A Project Titled

Plastic polymers and their remediation using microorganisms, nanoparticles, and integrated nano-bio approaches

A DISSERTATION REPORT

submitted in partial fulfillment for the award of the

Degree of Master of Science in Biochemistry

BY

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May 2022

Declaration

I hereby declare that the matter presented in this dissertation entitled ‘Plastic polymers and their remediation using microorganisms, nanoparticles and integrated nano-bio approaches’ is based on the literature survey carried out by **Master. Uttam A. Sawant** in the School of Chemical Sciences, Goa University under the supervision of **Dr. Amrita Pradeep Kharangate,** and the same have not been submitted elsewhere for the award of degree.

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CERTIFICATE

This is to certify that the dissertation entitled ‘Plastic polymers and their remediation using microorganisms, nanoparticles, and integrated nano-bio approaches’ is a Bonafide work carried out by **Master. Uttam A. Sawant** under my supervision in partial fulfillment of the requirements for the award of the degree of Master of Science in Biochemistry at the School of Chemical Sciences, Goa University.

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1.0 Abstract:

Plastics are a growing concern as it generates 400 million metric tonnes of waste per year. Although plastic polymers have become indispensable today, their persistent and non-biodegradable nature affects the health of both terrestrial and aquatic living organisms. Fragmentation of plastic polymers by natural factors into microplastics is a potential health hazard due to bioaccumulation. Remediation of plastic is being explored as an option for reducing the presence of pollutants in nature. Microorganisms have been known to degrade plastic polymers. The use of these microorganisms as individual species or consortiums of organisms has been explored for plastic polymer degradation. Remediation of plastic polymers using nanoparticles is also being explored due to the attractive catalytic reactions carried out by nanoparticles. Given the potential of both microbial and nanoparticle approaches, integrated techniques for plastic polymer remediation have evolved that are more efficient than the individual methods used alone.

2.0 Introduction to plastic polymers

Today, it is difficult to imagine a world without chemically synthesized polymers, which are recalcitrant. Plastic-related polymers are in high demand, which requires large-scale manufacture (Geyer et al., 2017). Polymers have been created for over a century, but the first synthetic plastics, such as Bakelite, came in the twentieth century. Eduard Simon discovered polystyrene in 1839, while Goodyear invented vulcanized rubber in 1839. ‘Alexander Parkes’ was the first to develop man-made plastic known as Parkesine, now recognized as celluloid, which was an organic material derived from cellulose that could be shaped once heated but kept its shape when cooled. Parkes claimed that this new material could do all of the functions that rubber could, but at a lesser cost. He discovered a material that could be carved into thousands of different shapes while remaining transparent (Andrady & Neal, 2009). In the first half of the twentieth century, the development of modern plastics advanced, with at least 15 new polymer types produced. The growth of plastic polymer as a material has been remarkable; natural polymers, modified natural polymers, thermosetting plastics, and biodegradable plastics have all proven to be versatile. (Andrady & Neal, 2009). Long synthetic chain units make up plastics. They're macromolecules built up of covalently bonded structural units that are repeated. Monomers are structural repeating units that join to make a polymer (Jayashree & Vanmathi, 2021). Polymers are complex, high-molecular-weight organic compounds that are molded, extruded, cast into various forms, films, and even made into fine textile fibres, mainly due to polymerization (Andrady & Neal, 2009). Plastics are manufactured from organic and inorganic components that are still utilized today, such as carbon, silicon, hydrogen, nitrogen, oxygen, and chloride. An extensive range of common polymers are made from hydrocarbon monomers. The majority of today's plastics are synthesized from non-renewable petrochemical products sourced from fossil fuels, natural gas, and coal. Thousands of organic subunits are linked together by strong covalent chemical interactions to form synthetic polymers. According to (Andrady & Neal, 2009) the first synthetic polymer was ‘Bakelite’. On a commercial basis, tens of thousands of different grade polymers are manufactured. Polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polytetrafluoroethylene (PTFE), and also high, low, and linear-low-density polyethylene (HDPE, LDPE, LLDPE), as also called thermoplastics or non-biodegradable polymers as they can be heated and cooled repeatedly to harden and soften the material. These polymers are made by linking many monomers together into long chains to form a polymer backbone (Chamas et al., 2020).

2.1 Polyethylene Terephthalate (PET or PETE)

PET is a clear, durable, stable polymer with good gas and moisture barrier qualities, making it ideal for carbonated beverage packaging and other food containers. Because it can endure high temperatures, it may be utilized in applications like heat-able pre-prepared food trays. Clothing and carpet fibres, bottles, food containers, strapping, and engineering plastics for precision-molded pieces are just a few of the applications (Tokiwa et al., 2009).

2.2 High-Density Polyethylene (HDPE)

For its high moisture protection and chemical resistance, HDPE is useful in a range of packaging applications. It's found in snack food packaging and cereal box liners, as well as milk and non-carbonated beverage bottles in bottle form. HDPE, like all forms of polyethylene, is only suitable for food packaging applications if an oxygen or carbon dioxide barrier is not required. Because HDPE is chemically resistant in film form, it is used to package a variety of home and commercial chemicals such as detergents, bleach, and acids (Karmakar, 2020).

2.3 Low-Density Polyethylene (LDPE)

LDPE is used to make flexible films like the one used in dry cleaning garment bags and product bags. With its hardness, flexibility, and transparency, LDPE is widely employed in the manufacturing of films. Because of its low melting point, LDPE is more suited to heat-sealing applications. Because of its steady electrical qualities and manufacturing features, LDPE is also utilized to make various flexible lids and bottles, and it is widely employed in wire and cable applications (Chamas et al., 2020).

