp. STR-YO and *Xanthomonas* sp. Bacterial strains isolated from the soil are effective for the degradation of polyethylene plastics [64]. The genetically modified soil bacteria *Pseudomonas putida* used as a bio-catalysts for mixture of different types of plastics.

Microorganisms degrade the monomer of PET and HDPE into polyhydroxyalkanoates in the cell membrane. Polyhydroxy-alkanoates are biodegradable compound used for the production of biodegradable bag. Awasthi *et al*. [65] reported that *Klebsiella pneumoniae* can degrade the thermal treated HDPE. The organism gets attached to the polymer surface forming biofilm with reduction in tensile strength and weight within 60 days by 60% and 18.4%.

Fungal biodegradation: Fungi can deteriorate chemical plastic substance *e.g.* persistent organic pollutants (POPs) [66], polycyclic aromatic hydrocarbons (PAHs) [67], benzene, toluene, ethyl benzene and xylenes (BTEX compounds) [68] and pest control substances [69] as they have a most compromising organism. Recent reports explain about fungi which have a vast range of enzymes and metabolic functions. The enzymes from fungi have capacity to decompose multiplex plastic compounds in the ecosystem that have prospect metabolic trait [70]. Further fungi isolated from plastic disposal area like *Penicillium chrysogenum* NS10 (KU559907) and *Penicillium oxalicum* NS4 (KU559906) has an ability to degrade LDPE and HDPE films by mineralization of polyethylene compound. Mixed inoculums of fungi like *Aspergillus flavus*, *Aspergillus oryzae* and *Aspergillus niger* organisms effectively degrade the low density polyethylene [45]. By understanding the role of fungi in degradation, *Pleurotus ostreatus* PLO6 is used for the degradation of the pretreated polyethylene with abiotic (different ranges of UV rays) and biotic processes (different concentrations of synthetic chemicals) [46]. Also, microfungi like *Trichoderma viride* and *Aspergillus nomiusis* have the effective role for degrading the plastic materials [71]. Polyurethanes can also be degraded by *Penicillium griseofulvum*, *Xepiculopsis graminea*, *Cladosporium cladosporioides* and *Leptosphaeria* sp., *Agaricus bisporus,* wood saprotrophs *Phanerochaete sanguinea*, *Fomitopsis pinicola* tree pathogens *Heterobasidion parviporum* and ectomycorrhizal fungi *Suillus granulatus* [50]. *Pestalotiopsis microspora* has effective degradation of polyurethane under an anaerobic process by utilizing polymer as the sole carbohydrate source [51].

A high esterase effect is identified from *Monascus ruber* and *Monascus sanguineus* [72], which helps to degrade the plastic material. Zahra *et al.* [73] identified that fungal strains of *Candida rugosa, Lichtheimia sp.*, *Arthrographis kalrae*, *Acremonium flavum*, *Emericella nidulans*, *Aspergillus* sp., *Fusarium solanifrom*, *Aspergillus fumigatus* and *Aspergillus terreus* isolated from the plastic contaminated landfill, which contain high affinity in the attachment and disintegrated on polyethylene. The fungi have reported that it has the potential to decompose plastic debris like high- and low-density polyethylene plastic material but still in need to explore novel strains or genetic manipulation to enhance the speed of degradation. Ojha *et al.* [74] that *P. oxalicum* NS4 (KU559906) and *P. chrysogenum* NS10 (KU559907) effectively degrade LDPE and HDPE. The potential of fungal strains is increased by optimizing growth media by response surface methodology to increase the mycelium weight.

Actinomycetes biodegradation: Actinomycetes and Actinobacteria dominate the microbial flora in the soil ecosystem, which plays a vital role in dead organic matter. *Streptomyces* sp., *Pseudonocardia*, *Actinoplanes*, *Sporichthya* are used in the plastic degradation and can be used for the production of novel antibiotics. Actinobacteria like *Streptomyces badicus* 252 and *Streptomyces setonii* 75 strains are also effective for the plastic degradation with the agitated submerged culture [52]. Due to its strong hydrophobicity, *Rhodococcus ruber* can build a substantial biofilm quorum sensing on the surface of polyethylene plastic films. This biofilm forming helps the organism to consume plastic particle as carbon and energy sources [53]. When plastic materials degrade, they emit carbon dioxide and water, which contribute to the degradation process.

