International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 4s, 2025
https://www.theaspd.com/ijes.php

Sustainable Approaches To Plastic Degradation In Aquatic Environments: A Review Of Mechanisms And Challenges

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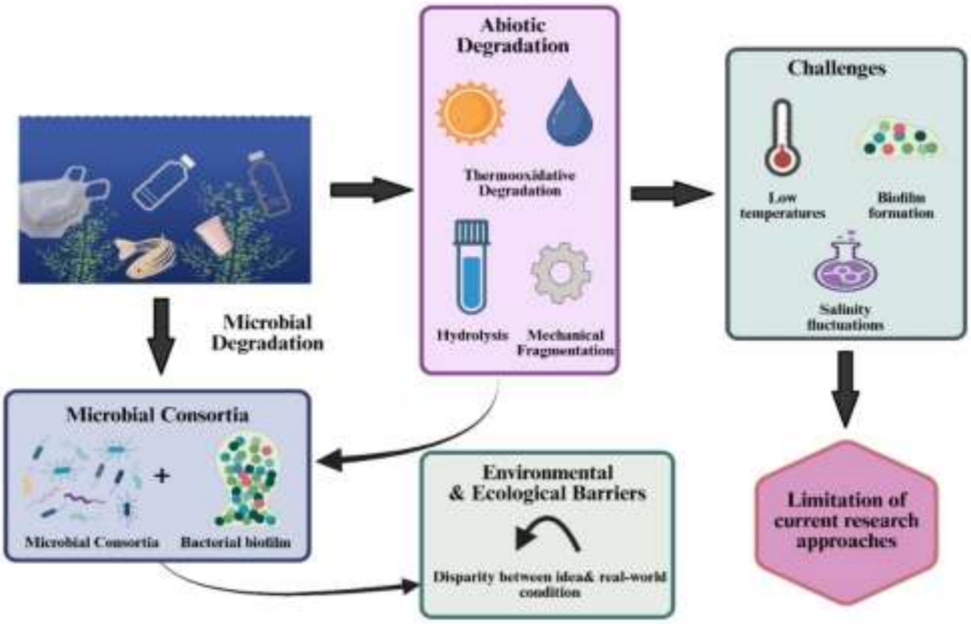
Abstract
Plastic has always been a pollutant in the marine ecosystem, where several kinds of plastics have been widely used along with their different applications. The increase in plastic waste in aquatic environments is a serious environmental concern, primarily due to its persistence in the degradation process. This review emphasizes the different mechanisms for plastic degradation, mainly in water sources. They can be further categorized into biotic and abiotic processes. Abiotic degradation involves many techniques, out of which photodegradation, thermos oxidative degradation, hydrolysis, and mechanical fragmentation are precursors to microbial degradation. Microbial influence on plastic degradation has also been examined, highlighting microbial consortia in breaking down synthetic polymers as well as bacterial biofilms. Many challenges persist due to environmental and ecological barriers despite promising microbial mediated degradation. Different types of barriers may include low temperatures, biofilm formation, and salinity fluctuations. In addition to that, the limitations of current research approaches, including the disparity between ideal and real-world conditions, hinder the development of scalable solutions. It is very important to address these gaps to advance sustainable plastic waste management and mitigate the long-term impacts of plastic pollution in aquatic environments.

Graphical Abstract



Keywords: Biodegradation, aquatic environment, high-density polyethylene, low-density polyethylene, microbial consortia.

Introduction

An ecosystem serves as a functional unit consisting of a specific environmental habitat or biotope and its organisms, referred to as biocenosis. Our everyday existence relies on numerous services provided by the Earth's ecosystems. Ecosystems of habitable planets are typically divided into two primary categories: water-centric aquatic and land-based terrestrial ecosystems. A terrestrial ecosystem refers to an ecosystem that pertains to or is associated with land, as opposed to water. Aquatic ecosystems represent a category of ecosystems where water plays an essential role. Aquatic ecosystems are defined as ecosystems that depend on constant freshwater flooding. Marine and freshwater ecosystems consist of all biotic and abiotic components and the interactions among them in a water-oriented environment [1]. The marine environment is a very productive area that includes various subsystems like coral reefs as well as seagrass. It is a diverse ecosystem featuring rich biodiversity that provides for different primitive species and more complex organisms. The oceanic habitat is the extensive water body that encompasses 71 % of the planet's surface. Nonetheless, the global ocean system is divided into five principal oceans and numerous seas, influenced by historical, geographical, cultural, and scientific traits and differences in size. Five ocean basins, namely the Arctic, Pacific, Indian, Atlantic, and Antarctic, are the majorly recognized marine ecosystems affected by human invasion [2].