2.4 Polyvinyl Chloride (PVC)

Its clarity, chemical resistance, long-term stability, and even electrical characteristics are all excellent. Vinyl products may be split into two types: stiff and flexible. Pipe and fittings, siding, hard flooring, and windows are all examples of stiff uses in the building industry. PVC's success in pipe and fittings may be due to its chemical resistance, inflexibility to attack bacteria or microorganisms, resistance to corrosion, and strength. Wire and cable sheathing, insulation, film and sheet, flexible floor coverings, synthetic leather items, coatings, blood bags, and medical tubing are all made of flexible vinyl (Asuquo, 2018).

2.5 Polypropylene (PP)

Polypropylene is a chemically resistant plastic that is often used in packaging. For its high melting point, it's perfect for hot-fill liquids. Polypropylene is utilized in a variety of products, including flexible and rigid packaging, fabric and carpet fibres, and large-scale molded parts for automobile parts. Water, salt, and acid solutions are all harmful to metals, but polypropylene, like other polymers, is resistant to them. Ketchup bottles, yogurt containers, pharmaceutical bottles, pancake syrup bottles, and vehicle battery casings are all common uses (Yani et al., 2020).

2.6 Polystyrene (PS)

Polystyrene is stiff, a translucent foamed substance with a wide range of uses. It’s used in medical and food packaging, laboratory gear, and some electronic applications, it is allowed to be utilized as Extruded Expandable Polystyrene (EPS) and often extruded into sheets for thermoforming into trays for meats, fish, and cheeses, as well as egg cartons and other containers. For dry goods such as dried soups, they may also be molded directly into cups and tubs. Both foamed sheet and molded tubs are extensively used in take-out restaurants due to their lightweight, rigidity, and good thermal insulation (Asuquo, 2018).

2.7 Bioplastics/Biodegradable plastic

Plastics are produced from natural sources such as algae, microorganisms, plants, and animals, which provide the cellulose, starch, and protein needed for their production. They are readily destroyed by UV radiation, water, enzymes, pH changes, and other factors. Microorganisms decompose these polymers into biogases and biomass (mostly carbon dioxide and water), leaving no hazardous by-products behind (Jain et al., 2010). For example, polyhydroxyalkanoate (PHA) (Raman Sharma & Sharma, 2014).

2.8 Thermoset plastics

Thermoset plastics are linear solids with highly cross-linked structures, whereas thermoplastics are not. Chemical changes are irreversible in this case, but they cannot be recycled. Thermoset plastics include polyethylene terephthalate (PET), and polyurethane (PUR) (Zheng et al., 2005)

2.9 Microplastics

Polymers with a diameter of less than 5 mm are known as microplastics. Microplastics have a variety of shapes, including spheres, pieces, and fibres. They are usually created when bigger polymers deteriorate (Hale et al., 2020). Microplastics are bioaccumulating contaminants that represent a major hazard to the marine ecology. It also harms marine species, which in turn impacts the food chain (Andrady, 2017).

Plastic garbage is produced at a rate of almost 400 million metric tonnes per year. Plastic is quickly accumulating in the environment, yet our understanding of its presence is severely restricted. Plastic material getting accumulated in the environment is becoming more of a concern because worldwide use of plastic is growing and their natural resistance to degradation increases. Plastic pollution has progressed where it now poses a hazard to the world ecosystem (Chamas et al.,2020). Toxic components such as Bisphenol A (BPA), thalates, antiminitroxide, brominated flame retardants, polyfluorinated compounds, and others, are present in plastic bottles and containers, posing a risk of human exposure. BPA and phthalates may be found in a variety of mass-produced items, such as medical equipment, food packaging, fragrances, cosmetics, toys, flooring materials, computers, and CDs, and can account for a large portion of the plastic content. In the production of polycarbonate plastics and the manufacture of PVC, BPA is used as a monomer. Phthalates may make up a significant amount of PVC by weight (Halden, 2010). Phthalates that are not chemically bonded to the plastic matrix can leach out of plastic items and have gotten a lot of attention due to their large manufacturing quantities and widespread use. Because of their volatility, phthalates and BPA can be found in dust, air, and aquatic ecosystems. BPA, a monomeric building component of plastic, and its additives, plasticizers, are hazardous to one's health. Though plastics release a variety of hazardous components, BPA and phthalates are of major concern. BPA is best known as the monomer that makes polycarbonate polymers possible. Because BPA polymerization produces unbound monomers, a significant portion of the bulk comes into contact with food. These are released into food and beverages over time from beverages and food containers (2017, Proshad et al.). Plastic has several negative and dangerous consequences on human health (Thompson et al., 2009). BPA disrupts the body's normal hormonal communication mechanism. The primary routes of BPA exposure in the human body are thought to be food and inhalation. BPA mimics hormones because it resembles the reproductive hormone estrogen. BPA has also been linked to ovarian chromosomal damage, lower sperm production, premature puberty, quick immune system alterations, type-2 diabetes, cardiovascular disease, obesity, and other health problems. BPA in women leads to impaired health, including obesity, endometrial hyperplasia, recurrent miscarriages, sterility, and polycystic ovarian syndrome, according to some studies (Proshad et al., 2017).

When plastics are discarded into the environment, they do not degrade naturally. This is rather expected, as one of the key reasons for many polymers' popularity and extensive use is their outstanding stability and endurance (Webb et al., 2012). Yet degradation of plastic polymers is seen in the process of photodegradation, thermo-oxidative degradation, hydrolytic degradation, and microbiological degradation are all methods used to degrade and remediate plastics in the environment (Zeenat et al., 2021).