Microbial consortia: For the environmental and agricultural pollutants, the bioremediation is done by the axenic microbial inoculums but the use of different microbial symbiotic consortia has more favourable than pure cultures. The enrichment cultures of various specific consortia help in bioremediation. The microbial consortium was more effective in the bioremediation than individual pure isolates. Studies have notified that effective bacterial mixed inoculum formulation by the combination of various bacteria such as *Pseudomonas putida*, *Bacillus cereus*, *Pseudomonas otitidis*, *Pseudomonas aeruginosa*, *Microbacterium* spp., *Bacillus aerius*, *Bacterium* Te68R and *Acanthopleurobacter pedis* showed bioremediation of single use plastic materials [75,76]. Mixed microbial inoculum consists actinomycetes and fungi give better results for plastic and its polymer degradation [77].

Mechanism of microbial biodegradation: Microbial biodegradation is a process of degradation of different types of polyethylene polymers with the involvement of microbial activity. The four major steps *viz.* biodeterioration, depolymerization, assimilation and mineralization are carried out in the microbial biodegradation.

Biodeterioration is first process of degradation of plastics. During this process the mechanical, physical and chemical strength of the plastics is changed based on the structure, composition and environmental factors. The biofilm and substrate formation are happen during the biodeterioration processes [78]. Followed by bio-fragmentation process that break the plastics polymer structure using the microbial enzymatic action. In the first enzymatic reaction, the microorganism with the help of oxygenase's which add oxygen molecule to polymer structure. As a result of hydrolysis, it cleaves the carbon chains into peroxyl products and alcohol. The resulting products are less toxic [79]. After this reaction a group of enzymes like endopeptidases, esterase's and lipases works together for the biotransformation reaction of carboxylic groups. End of the bio-fragmentation process the multiple chain of polymer are break down into monomers. The monomers are further mineralized by microbial metabolic process. Microbes' uptake the monomers into the cell through cell membrane and oxidized [80,81]. The complete degradation happens in the assimilation process. During this process, microbes produces extracellular secondary metabolites pass to other microbes and enhance the degradation. The quorum sensing microbes taken place for effective degradation. The oxidized products water, carbon dioxide, nitrogen and methane released outside the environment [80,82]. The rate of microbial biodegradation relays on the type of substrate and environmental condition it can be enhanced by physical deterioration, photolysis and abiotic hydrolysis. In the organic process of microbial biodegradation, microorganisms attached to plastic material in the presence of oxygen stimulates the degradation process by releasing the extracellular enzymes to cleave a chemical structure of the plastics and byproducts like carbon dioxide and water [83]. Various microorganisms have been identified to deteriorate plastic waste, but the high molecular mass of polyethylene with a three-dimensional structure and hydrophobic nature make it averse towards degradation [84]. The surface of plastic material has properties like repulsion to the mass of water, which leads to the formation of extracellular polymers facilitates attachment, adhesion and colonization of microorganisms. Prior pre-treatment is needed to enhance biodegradation. The degradation of plastics polymer is determined by the changes in its structure by mechanical, optical or electrical characteristics, crack, fission, rusting, disappearance of colour, phase separation, functional groups modifications and addition of new functional groups to the polymers after biodegradation reaction.

The chemical structure of plastic materials breaks into monomers and releases carbon dioxide and water in humidity and warm aerobic conditions (eqn. 1).

$$\text{Organic matter} + S{+}O_2 \rightarrow CO_2 + H_2O + NO_2 + SO_2 \quad (1)$$

In absence of oxygen plastics go through biodegradation and liberate methane and CO_2 gases (eqn. 2) [85]

$$\text{Organic matter} + H_2O + \text{Nutrients} \rightarrow \text{Residual matter} + CO_2 + CH_4 + NH_3 + H_2S + \text{heat} \quad (2)$$

The general mechanism of degradation of the plastics is the cleavage of polyethylene into fragments of monomers under abiotic factors (heating, ultraviolet (UV) radiation, freezing, or wetting) and biotic (enzymes) conditions. The cleaved plastic monomer was further degraded and the byproducts were absorbed and metabolized by that plastic degrading organism is called as bio-fragmentation [86]. The metabolism undergoes with the presence of enzymes like multicopper oxidizes that change microplastics to carbon dioxide, nitrogen gas, methane, water and release energy of adenosine triphosphate (ATP). After degradation, a visible change is observed in the physical properties like reduction of weight and resistance to tension [87] and synthetic property like surface moiety and hydrophobicity/repulsion to water [88]. In general, the degradation process begins with the excretion of depolymerase, which cleave the elongated chain of polyethylene polymers into low molecular weight monomers and release CO_2. The way of valorizing the plastic wastes was done by bioproducts of high-value depolymerization chemical products. This valorizing was achieved through a specific constructive metabolism pathway, which is the fundamental principle of circular economy [89]. The bacterial and fungal degradation mechanism are similar in converting plastic material into carbon dioxide and water or methane.

