MINI REVIEW

A Review of Microalgae as Catalysts for Plastic Degradation in Marine Environments

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Abstract

Plastic pollution poses a significant threat to aquatic ecosystems due to the material's longevity and its common use. This review covers the sources, types, and environmental impacts of plastic debris, with a focus on biodegradation processes in aquatic environments. Worldwide plastic production was driven by the material's adaptability and low cost. Common plastic types include Polyethylene (PE), Polypropylene (PP), Polyvinyl chloride (PVC), and Polyethylene terephthalate (PET). Plastic degradation occurs through physio-chemical and biological series. Physio-chemical degradation is usually initiated by UV radiation, heat, or hydrolysis, and biodegradation involves a microbial enzymatic process. Key enzymes identified in plastic biodegradation include cutinase, lipase, PETase, lignase, and Peroxidase. The initial steps involve biofilm formation on plastic surfaces that can facilitate degradation, with diatoms being early colonizers along with bacteria. Multiple factors affect biodegradation, including polymer characteristics, environmental conditions, and microbial community composition. Various analytical techniques are used to assess plastic degradation, such as mass loss measurements, gel permeation chromatography, spectroscopic methods, and microscopy. The persistence of plastics in marine environments, coupled with their potential to release harmful additives and adsorbing pollutants, represents an ongoing challenge. Understanding degradation mechanisms is important for developing effective mitigation strategies and biodegradable alternatives. Future research is needed to understand the complexity between plastics, microalgae, and marine ecosystems, as well as to enhance biodegradation processes for more sustainable materials management.

Highlights:

- Plastic pollution threatens marine ecosystems due to longevity and widespread use.
- Common plastic materials include PE, PP, PVC, and PET and their fate in the Ocean.
- Degradation occurs through physio-chemical and biological processes, involving key enzymes like cutinase and PETase by microalgae and bacteria.
- Biofilm formation, including diatoms and bacteria, initiates biodegradation.
- This review focuses on research needed for plastic-microalgae interactions and enhancing biodegradation for sustainable material management.

Keywords: Biodegradation, Enzymes, Marine debris, Microalgae, plastisphere

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Introduction

Aquatic ecosystems are intricately linked to the terrestrial environment, resulting in interlinked impacts when changes occur. Industrialization and human evolution altered emerging new outputs on the planet, Plastics are the chain-like molecules that constitute a specific group of polymers. The worldwide plastic production has significantly grown from 1.5 million tons in the 1950s to 335 million tons in 2016 (W. C. Li *et al.*, 2016). Hydrocarbons are the main component of plastics, also a wide range of additives, such as fillers, plasticizers, flame retardants, UV and thermal stabilizers, antimicrobials, and coloring agents, may be added to the resin. During the resin-to-product conversion process improve the performance and look of the plastics. As a result, a class of products is created that can be rigid or flexible solids, adhesives, foams, fibers, and films. They have a wide range of desirable and adaptable features, such as strength, durability, light-weight, thermal and electrical insulation, and barrier capabilities (Law, 2017). Plastics are very adaptable materials because of their low cost, light-weight, robust, long-lasting, resistance to corrosion, and excellent electrical and thermal insulation qualities (Thompson *et al.*, 2009). The use of plastics is rising in developing nations as a result of their reduced unit costs and improved performance requirements, which encourage them to be substituted for commodities including paper, metal, wood, and glass. Approximately 90% of global

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plastic production is attributed to the widespread use of high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP), and polyethylene terephthalate (PET) (Andrady & Neal, 2009).