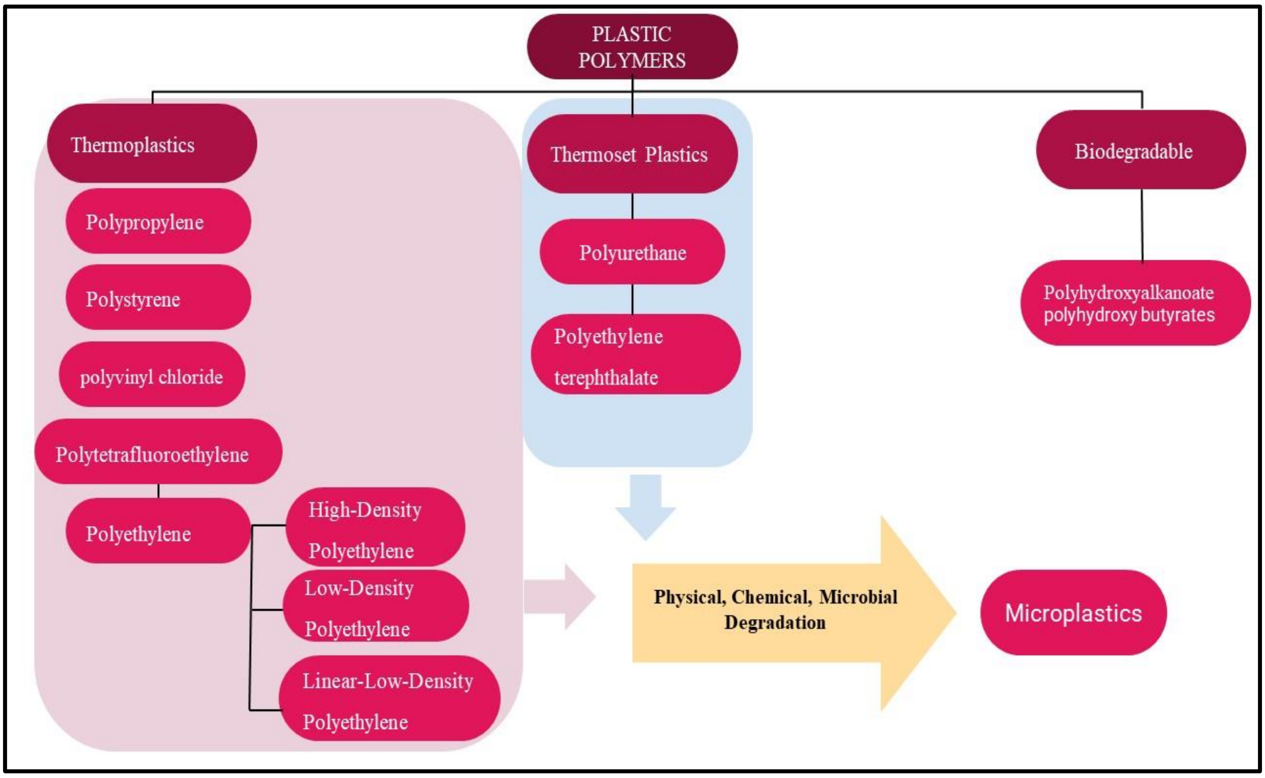


Fig: 1. Classification of Plastic Polymers

3.0 Biodegradation of plastic polymers in nature

The use of microorganisms to remove or remediate a polluted site is called bioremediation. Living creatures such as algae, bacteria, yeast, and fungus are used (Kharangate-Lad & D'Souza, 2021). These microorganisms consume plastic polymer to gain carbon source and other nutritional requirements for the life cycle completion and completion. Microorganisms utilize carbon sources, and polythene is one of them (Shahnawaz et al., 2019. Nano remediation is a technique that involves the use of nanoparticles with specific physiological features. Nanoparticles are subatomic particles that range in size from one to one hundred nanometres. They have extraordinary physicochemical qualities because of their nanoscale size, high specific surface area, and high reactivity. Because of their small size, nanoparticles show plasmon resonance, which allows them to contain their electrons and induce quantum effects (Kharangate-Lad & D'Souza, 2021).

4.0 Mechanism of plastic degradation in nature

The degradation of plastic in the natural environment involves the collaboration of physical, chemical, and biological processes. Natural degradation of plastics starts with photodegradation, which leads to thermo oxidative degradation. The activation energy necessary to induce the incorporation of oxygen atoms into the polymer is provided by ultraviolet radiation from the sun. This will cause the plastic to become brittle and to break into smaller and smaller pieces until the polymer chain reaches a sufficient stage possessing a lower molecular weight to be metabolized by the microorganisms (Webb et al., 2012). The microorganisms either convert the carbon in the polymer chains to carbon dioxide or integrate it into biomolecules; nevertheless, the entire process is slow, and it can take 50 years or more for plastic to decompose completely (Müller et al., 2001).

4.1 Degradation by physical factors

4.1.2 Photo-oxidative degradation

The most common cause of polymer degradation is light. Absorption of UV (ultraviolet) radiations has the potential to damage synthetic polymers. UV radiations with wavelengths ranging from 290 to 400 nm, which are emitted by sunshine, determine the duration of polymeric materials utilized for diverse purposes (Teare et al., 2000). At the soft segments of polymers, where degradation happens, photo-irradiation creates ester, aldehyde, propyl, and formyl groups. UV radiations easily split the C–C bonds (Zeenat et al., 2021).