Polyethylene: The vast diversity of microorganism is most promising tool for polythene degradation [90]. Microorganism can metabolize linear chain of *n*-alkanes with the help of alkane hydoxylase enzymes. The degradation starts with the hydrolysis and oxidation reaction. In this reaction enzyme reacts on carbon chains with release of primary and secondary alcohols. The released alcohols are further oxidized to aldehydes or ketones and carboxylic acid [91,92]. The formation of carboxylic acid reduces the series of carbonyl-groups with the help of microbial oxidation. Through β-oxidation system pathway, bacteria catabolize the carboxylated *n*-alkanes [93]. Similarly, Yoon *et al*. [94] also reported that bacterial oxidation of *n*-alkanes through tricarboxylic cycle and β-oxidation pathway. The resultant products of oxidation products are further assimilated by microbial cell and catabolized.

Polystyrene: Polystyrene is a solid or foam polymer used to protect the selling products *e.g.* like food package, CD and DVD cases, *etc.* It is a thermoplastic made from petrochemical products but can be degraded by most of the microorganism. Microorganism uses styrene as a carbon source for its growth and reproduction [95]. Mor & Sivan [96] reported that *R. ruber* degrade polystyrene material by forming biofilms. The degradation styrene initially starts by oxidation react of styrene to phenylacetate by the TCA cycle [97]. Microbial degradation of polyethylene and polystyrene are similar process, which involves hydroquinone peroxidase and AlkB family hydroxylases of laccase and oxidoreductases [98]. Similarly, Xu *et al*. [99] reported the biocatalysis of carbon-carbon backbon in polyethylene and polystyrene using P450 monooxygenase. To speedup polystyrene films and foams biodegradation of change in molecular structure of can be done by blending the polymer with starch [96]. Accordingly, Ojeda *et al*. [100] explained the polystyrene degradation by manganese and cobalt additive prooxidants. This additive prooxidants promotes the breaking of multi-molecules into monomers having oxygenated hydrophilic functional groups, which can be easily assimilated of microorganism in the ecosystem [79].

Polyvinyl chloride: Zhe *et al*. [33] reported that initially the degradation is initiated by photolysis and oxygen by the process of chain scission in the carbon-carbon and carbon-hydrogen bond. These abiotic factors modify the structure of polyvinyl chloride through the carbonylation and hydroxyl dichlorination. The sequence enzymes responsible to the biodegradation of polyvinyl chloride is esterase, laccase 34, aldehyde dehydrogenase, dihydroxy-acid dehydratase and monooxygenase 55. Among this, the sequence of enzymatic action, dioxygenase modify the carbon double bond through oxidation of polymer materials. Other enzymes help in transportation of fragmented polymer and fatty acids to the intracellular of microorganism and supports the catabolism processes.

Polyethylene terephthalate: Yoshida *et al*. [84] investigated that PETase is the enzyme responsible for polyethylene terephthalate degradation. PETase converts polyethylene terephalate into mono(2-hydroxyethyl)terephthalic acid (MHET), *bis*(2-hydroxyethyl)-TOA and terephthalic acid (TPA). Moreover, MHETase (MHET eating enzyme) is another enzyme responsible for hydrolysis of MHET into the two fragments of ethylene glycol (EG) and terephthalic acid (TPA). Similarly, Li *et al*. [101] reported that ethylene glycol metabolism in *Pseudomonas putida* KT2440 through oxidation, which results in the production of the different end product like glycolate, glyoxylate, glycolaldehyde and glyoxal. However, these resultant products are less harmful and can be used in different applications.

Polyurethane: Polyurethane is degraded by few bacterial and fungal species by the hydrolysis of urethane bonds [102, 103]. With the help of polyurethane esterase, polyurethane is converted into polyisocyanate and ethylene glycol [104]. Further assimilated by microorganism and converted into CO_2 and water.