After use, the plastic ends up in water and soil as an inert matter. The sources of plastic pollution are complex, primarily stemming from a range of human activities (P. Li *et al.,* 2021). The amount of waste materials, particularly thermoplastic items, that end up in urban litter is growing. The environment cannot quickly biodegrade thermoplastics; thus, plastic waste can linger in the ecosystem for a long time. The lifetime of discarded plastics is very varied and relies on several factors such as the chemical composition of the material, and the degrading environment (Andrady, 2003). When describing the size of plastic contamination, three categories are commonly used: macroplastic (diameter >20 mm), mesoplastic (diameter 5- 20 mm), and microplastic (diameter<5 mm). However, reports of nanoplastics (less than 1000 nm) are increasing. (Thompson *et al.,* 2009) Micro and nano plastics can originate from primary industrial sources or the degradation of macro plastics (particle size: >5 mm) (Cole *et al.,* 2011). This is facilitated by different types of physical, chemical, and biological processes, which can lead to the fragmentation and degradation of plastics (Gewert *et al.,* 2015).

In the water column, Microplastics occupy the same size as plankton and sand grains, making them accessible to a wide range of species with varying feeding techniques. Organisms may thus consume unknown quantities in combination with natural prey items, particularly filter feeders, which filter enormous amounts of water and sediment for organic nutrients (Browne *et al.,* 2008).

Surface water organisms are likely to encounter plastics with a specific density less than that of seawater, such as polystyrene (PS), polypropylene (PP), and polyethylene (PE), whereas benthic organisms are susceptible to more dense or fouled plastics, including polyethylene terephthalate (PET) and polyvinyl chloride (PVC) (Cole *et al.,* 2013) (Fig.1). Nanoplastics (< 100 nm), either released to the environment or formed via the degradation of microplastics, may enter the food web via algae and bacteria, or be assimilated by filter-feeding organisms (Koelmans *et al.,* 2015). They are of unique importance because their small size allows them to penetrate biological membranes, affecting the function of blood cells and photosynthesis. (Galloway & Galloway, 2015).

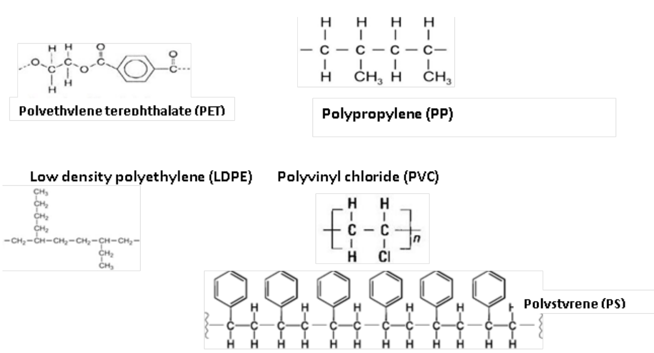

Fig. 1: Chemical structures of major plastic materials; PET, LDPE, PP, PVC and PS

The term "garbage patches" describes the vast expanses of water were waste and trash build-up. Gyres, which are ocean currents that aid in the movement of ocean waters around the earth, are responsible for these patches. In addition to moving ocean waves, they also move marine trash, particularly solid garbage from places near the coastline (Filho *et al.,* 2019). Specifically, there are six large and significant gyres: the North Atlantic, South Atlantic, East Pacific, North Pacific, South Pacific, and Indian Ocean. These gyres include garbage patches. The Great Pacific garbage patch, situated within the North Pacific gyre, is the largest in the world. The patch has an estimated 1.6 million km^2 in extent (Lebreton *et al.,* 2018); (Fig. 2)

Plastic debris in the marine environment

Debris or trash buildup is one of the anthropogenic risks to marine and coastal systems caused by unsustainable development and building activities (Thushari & Senevirathna, 2020). In contrast to various types of waste like glass, fabric, paper, organic matter, metal, rubber, medical and personal hygiene products, and wood; plastic debris exhibits an enduring presence in marine basins owing to distinctive attributes inherent in plastics for instance, their susceptibility to effortless conveyance by oceanic currents and air currents facilitated by extended durability. (C. Martin *et al*., 2022).

The destiny of plastic debris in marine environments

Polymer degradation is referred to as processes causing changes in the characteristics of polymers (deterioration of functionality) as a result of physical, chemical, or biological events that lead to bond cut and subsequent chemical modifications (creation of homologous) (Shah *et al.,* 2008). Plastic UV photo-oxidation, thermal oxidation, incineration, chemical oxidation, and landfilling are examples of processes presently used for the degradation of plastic.