4.1.2 Thermal degradation

Thermal degradation includes comparable processes that are classified as oxidative processes or oxidative degradation, as previously stated. The first distinction is the order of the early stages, whereas the second is the reaction site (Zeenat et al., 2021). Thermal breakdown causes reactions to occur throughout the polymer. Thermal degradation occurs as a result of an unintentional or unintentional depolymerization process. Temperature and UV light are essential for its start (Teare et al., 2000). Due to errors in the chain, the bonds (peroxide/ether link) become weak, and depolymerization generally begins at these weak bonds. A vast variety of polymers are depolymerized at high temperatures (Ramis et al.,2004).

4.1.3 Ozone degradation

Ozone, which is naturally present in the environment, induces polymer breakdown. When oxidative reactions are not present, polymers have a longer shelf life (Teare et al., 2000). Although ozone is present in trace amounts in the atmosphere, it has a significant impact on polymers. The production of reactive oxygen species by ozone destroys polymeric materials (ROS). Reduced molecular weight, as well as changes in and mechanical characteristics of polymers, produce reactive oxygen species. Different forms of carbonyl and unsaturated carbonyl compounds are generated when polymers are subjected to ozone. Aromatic ring ozone reactions occur in polymers with C–C bonds and other saturated hydrocarbon linkages. Intermediates are produced during the reactions, which are unstable and induce the breakdown of big molecules or polymers (Zeenat et al., 2021).

5.0 Degradation by chemical methods

Chemical Degradation of plastic involves mechanochemical and catalytic degradation.

5.1 Mechanochemical degradation

The breakdown of polymer chains under mechanical stress and ultrasonic irradiation is known as the mechanical degradation of polymers (Li et al., 2005). The number of branches in chains grows as a result of side-chain radical reactions. The breadth of a molecule's weight distribution function is reduced, altering the association between crosslinks and ruptures, as well as the concentration of double bonds (Striegel, 2003).

5.2 Catalytic degradation

The catalytic conversion of waste polymers to hydrocarbons is a growing trend. When polyolefins are catalytically degraded, they give out oils and gases. The catalytic degrading process not only increases the quality of the acquired goods but also makes it possible to produce the required products. Pt-Mo and Pt-Co sustained by SiO_2 are two examples of polymer degradation catalysts that have been described (Gimouhopoulos et al., 2000).

6.0 Biodegradation of plastic polymers by microorganisms

The ability of these microbes to metabolize and transform plastic polymers is a critical mechanism in their bioremediation. The use of microorganism-produced enzymes for the breakdown of plastic polymers is a viable option. Due to their interaction with enzymes, enzymes are known to be substrate selective. Laccase is an enzyme that helps in the breakdown of polyethylene's hydrocarbon backbone. This enzyme is discovered in fungi that degrade lignin and catalyze the oxidation of aromatic chemicals. Proteases are also responsible for the breakdown of polyethylene by bacterial strains such as *Brevibacillus sp.* and *Bacillus sp.* (Jayashree & Vanmathi, 2021). Microorganisms utilize the degrading polymer as a source of energy by secreting extracellular enzymes. Polymer breakdown occurs both extracellularly and intracellularly. Exoenzymes are a type of extracellularly synthesized enzymes that assists in the breakdown of large polymers and the formation of small water-soluble molecules. These compounds can pass across a semipermeable bacterial barrier and provide energy. Depolymerization is the breakdown of large polymers, whereas mineralization is the breakdown of inorganic species such as H_2O, CH_4, and CO_2. In an aerobic environment, only H_2O, CO_2, and microbial mass are produced (Zeenat et al., 2021).

The ability of microorganisms to degrade plastic polymers has been tapped to obtain microorganisms that can be efficiently used for clean-up of plastic polluted sites. The bioremediation of plastic polluted sites involves either introducing deliberately microorganisms capable of degrading these polymers or the microorganisms such as bacteria, fungi, algae, and yeast that play an important role in plastic polymer bioremediation. Physical and chemical factors play an important role in the initial breakdown of plastic polymers. Microorganisms degrade plastics by oxidation or hydrolysis using the microbial enzymes which lead to the cleavage of the chains of the large compound polymer into small molecular monomers (Gu, 2002). Several factors influence microbe development, including water availability, redox potential, temperature, carbon, and energy supply (Raziyafathima et al.,2016).