Polypropylene: Polypropylene degradation is less studied. With the prior pre-treatment of polypropylene with biotic and abiotic factors. This physical and chemical treatment leads to the formation of hydroxyl and carbonyl compounds with enhance the growth of microorganism susceptible for degradation of polymer. *Bacillus flexus* has capacity to degrade polypropylene, which is pre-treated [3].

Enhancement of microbial biodegradation: To enhance the microbial biodegradation prior pretreatment is needed. Pretreatment of the plastic materials is done to enhance the microbial degradation *in situ* and *ex situ* method. Plastic materials are subjected to the pre-treatment of various abiotic factors like heat, UV, synthetic treatments or incorporation of additives such as biooxidants or carbohydrates to promote biodegradation of highly stable materials like plastic polymer because of its water repulsion nature and high molecular mass [105].

Mechanical treatment: The pretreatment includes mechanical (physical) and chemical modification. The mechanical treatment of plastic, like cutting and impact, crushing and grinding, fractionation, cryogenic cooling step, dessicating, dehydration, agglomeration or granulation. Another alternative to overcome the plastics accumulation in the environment is being recycled and reused. The plastic materials are recycled mechanically by reprocessing and manufacturing into new usable products but end of the day they should be degraded by microorganisms. Various types of plastics like PET, PE or PP were collected, graded and crushed into flakes, melted and extruded in pellets and modified into new products and marketed.

Physical treatment: Plastics are liable to degradation by ultraviolet (UV) light. The ultraviolet light from the sun reaches the earth surface with a wavelength between 280 and 400 nanometers. The degradation of the plastics in the environment is naturally done by the photolytic process in which the UV light cleaves the molecules present in the plastic material. The chemical reaction that takes place in plastic when exposed to UV light results in the retrogression of polymer molecules. The pre-treatment of polyethylene is done to reduce its hydrophobicity by introducing the carbonyl or hydroxyl groups. Recent studies notified that combinational activity of UV irradiation of specific wavelength [47], pyrolysis treatment or treatment with nitric acid at a particular concentration [58] on the plastic materials will stimulate microbial activity effectively.

Chemical treatment: Sulfuric acid and chromic acid are used for the chemical treatment of low density polyethylene. The pretreatment of the chemical compounds has introduced the polar groups in it [106]. High density polyethylene is highly degraded by microbes when the plastic materials undergo a pretreatment procedure [107]. Also used for various types of polymer material.

Biosolvent: Biosolvents are synthesized from the natural products, less toxic and biodegradable than chemically synthesized solvents. Biosolvents are used to remove the additives or colourants from the plastic waste [108]. Biosolvents like cyrene, glycerol ethers, γ-valerolactone, limonene, *etc*. are used in different applications. The butanediol obtained from natural products used to remove cadmium sulfate inorganic biocolournant used in high-density polyethylene (HDPE) [109]. After removal anti-solvent derived from alcohols are used to precipitate HDPE. Anti-solvents are used to inactive the interaction of solvent to HDPE surface. Limonene is the best alternative solvent of dissolution of polymers [110].

Prooxidants: Prooxidants are the chemicals responsible to form reactive oxygen species that trigger the oxidative stress. This prooxidants used in blending with plastics trigger the plastic degradation by releasing free radicals to react with molecular oxygen in the environment. Prooxidants used to break the polymer into monomers forming low molecular mass oxygenated hydrophilic functional group, which facilitates the microorganism to degrade easily in ecosystem [111]. Examples of prooxidants are metal salts like cobalt, manganese and iron reported to enhance the biodegradation. Ojeda *et al*. [100] reported the acceleration of polystyrene degradation by proxidants like manganese and cobalt. Similarly, Gorghiu *et al*. [112] investigated the enhancement rate of oxidative degradation of plastic by iron, copper, manganese, cobalt and nickel.