Degradation of plastic polymers can proceed by either abiotic or biotic pathways (Małachowska *et al.,* 2021). Abiotic degradation typically occurs before biodegradation and is brought on by environmental UV radiation, heat, or hydrolysis (Andrady, 2011). Although biological enzymes can biodegrade smaller polymer fragments produced by abiotic degradation across cellular membranes, some microorganisms can release extracellular enzymes that can react with specific plastic

Fig. 2: Schematic overview of the major global plastic gyres with showing great pacific garbage patch in the North pacific gyre (Leal Filho *et al.,* 2021)

polymers (Shah *et al.,* 2008). The polymer surface is exposed and open to chemical or enzymatic attack, where plastics break down first. Because microplastic has a larger surface-to-volume ratio than meso- and macroplastic, it degrades more quickly (Gewert *et al.,* 2015); (Table.1). When a plastic material has surface cracking, the inside becomes more prone to deterioration, which ultimately results in embrittlement and disintegration. The degradation pathways for plastics: polymers having a carbon-carbon backbone and polymers with heteroatoms in the main chain. The backbone of PE, PP, PS, and PVC is made entirely of carbon atoms. Heteroatoms are present in the primary chain of PET and PU polymers (Gewert *et al.,* 2015). Plastics are expected to persist in the environment for thousands of years (Hassan & Haq, 2019). As plastic ages in the marine environment, it gives rise to a potential chemical hazard that results from the breakdown of the plastic polymer itself as well as the release of POPs from the plastic's surface and chemical additives leaking out of it (Gewert *et al.,* 2015) (Table .2). 20 % of marine plastic litter reaches the ocean, with commercial fishing being the principal human activity responsible for it. These abandoned fishing gear, such as nylon netting and monofilament lines, float at particular water depths, resulting in "ghost fishing" and possibly entangling aquatic life, there is a remarkable connection between the quantity of plastic debris from the ocean that washes up on beaches and the extent of commercial fishing (W. C. Li *et al*., 2016; Walker *et al*., 1997). Persistent, bioaccumulate, toxic compounds (PBTs) and plastic litter are two frequent ocean contaminants that work together to have an adverse effect.

In the marine food chain and human diets, plastic helps to concentrate and transport harmful substances from the ocean (Engler, 2012). Even though numerous additives have been identified as dangerous, plastic additives to marine organisms in contrast with hydrophobic organic compounds (HOC; Table 2)

Biodegradation of plastic debris in marine environment

In a material, any physical and chemical change that is caused by the action of microorganisms is known as biodegradation (Elahi *et al.,* 2021). Polymer characteristics, such as mobility, tacticity, crystallinity, molecular weight, the kind of functional groups and substituents present in its structure, and plasticizers or additives added to the polymer, all play a significant role in the degradation of biodegradation (Alhanish & Ali, 2023). Other factors that govern biodegradation include organism type pretreatment type and polymer characteristics (Artham & Doble, 2008). Degradation can occur both aerobically and anaerobically. In the aerobic form, bacteria use oxygen as an electron acceptor to break down large organic molecules into smaller ones,

Table 1: Report of microplastic pollution in Freshwater and Marine Aquatic ecosystems