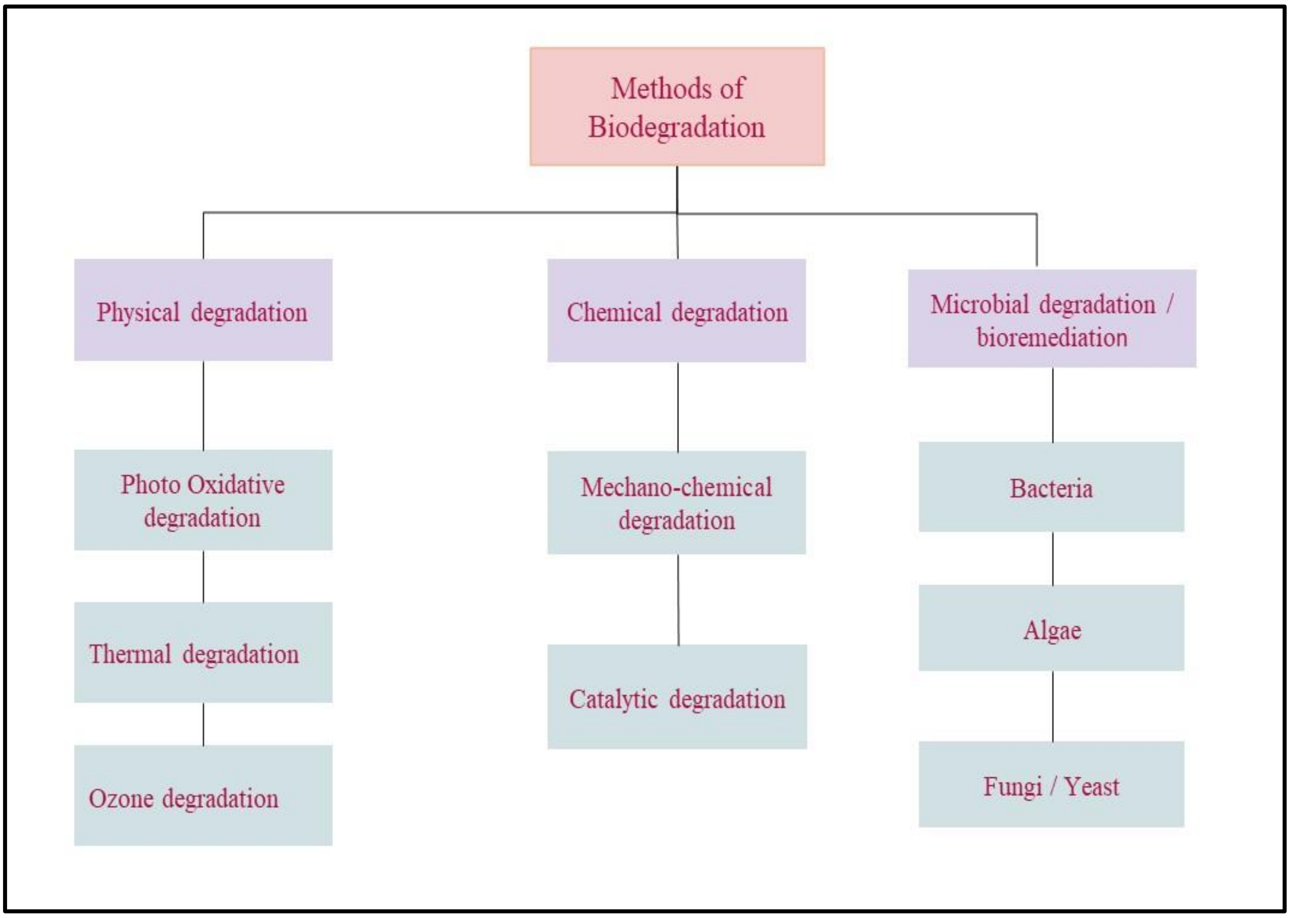


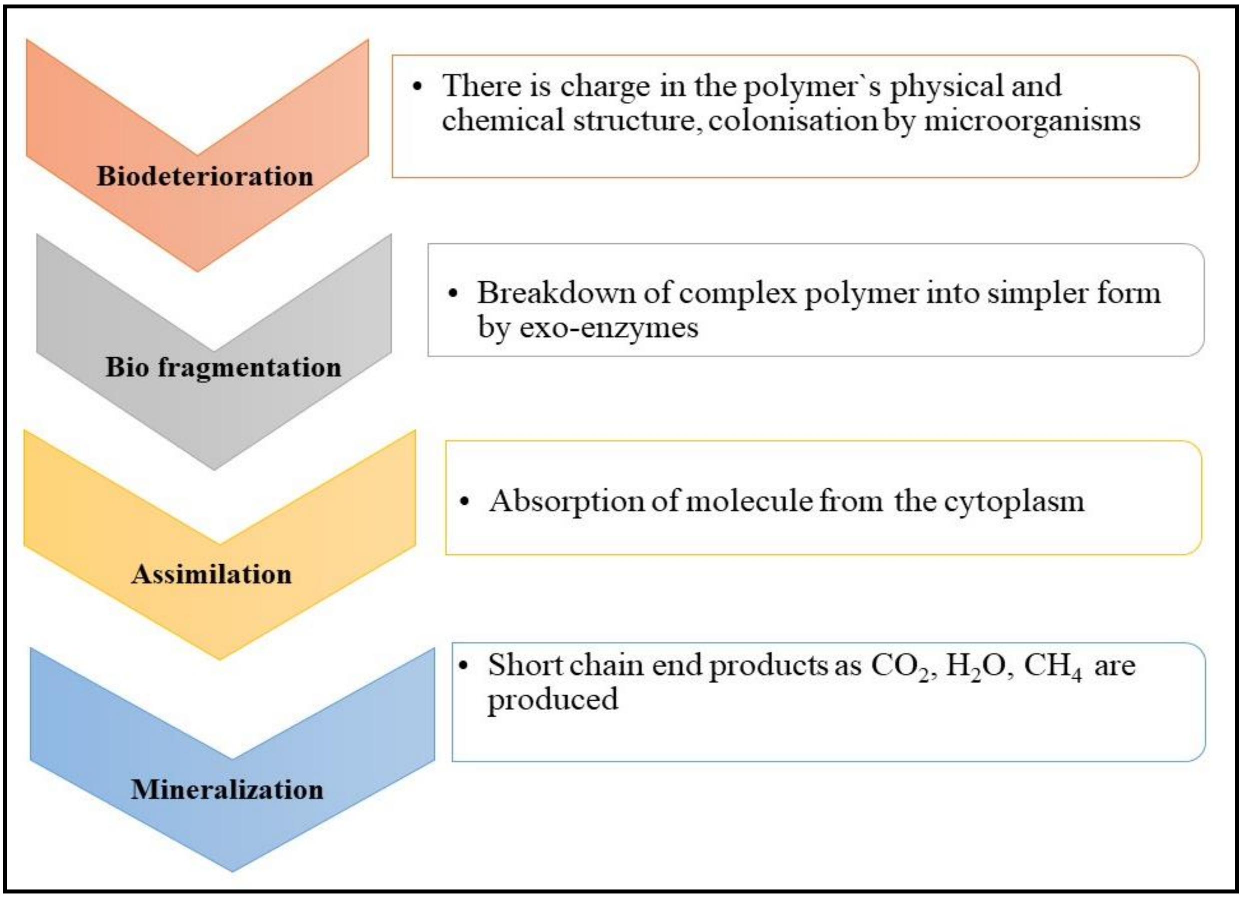
Fig: 5. Methods of biodegradation

6.1 Mechanism of bioremediation of plastic polymers by microorganisms

Biodegradation of plastic polymers by microorganisms involves four steps: biodeterioration, bio fragmentation, assimilation, and mineralization.