Enzymes: Microbial enzymes from different microorganisms like bacteria, fungi and actinomycetes produce the extracellular enzymes to degrade the toxic environmental pollutants. The major enzymes involved in the degradation of polyethylene plastic wastes are cutinase, esterase, lipase and PETases [113]. Hydrolase is an enzyme that helps for deterioration of plastic waste matters piled up in the ecosystem with the help of its enzymes like cutinase and lipase belong to esterases [18]. The catalytic activity of the hydrolases cleave the chemical bonds in the presence of water leads to the cleavage of larger molecule to smaller molecules. Yeast *Pseudozyma antarctica* produced from esterase enzyme has been shown to speed up the degradation process of plastic mulch films [114]. From yeast *Cryptococcus* sp. MTCC 5455 extracted an enzyme lipase from the residual agricultural waste as solid state fermentation of which it exhibited a capability to polymerization of polybutylene succinate (PBS) and polybutylene succinate-*co*-adipate (PBSA) [115]. *Candida rugosa* synthesized lipase is employed for the biodegradation of poly(butylene succinate-*co*-hexamethylene succinate) [116]. Cutinase synthesized from *Fusarium solani* gene has expressed in *Pichia pastoris* for enhancement of enzyme to cleave PBS plastic [117] into monomer, polytrimethylene terephthalate (PTT) [118], aliphatic aromatic co-polyesters, aliphatic polyesters [119] and PET [120]. The *Cryptococcus* sp. strain S-2 produces similar enzyme functions like cutinase, which have the capacity to degrade heavy molecular mass of PLA based plastics [121]. Polyhydroxybutyrate (PHB), polybutylene succinate (PBS) and polyethylene succinate (PES) polymers were also degraded by PHB depolymerize [122], which is synthesized from *Aspergillus fumigates*. Webb *et al*. [123] identified the novel bacteria that grow on PET plastic waste, which had been accumulated in the environment for several years. The identified novel bacteria *Ideonella sakaiensis* has the capacity to reproduce and survive on PET based recycling drinking cans by consuming polymer as main carbohydrate materials [84] and degrade it. Polyesterase has an ability to hydrolysis the aromatic chain of polyesters which is first observed in the microorganism *Thermobifida fusca* [16]. Different types of cutinase enzymes were purge and characterized from strains of thermophilic actinobacteria [124] like *Thermobifida cellulosilytica* [120], *Thermomonospora fusca* [125], *Thermobifida alba* [117], *Thermobifida fusca* [119] and *Thermomonospora curvata* [126]. Enzyme polyesterases synthesized by the expression of gene polyesterase in *Pseudomonas pertucinogena* have been firmly established by sequence similarity [127]. Few microbial enzymes listed in Table-3 are capable to degrade various plastics.

Zelezniak *et al.* [31] investigated the plastic eating enzymes are present in the bacterial genomes, which is isolated from the soils and ocean. The bacterial diversity in ocean has a strong correlation with plastic waste and enzymes. Over 60 years, due to the plastic pollution in the environment make the bacteria adopted and improving capacity to use plastic as a food and energy source. Genetic engineering of bacteria stimulates the enzymes and helps the ecosystem for better recycling of plastic wastes. The information about the taxonomical data of bacteria by using advance genomic protocol and computational tools like machine learning, the researchers [31] identified more than 30,000 new potential plastic eating characteristics of different synthetic plastics. Some of the biotechnological strategies will enhance microbial bioremediation effectively. The synthetic bioremediation strategies like genetic manipulation by gene editing and metabolic reconstruction form a potent functional bioremediation gene.

Benefits of microbial bioremediation: The contaminated soil and water have wide range of microbial, organic, inorganic and radioactive compounds. Microbial biodegradation is useful because it helps restore the environment by resurrecting healthy ecosystems (Fig. 1). Proper usage of the unique instruments designed for bioremediation to safest cleanup of contaminated soil. Biodegradation has capability to degrade organic compounds produced from microbial pathogens, radioactive metal like arsenic, fluoride, nitrate, volatile organic compounds, metals and other contaminants like ammonia and phosphates. Microbial biodegradation is also designed to eliminate the toxic contaminants from insecticides, herbicides and saltwater intrusion

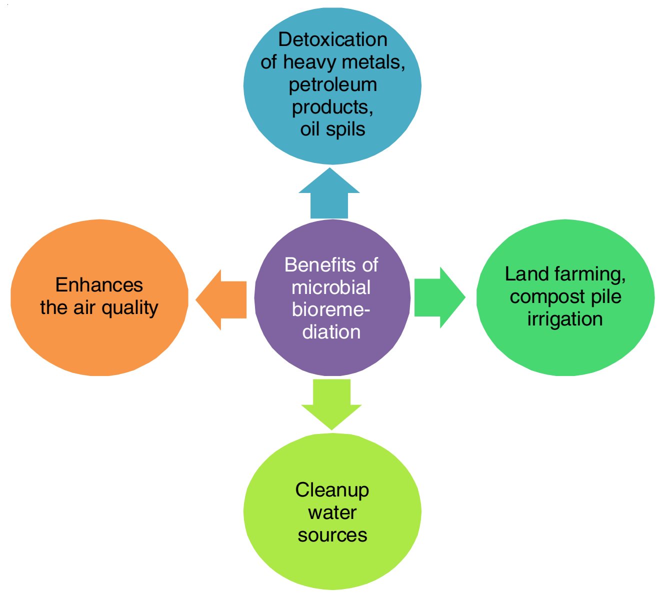

Fig. 1. Represents the schematic chart of microbial bioremediation in the theme "green route for ecosystem"