Study Title	*Types Of Plastic*	*Key Findings*	*References*
Holistic assessment of microplastics in various coastal environmental matrices, southwest coast of India	Polyethylene (PE) and Polypropylene (PP)	Polyethylene dominates marine plastic pollution. It's most common in fish digestive tracts The study assessed microplastics in waters, sediments, and fish along India's SW coast. Widespread microplastic pollution found, posing potential environmental risks	(Robin *et al.,* 2020)
Microplastic pollution in Vembanad Lake, Kerala, India: The first report of microplastics in lake and estuarine sediments in India	Low-density polyethylene	First microplastic study in Vembanad Lake, India. All sediment samples contained microplastics (252.80 ± 25.76 particles/m^2). Poses threat to local food web contamination.	(Sruthy & Ramasamy, 2017)
Microplastics in Freshwater Ecosystems of India: Current Trends and Future Perspectives	Polypropylene (PP), polyethylene terephthalate (PET), and polyethylene (PE)	Reviews microplastics research in Indian freshwater ecosystems. Highlights growing MP contamination problem.	(Neelavannan & Sen, 2023)
A review of microplastic pollution research in India	PET, PE, PP, nylon, and PS	Summarizes microplastic pollution research in India. Covers sample types, common polymers, and adsorbed pollutants. Identifies research gaps and future directions.	(Chinglenthoiba *et al.,* 2023)
Microplastics along the beaches of the southeast coast of India.	polyethylene, polypropylene, and polystyrene	Microplastics accumulate on SE India beaches, higher near river mouths. Detected in the gut of commercial fish species. Indicates entry into the marine food web.	(Karthik *et al.,* 2018)
Characteristics and spatial distribution of microplastics in the lower Ganga River water and sediment.	Polyethylene	Microplastics found in Ganga River water and sediment. Higher concentrations in water; mostly white, film-shaped, 2.5-5 mm. Polyethylene most common plastic type.	(Singh *et al.,* 2021)
Microplastics as contaminants In Indian environment: a review	Microplastics (less than 5 mm in size)	Covers aquatic, terrestrial, atmospheric, and human consumables. Identifies knowledge gaps and future research needs.	(Vaid *et al.,* 2021)

Table 2: Commonly produced polymers and their associated plastic additives. (Adapted from (Hansen *et al.,* 2013)

Polymer	*Consumption in the EU27 (million tons) in 2015*	*Additive types*	*Amount in polymers (% w/w)*	*Hazardous substances*
PP	9	Antioxidant	0.05 - 3	Bisphenol A; Octylphenol; Nonylphenol
	9	Flame retardant (cable insulation and electronic applications)	12 - 18	Brominated flame retardant; Boric acid; Tris(2-chloroethyl) phosphate
HDPE	8	Antioxidant	0.05 - 3	Bisphenol A; Octylphenol; Nonylphenol
	8	Flame retardant (cable insulation application)	12 - 18	Brominated flame retardant; Boric acid; Tris(2-chloroethyl) phosphate
LDPE	6	Antioxidant	0.05 - 3	Bisphenol A; Octylphenol; Nonylphenol
	6	Flame retardant (cable insulation application)	12 - 18	Brominated flame retardant; Boric acid; Tris(2-chloroethyl) phosphate
PVC	5	Plasticizer	10 - 70	Phthalate
	5	Stabilizer	0.05 - 3	Bisphenol A; Nonylphenol
PUR	3.5	Flame retardant	12 - 18	Brominated flame retardant; Boric acid; Tris(2-chloroethyl) phosphate

producing carbon dioxide and water as byproducts (Müller, 2002). Anaerobic biodegradation is possible in thermophilic environments. Thus, bioplastic preparation before digestion is critical to promote biodegradability (Kaur *et al.,* 2024)

In the marine environment, plastics degrade through three main mechanisms: (i) microorganisms colonizing the polymer surface and forming a biofilm that causes biodegradation via surface erosion; (ii) abiotic hydrolysis of functional groups (esters, carbonates, and amides), which accounts for the molecular weight reduction and may be aided by the presence of hydroxide ions; and (iii) photodegradation caused by exposure to UV light and oxygen, which reduces the molecular weight and causes the material to crack. There are several methods for tracking the deterioration of polymeric materials. One may readily quantify the degree of polymer breakdown by assessing weight changes and calculating the mass loss (Viel *et al.,* 2023). Because both biotic and abiotic degradation can result in chain scission that produces low molecular weight chains and oligomers (Gewert *et al*., 2015). Microorganisms break it down into monomers that are taken up by microbial cells. Monomers are further degraded enzymatically within cells, serving as a carbon source for growth. The process can be altered by treating plastics before microbial attack to break down polymer using methods like heating, cooling, freezing, thawing, and chemical degradation. Enzymatic breakdown results in the mineralization of monomers yielding CO_2, H_2O, CH_4, N_2, and other metabolic products (Kaushal *et al.,* 2021).