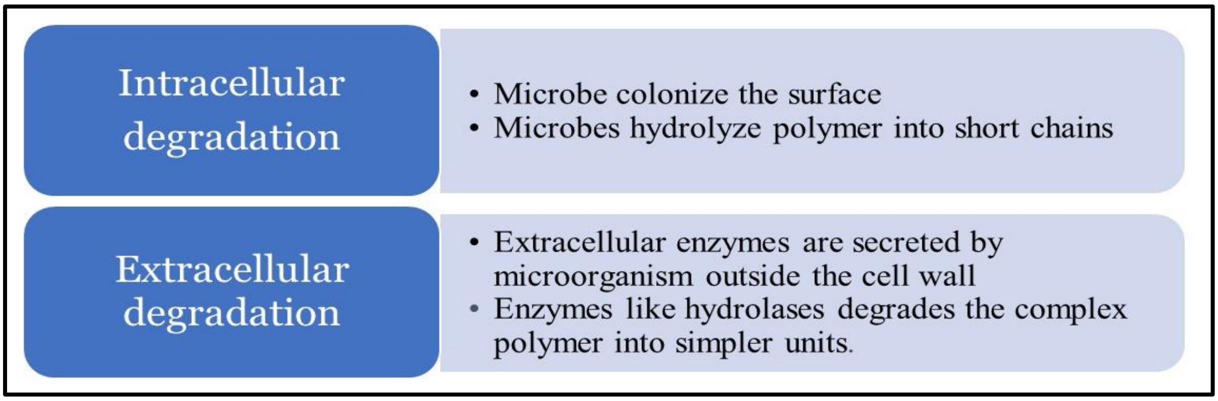
1. Microorganism adherence causes biodeterioration, which affects the physical, chemical, and mechanical characteristics of plastic polymers. Microorganisms colonize and produce biofilms or extracellular polymeric substances, which invade the polymeric pores and cause grooves and cracks, weakening the polymeric structure of the plastic and physically deteriorating it.
2. Bio fragmentation involves the cleavage of the polymeric plastic into oligomers, dimers, or monomers by the action of exo-enzymes or free radicals produced by the microorganisms.
3. Assimilation involves the absorption of molecules across the cytoplasm for metabolic processes to form cell biomass or cell structures.

4. Mineralization is the complete degradation of the absorbed molecules into oxidized metabolites such as carbon dioxide, nitrogen, methane, and water vapor (Kharangate-Lad & D’Souza, 2021; Zeenat et al., 2021)



- There is charge in the polymer`s physical and chemical structure, colonisation by microorganisms
- Breakdown of complex polymer into simpler form by exo-enzymes
- Absorption of molecule from the cytoplasm
- Short chain end products as CO_2, H_2O, CH_4 are produced

Figure 2: Mechanism of biodegradation of plastic polymer using microorganisms (Wilkes & Aristilde, 2017; Yuan et al., 2020



- Microbe colonize the surface
- Microbes hydrolyze polymer into short chains

- Extracellular enzymes are secreted by microorganism outside the cell wall
- Enzymes like hydrolases degrades the complex polymer into simpler units.

Figure 3: Intracellular degradation and extracellular degradation (Shah et al., 2008; Yuan et al., 2020).

6.2 Microorganisms degrading plastic polymers

Biodegradation of plastic polymers has been mainly focused on the studies of bacteria. Plastic polymer degrading bacteria studied include *Streptococcus, Klebsiella, Micrococcus Staphylococcus, and Pseudomonas* (Zeenat et al., 2021). Bacteria such as *Pseudomonas* and *Clostridium* are the most dominant bacteria that can metabolize plastics like polyethylene, and polyvinyl chloride (PVC). Also, the *Rhodococcus sp.* has demonstrated the ability to degrade plastic by 8% of its dry weight in 30 days. *Acidovorax sp., Alcaligenes sp., Brevibacillus borstelensis*, *Comamonas acidovorans*, *Diplococcus sp., Moraxella sp., Pseudomonas sp., Streptococcus sp., Staphylococcus sp., Micrococcus* sp., *Thermomonospora fusca*, *Schlegelella thermodepolymerans*, and *Amycolatopsis sp.,* are studied bacterial species showed degradation towards plastic polymers. Other bacteria such as *lcanivorax*, *Shewanella, moritella, Psychrobacter,* and *Tenacibaculum* also exhibit a biodegrading property against polyester PCL in the deep-sea sediments. The highest capacity for PCL biodegradation was observed in *Pseudomonas* and *Rhodococcus* (Kharangate-Lad & D'Souza, 2021). The addition of additives improves ethylene polymer biodegradation. The added additives cause auto-oxidation of the polymer, lowering its molecular weight and making it easier for bacterial cultures to degrade (Zeenat et al., 2021). Strains of *Ideonella sakaiensis* 201- F6 are also found to degrade Polyethylene Terephthalate (PET). This bacterium produces two enzymes, PETase and METHase. during the degrading process, the breakdown products formed are Ethylene glycol and terephthalic acid, which are utilized by bacteria as a source of energy. PET degradation of a thin film takes about six weeks at a temperature of 30°C (Palm et al., 2019).