TABLE-3
REPRESENT THE MICROBIAL ENZYMES CAPABLE TO DEGRADE DIFFERENT TYPES OF SYNTHETIC PLASTICS

Phylum	Type of plastic	Organism	Enzyme involved in degradation	Ref.
Bacteria	Polyethylene	*Klebsiella*	Esterase, peroxidase, laccase, alkane monooxygenase, lipase and carboxylesterase	[33]
	Polystyrene	*Acinetobacter johnsonii* JNU01	Alkane-1-monooxygenase	[39]
	Polyurethane	*Pseudomonas capeferrum*	Esterase	[43]
		Ideonella sakaiensis 201-F6	PETase	[31]
		Bacillus subtilis	Nitrobenzylesterase	[128]
		Pseudomonas	Cholesterol esterase	[129]
	Polyethylene terephthalate	*Pseudomonas putida* KT2440	Dehydrogenase	[130]
		Klebsiella sp.	Esterase, peroxidase, laccase, alkane monooxygenase, lipase and carboxylesterase	[131]
	Polyvivl chloride	*Klebsiella* sp.	Catalase-peroxidase, esterase, monooxygenase, laccase, carboxylesterase and lipase.	[132]
Fungi	Polyethylene	*Aspergillus flavus* PEDX3	Laccases	[131]
		Pleurotus ostreatus	Manganese peroxidase (MnP), lignin peroxidase (LiP) and laccases	[133]
		Phanerochaete chrysosprium	Manganese peroxidase	[134]
		Trametes cervine	Lignin peroxidase	[134]
		Trametes versicolor	Laccase	[134]
		Agrocybe aegerita	Unspecific peroxygenase	[134]
	Polystyrene	*Lentinus tigrinus*	Esterase	[135]
	Polyurethane	*Aspergillus niger*, *Candida rugosa*	Lipase	[129]
		Aspergillus fumigatus	Esterase	[136]
	Polyethylene terephthalate	*Aspergillus tamarii* and *Penicillium crustosum*	Lipase and Cutinase	[137]
		Penicillium simplicissimum	Lipase	[138]
		Fusarium solani	Cutinase	[139]
Actinobacteria	Polyethylene terephthalate	*Thermobifidafusca*	Cutinase	[128]
		Saccharomonospora viridis AHK190	Cutinase	[47]

into aquifers. Tilley [140] developed an anaerobic digestion technology for converting the plastic wastes into fertilizer and energy source. Better plastic recycling and less plastic pollution in the environment will be achievable once the microbes and/ or enzymes responsible for breaking down plastic are identified and genetically modified. The microbes used for waste water treatment itself used for the treatment of plastics. These resultant treatment with microbes it appears as solid and liquid biomass. The biomass is used as biogas and fertilizer by separation of carbon dioxide and methane gas. This methane gas used as heat and energy for the same wastewater plant and carbon dioxide is reused.

Conclusion

This concise review summarizes about the microbial bioremediation of the synthetic plastics which thrives in the environmental ecosystem. The petroleum derived plastic polymers are used in various sector for production, packaging and distribution for several application. It has a unique property like highly stable, flexible, inert nature and hydrophobic nature. Due to its ideal characteristics, it is difficult to cleave the long chain of petrochemical polymer. Deposition of this plastic waste is major issue faced by terrestrial and marine ecosystem. Emerging uses of plastic are forcing people to keep using it. Among the biodegrading methods, biological treatment using microbes is quite effective as compared to physical and chemical treatments. Microbial bioremediation is the most effective and ecofriendly method for degradation of the plastic materials, which sustain in the environment for the prolong time. Future prospective is to identify effective microbial enzymes and combination of enzymes by studying its interaction with plastic polymers by *in silico* computational biology.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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