The degradation is assessed in the laboratory using gel permeation chromatography (GPC), which aids in determining changes in polymer molecular weight during degradation (C. Li *et al*., 2024). The presence of functional groups of degraded products in the polymers as well as the occurrence of oxidation/hydrolysis processes during degradation can also be detected by molecular analysis of the polymer using nuclear magnetic resonance (NMR) and Fourier transform infrared (FTIR) spectroscopies (Rizzarelli *et al*., 2019). Moreover, degradation can be followed by determining changes in physical and functional properties. Polar functional groups can change polymer hydrophobicity/hydrophilicity during the degradation (C. Li *et al*., 2024). Water or Solvent method is the medium with angle measurements, mechanical and dynamic analyses of the materials can be used to determine the degradation point. Changes in glass and phase transitions of polymers can be evaluated via differential scanning calorimetry (DSC) (King, 2022), while the degradation effect on material thermal stability can be evaluated using thermogravimetric analysis (TGA). Morphological analysis using scanning electron microscopy (SEM) (C. Li *et al*., 2024) enables us to observe mechanisms of degradation on polymer surfaces. All of these technologies allow us to determine and follow the degradation of a polymer based on the triggers to which it is subjected (Viel *et al.,* 2023).

Anaerobic biodegradation is a process in which chemicals are broken down by microorganisms without the need for oxygen (McCarty & Smith, 1986). At locations where hazardous waste is stored, oxygen plays a crucial role in the natural attenuation of pollutants. Nitrate, iron, sulfate, manganese, and CO_2 are used by anaerobic bacteria as electron acceptors in place of oxygen to break down organic molecules into smaller units (Elahi *et al.,* 2021). Microorganisms can secrete extracellular enzymes to utilize the polymers as a source of energy. Outside of the microbial cells, these enzymes depolymerize polymers. Enzymes participate in the biodegradation of polymers both within and outside of cells. Depolymerization and mineralization are the two processes involved in anaerobic biological degradation of plastic polymers.

Enzymatic Pathways in Plastic Degradation

Enzymes are biocatalysts that operate on a specific substrate, take part in the reaction, and accelerate the transformation of that substrate into a useful product (A. Martin *et al*., 2023). The class "Hydrolases" includes all known enzymes that break down polymeric polymers. In the presence of water, this class of enzymes participates in a catalytic process that breaks the chemical bonds in its Substrate (Tokiwa & Suzuki, 1977). Enzymes that have been recently studied in enzymatic degradation of plastics comprise mainly esterase, cutinase, lipase, and PETase (Kyrikou & Briassoulis, 2007). Similar to one another, these enzymes work on the plastic polymer to hydrolytically cleave the lengthy carbon chains. The microbial cell then absorbs these smaller subunits for additional enzymatic breakdown and the release of metabolic products (Tokiwa & Suzuki, 1977). Recent research has demonstrated that the esterase enzyme from the yeast *Pseudozyma antarctica* speeds up the breakdown process (Martin-Closas *et al.,* 2016). A lipase derived from *Candida rugosa* was employed to break down the copolymer known as poly-butylene succinate-co-hexamethylene succinate (Shi *et al*., 2019). Cutinase from fungi *Fusarium solani* expressed in *Pichia pastoris* for enzyme overexpression to degrade PBS plastic (Hu *et al.,* 2016). PBS films degraded by enzymatic attack showed amorphous and crystalline structure degradation by recombinant enzyme (Maeda *et al.,* 2005) by *Aspergillus oryzae.* An enzyme with comparable functionality to cutinase, isolated from a yeast strain identified as *Cryptococcus sp*. Strain S-2, exhibited the capability to break down a high molecular weight plastic substance, specifically a polylactic acid (PLA) derived plastic (Van Gemeren *et al.,* 1998). *Ideonella sakaiensis* was identified as a bacterial strain capable of thriving on PET waste bottles by utilizing PET as its primary carbon source, facilitated by the enzyme PETase; This microorganism breaks down PET plastic into valuable monomers of terephthalic acid and ethylene glycol (Paci & La Mantia, 1999). The resilience of the enzymes that break down plastic allows them to function under unfavorable environmental circumstances, such as extreme environmental factors. A Technique that may be used to modify the functional groups of the enzyme's active site, so that it can more easily accept plastic polymers and function in a variety of pH and temperature ranges, results in mutagenesis.