In the breakdown of plastic polymers, fungi play a vital role. They dissolve the matter, and can also grow in low moisture areas and low pH solutions (Spellman, et al., 2007). Fungi are diverse with extracellular enzymes which help in the degradation. Degradation is with the hyphal system where the fungi can penetrate substrates rapidly thereby improving the transport and supply of nutrients within their mycelium (Matavulj & Molitoris, 2009). Low-density polyethylene (LDPE) is actively degraded by *Aspergillus versicolor and Aspergillus sp. Saprophytic* fungi are able to degrade polyurethane, and fungi such *Alternaria sp., Aspergillus niger, Geomyces pannorum, Nectria sp., Phoma sp., Paraphoma sp., Penicillium sp., Plectosphaerella sp. and Neonectria sp.* utilize carbon from the polymer polyurethane (Kharangate-Lad & D'Souza, 2021). The fungi *Aspergillus niger* and *Aspergillus japonicus* showed marked ability to degrade LDPE. These fungi degraded 8-12% polyethylene after one month of incubation (Munir et al., 2018).

Table 1: Microorganisms used in bioremediation of plastic polymer.

Microorganism	**Pollutant**	**References**
Bacteria *Bacillus cereus*	Polyethylene	Vimala & Mathew, 2016)
Streptomyces sp.	LDPE	Deepika & Madhuri, 2015
Pseudomonas putida	Milk packets	Ponniah, et al 2014
Pseudomonas putida	Polythene and plastic	Kathiresan, K. 2003
Bacillus brevis	Polycaprolactone	Urbanek et al. 2018
Fungi *Myceliophthora sp.*	Polyethylene	Ibrahim 2013
Trichoderma viride	LDPE	Munir et al. 2018
Aspergillus niger	Powdered LDPE	Volke-Sepúlveda et al., 2001
Aspergillus oryzae	High-density polyethylene	Konduri MKR et al., 2010
Yeast *Pseudozyma sp*	Polybutylene succinate	Kitamoto et al.2011
Candida rugosa	Polyurethane	Russell et al. 2011
Algae *Anabaena spiroides*	Polyethylene	Kumar et al. 2017
Scenedesmus dimorphus	Polyethylene	Kumar et al. 2017
Navicula pupula	Polyethylene	Kumar et al. 2017

Candida rugosa's polyurethane degrading enzymes were also discovered to be capable of degrading polyurethane. *Pseudozyma sp.* was also found to be capable of degrading poly-butylene succinate or poly-butylene films (Kitamoto et al., 2011).

Algae showed degradation of polythene by the production of enzymes ligninolytic and exopolysaccharide for degradation. The alga utilizes plastic polymers as a carbon source (Chia et al., 2020). Studies suggest that the microalgae *Anabaena spiroides* (blue-green alga), *Scenedesmus dimorphus* (Green microalga), and *Navicula pupula* (Diatom) are the best organisms for the degradation of polyethylene (Kharangate-Lad & D'Souza, 2021).

6.3 Methods of bioremediation

Bioremediation processes usually employ microorganisms. In-situ or ex-situ bioremediation is both good alternatives in remediation processes. The term "in-situ treatment" refers to the process of creating a polluted location without removing it. Biostimulation, bioattenuation, and bioaugmentation are some of the processes used in in-situ treatment. In-situ treatments are more desirable because they are less expensive and do not disrupt the environment (Kharangate-Lad & D'Souza, 2021).

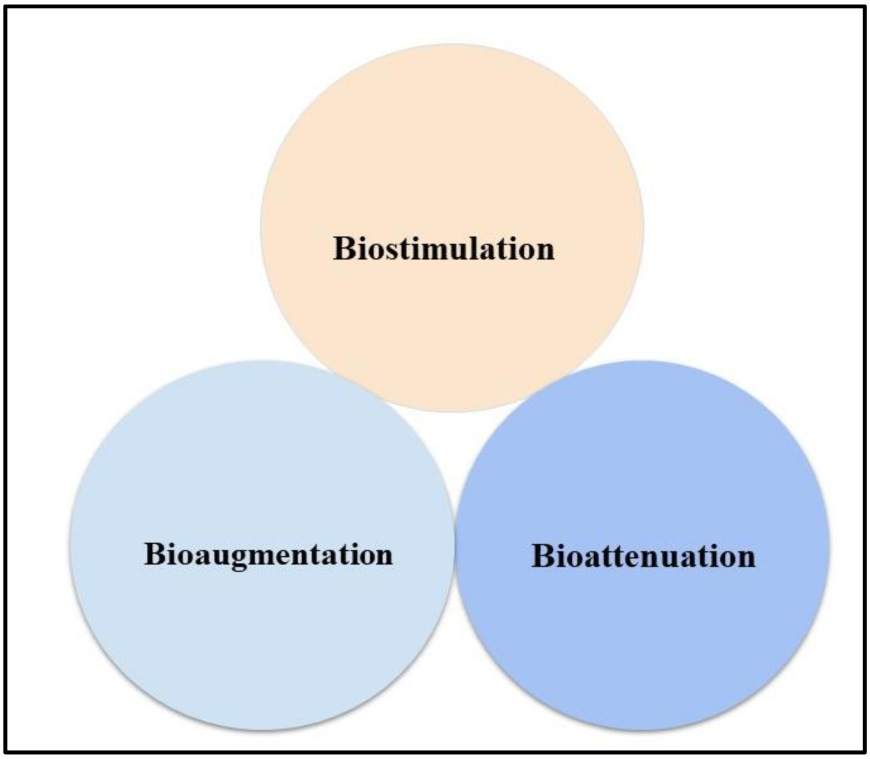


Fig: 4. Methods of bioremediation

6.3.1 Biostimulation

Biostimulation is a technique that involves injecting specific nutrients into the soil to stimulate indigenous microorganisms. As a result, the indigenous and naturally occurring microbial population will benefit. This includes providing fertilizers, growth supplements, and environmental conditions such as pH, temperature, and oxygen to ensure that metabolic processes run smoothly. (Omokhagbor Adams et al., 2020).