The formation of microbial biofilms on the plastic surface can indirectly initiate the degradation of plastic polymers (Kumar *et al*., 2019). The environmental conditions of the tropical region make the growth of microbial biofilms faster (Villanueva *et al.,* 2011). Various microorganisms will find a new habitat in the plastic trash that builds up in the marine environment. It offers a robust substrate that enables the formation of microbial biofilms and is colonizable by microbes. The plastisphere is an ecosystem

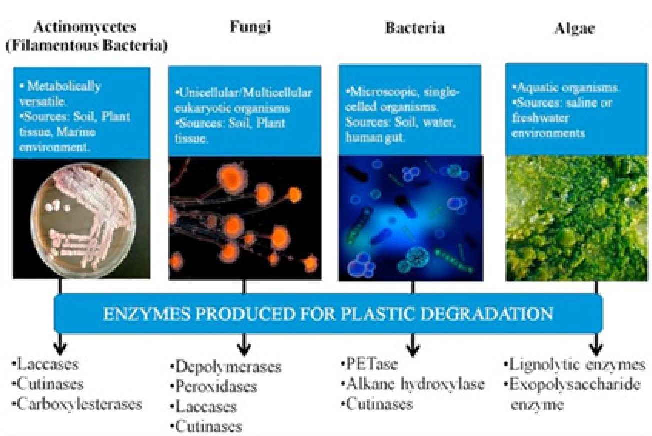

Fig. 3: Critical enzymes for plastic degradation from Actinomycetes, Fungi, Bacteria, Algae (Kaushal *et al*., 2021)

that has developed to survive in plastic environments. The combination of microbes with both organic and inorganic materials forms the plastisphere. (Galgani *et al.,* 2018).

When bacteria initially connect to the plastic waste substrate, a film layer forms that might impact the surface qualities of the material and influence the colonizing of microorganisms (Rummel et al., 2017). Microbes create extracellular polymeric substances (EPS) that aid in cell adherence to surfaces bind other organic compounds in the surrounding environment, speed up the metabolism of the microbes by utilizing their extracellular enzymes, and offer mechanical and physical stability (Flemming & Wingender, 2010). EPS is composed of polysaccharides, proteins, nucleic acids, and phospholipids (Sheng et al., 2010) (Fig.3)

Microalgae-Mediated Plastic Degradation

Microalgae such as Diatoms, Cyanobacteria, and Coccolithophores groups are the fastest and earliest microbial groups to attach and form colonies on plastic substrates (Casabianca *et al.,* 2019). A robust substrate and an attachment point for a variety of marine micro and macro-organisms are provided by the macroplastic debris in the waters. In approximately one- week, native bacteria found in aquatic environments will be able to adhere and create a biofilm layer on plastic materials like PS (polystyrene), PVC (polyvinyl chloride), and PET (polyethylene terephthalate) that have been submerged in water. Furthermore, among the first and fastest microbial species to adhere to plastic substrates coated in microbial biofilms are the microalgae belonging to the Diatom, Cyanobacteria, and Coccolithophores families (Casabianca *et al.,* 2019; Eich *et al.,* 2015).