6.3.2 Bioaugmentation

Microorganisms with the ability to degrade the target pollutants are added to boost the biodegradative capacity of the contaminated site's indigenous microbial population. Microbes are even collected from the site of remediation and are cultured separately or genetically modified and returned to the site for remediation purposes (Abatenh et al., 2017). This improves degradative efficiency by degrading complex pollutants while also increasing the genetic capacity of the desired site (Tribedi et al., 2018).

6.3.3 Bioattenuation

Bioattenuation or natural attenuation refers to the reduction in pollutant concentrations from the contaminated site. It involves aerobic and anaerobic biodegradation by microorganisms as well as plant, animal, and microbial uptake. Physical processes such as advection, dispersion, dilution, diffusion, volatilization, sorption/desorption, and chemical reactions such as ion exchange, and complexation result in pollutant transformation (Sarao & Kaur, 2022).

7.0 Bioremediation of plastic using nanoparticles

Nanoparticles formed from titanium dioxide (TiO_2) have excellent catalytic properties. It has the best optimal catalyst properties as well as good semiconductor properties. Because it is quite stable. It's cheap, harmless, and possesses photocatalytic properties. Metal doping agents were utilized to change the substance's biological makeup and help in the absorption of visible light (Remya, et al., 2022). This nanoparticle is synthesized using a variety of processes, including Sol-gel, hydrothermal, micelle, and inverse micelle synthesis (Zan et al., 2006). When compared to conventional photolysis of plastic under natural conditions, the degradation of polymer polystyrene and TiO_2 has been successful in the breakdown process. The formation of reactive oxygen species on the TiO_2 surface favored the light catalytic reaction, resulting in a simple breakdown. Plastic deterioration using a polymer- TiO_2 composite is a promising method. By absorbing photons, pure polyethylene experiences scission, cross-linking, and photolytic destruction, which differs from photocatalytic degradation of nanocomposite films. The strong photodegradation capabilities of nanocomposite films in natural sunlight were specified during the fabrication of photodegradable LDPE - TiO_2 nanocomposite films (David et al., 2021).

8.0 Nanobioremediation

The iron oxide or magnetic core of paramagnetic iron oxide nanoparticles, also known as iron oxide nanoparticles, contains two unpaired electrons. Medicine, drug delivery systems, and LDPE degradation have been utilized by superparamagnetic iron oxide nanoparticles. The polymer was broken down using a bacterial consortium. The use of a superparamagnetic iron oxide nanoparticle in conjunction with a bacterial consortium was demonstrated to be effective in the degradation of polymeric polymers (LDPE). It was also demonstrated that superparamagnetic iron oxide nanoparticles in the bacterial broth, regardless of the presence of LDPE, resulted in increased growth (Kapri et al., 2010).

Fullerene 60 is a carbon-based nanoparticle with 60 carbon atoms. When used to manage the growth phase of LDPE disintegrating consortia of bacteria in minimum Davis broth lacking dextrose, these 60 carbon atoms cling together and form a closed structure resembling a soccer ball, indicating a powerful degradation analysis. *Pseudomonas putida* and *Pseudomonas aeruginosa* can degrade polyethylene (LDPE), epoxy, and silicone epoxy and act as a catalyst for the production of enzymes that cause plastic breakdown (Poornima, et al., 2022).

Nano barium titanate is made from a mixture of barium and titanium oxides (NBT). The use of nano barium titanate in the degradation of low-density polyethylene (LDPE) demonstrated that NBT can increase the exponential phase of the bacterial consortium (David et al., 2021). It was made with very little broth and can control the growth of LDPE disintegrating bacterial populations. Nutritional support is provided for the rapid evolution of bacterial consortiums, allowing the consortia to biodegrade plastic pollutants (Remya, et al., 2022). In the presence of nano barium titanate particles, bacterial consortiums demonstrated enhanced LDPE biodegradation (Sah, 2010).

9.0 Conclusion:

In this growing world, there is a large demand for chemically synthesized polymers. Polymers are long-chain molecules that are characterized by their side-chain structure and chemical composition. Though they are high-performance polymers they are non-biodegradable and therefore raise environmental concerns. Plastic poses harm to humans, marine life, and the environment. There is a serious need to reduce plastic pollution. Natural degradation results in microplastics that result in bioaccumulation. Bioremediation using microorganisms such as *Idionella sakaiensis, Brevibacillus sp.,* and, *Bacillus sp.*, have been identified for the degradation of plastic polymers.

Nano remediation employing nanoparticles like the TiO_2 has been explored. Integrated methods using both microorganisms and nanoparticles are of great interest as the efficiency of plastic polymer degradation is more. Although great results have been obtained for the degradation of plastic polymers using all three approaches has their drawbacks. The microbiological approach is time-consuming while neurotoxicological assessments need to be carried out while using nanoparticles. Therefore, analysis and assessment of the impact of nanoparticles on the environment are crucial before field application.

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