Chlamydomonas reinhardtii CC-124 (mt- [137c]) is a Common laboratory wild-type strain that harbors the nit1 and nit2 mutations and is commonly employed for gene transformation, A cell wall-less mutant of CC-125 called *C.reinhardtii* CC-503 was created for effective transformation. PET's catalytic activity Cell lysate of the transformant, generated by *C. reinhardtii*, and PET samples were co-incubated at 30 °C for a maximum of 4 weeks. Terephthalic acid (TPA), or the fully-degraded form of PET, was found using high-performance liquid chromatography (HPLC) analysis following incubation (Kim *et al.,* 2020). Protein enzyme genetic engineering methods aimed at producing ecologically friendly bioplastics from natural fibers as an alternative to synthetic petroleum-based plastics and enhancing the catalytic activity of hypothesized plastic-biodegrading enzymes. Plastic-degrading enzymes that have undergone genetic modification exhibit enhanced substrate interaction, greater hydrophobicity, superior catalytic efficiency, elevated thermostability, and optimized plastic biodegradability (Nyakundi *et al.,* 2023). *Uronema africanum* Borge, a possible microalga was isolated from a plastic trash bag that was discovered from a home garbage dump at Kallukuttai Lake, Tamil Nadu. Once the LDPE sheet was applied to this microalga, deterioration was seen (Sanniyasi *et al.,* 2021). More research is going on consortia of marine microalgae for the unveiling of plastic degrading enzymes for a fast degradation process.

Microalgae-Driven Plastic Breakdown in Environment

The plastic degradation process is a complex process involving a consortium of microorganisms in the biofilm (Afianti *et al.,* 2022). Diatoms were one of the first colonizers and also the most commonly abundant microalgae on the plastic debris in the ocean (Amaral-Zettler *et al.,* 2020; Carson *et al.,* 2013). Among the diatoms group, pennate diatoms, particularly of the genera *Mastogloia, Haslea, Frustulia, Diploneis, Ardissonea*, *Fragilaria, Protoraphis*, and *Thalassionema* were commonly found and abundant on the plastic debris in the Northeast Pacific Ocean (Carson *et al.,* 2013).

The intricate process of biodegradation is influenced by several factors, including the availability of the substrate, its shape, its surface properties, and the molecular weight of the polymer. Naturally, things can deteriorate chemically, physically, or biologically. Microorganisms will aid in the biological degradation process and function as efficient bioremediation agents (Ammala *et al.,* 2011). Targeting carbohydrate-active enzymes (CAZymes) and plastic-degrading enzymes (PDZymes), metagenomics, and genome binning techniques were used to analyze DNA samples taken from MPs' plastisphere and soils. The findings showed that all investigated exoenzyme abundances were greater in the plastisphere of MPs than in soils, and that the plastisphere of MPs had substantially different patterns of CAZymes and PDZymes from soils (Hu *et al.,* 2024). Effective techniques that combine sequence- and function-based screening to isolate new polyethylene terephthalate-degrading enzymes (PETases) from culturable and non-culturable bacteria. This methodology may be modified to identify more plastic hydrolases and other enzymes (Pérez-García *et al.,* 2021). The degradation of plastic polymer will be analyzed in future studies.

Conclusion

The kind of plastic and its additives, the environment (temperature, pH, oxygen content), the availability of nutrients, and the composition of the microbial community are some of the variables that affect how efficiently plastic biodegrades. Nevertheless, the process faces several difficulties, including incomplete degradation that results in the production of microplastics, weak degradation rates, particularly for resistant plastics, and the possible release of hazardous compounds during breakdown.

Identifying and improving microbes that break down plastic, creating more biodegradable polymers, and comprehending the long-term ecological effects of this process are the major bottlenecks in this line of study. Increasing our understanding of microorganism-mediated biodegradation is crucial for creating practical mitigation plans and maintaining the health of our oceans as plastic pollution continues to endanger marine ecosystems.

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Author's Contribution

Ayana P P: Manuscript preparation and writing
Swetha M K: Writing of the manuscript
V P Limna Mol: Formulation of the work plan, manuscript preparation, and edition

Conflict of Interest

The authors declare that they have no conflicts of interest relevant to this manuscript.

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