Aquatic ecosystems are linked to the terrestrial ecosystems; thus, modifications in one system affect the other. For many years, various factors, such as human activities, have put pressure on coastal and marine ecosystems. These pressures encompass environmental pollution and tangible damage to nature. The buildup of trash or pollutants creates a significant danger to marine and coastal ecosystems, resulting from unsustainable development and construction practices. Plastic pollution is enduring in ocean basins because of the distinctive properties of plastics. With a total of five trillion pieces weighing over 260,000 tons, plastic waste is drifting on the ocean's surface due to inadequate waste management [3].

Plastics negatively impact the environment by damaging habitats [4], entangling marine creatures [5], aiding the movement of invasive species between ecosystems [6]. When ingested by marine creatures, plastic can cause chemical and physical effects. Aside from entanglement, physical effects encompass obstructions in the digestive system when marine creatures ingest plastic [7], potentially causing false feelings of fullness [5].

There exist thousands of varieties of plastic polymers, yet six substances predominantly govern the market and the waste present in marine ecosystems: polypropylene (PP), polyurethane (PUR), polyethylene (PE), polyvinyl chloride (PVC), poly terephthalate (PET), and polystyrene (PS). These account for around 80 percent of overall plastics production [8]. Not every type of plastic poses the same level of issues. Surveys of litter on beaches, in oceans, and along rivers indicate that some plastic products and materials have a higher likelihood of entering the environment compared to others, and approximately 50% of items discovered in beach surveys highlight single-use plastic products [9]. Approximately 70% of ethylene in the Middle East is used for producing polyethylene, whereas 91% of propylene is for polypropylene. Another broadly used plastic is polyethylene, a thermoplastic polymer, which represents 64% of synthetic plastics produced. Low-density polyethylene (LDPE) and high-density polyethylene (HDPE) are the two most prevalent varieties of polyethylene [10], [11]. According to several researchers, LDPE plastic is responsible mainly for microplastic pollution, posing significant environmental risks due to inadequate management at the final stage of the value chain and severely contaminating the oceans [12][13]. LDPE finds extensive applications in the production of polythene bags as well as food storage containers [14] [15].

Plastic waste thrown into water bodies slowly breaks down into tiny pieces called microplastics, ranging in size from 0.05 to 5. The prevalence of microplastics (MPs) represents a significant threat to aquatic ecosystems and, consequently, human health, as these particles are consumed by numerous marine species, such as crustaceans, zooplankton, and fish, ultimately making their way into the human food chain. This pollution endangers the whole ecological equilibrium, including food safety and the well-being of aquatic ecosystems [16].

The presence of plastics in aquatic ecosystems influences various factors, such as density and fouling, which shape their impacts on marine life. Once fragmented, lower-density MPs float on the surface of water, while high-density

MPs sink and accumulate in the sediment [17]. Following this, MPs move between organisms, water, and sediment through ingestion and bioturbation, followed by excretion. Furthermore, the influx of freshwater and ensuing turbulence can result in the spread or disturbance of microplastics in aquatic settings. A recent investigation employing simulation methods has shown that the migration of microplastics in rivers is significantly affected by water flow, which impacts their transport into aquatic habitats. The influence of microplastics is more significant than that of the initial large-size plastic particles because of their ability to penetrate viable tissue [18].

Plastics consist of various compounds, encompassing a wide array of chemicals. These comprise fundamental substances like monomers, oligomers, or polymers, which are primarily categorized into antioxidants, plasticizers, pigments, and heat stabilizers [19]. Upon being discharged into the ecosystem, plastics, along with microplastics, may undergo degradation processes, including hydrolysis, thermal oxidative degradation, biodegradation, and photodegradation [20]. Microbial-driven degradation is considered a primary method to address plastic pollution effectively, where microorganisms utilize carbon sources derived from biodegradable substances to metabolize, resulting in the production of non-toxic by-products and supplying nutrient sources and energy source to microorganisms or converting them into other beneficial materials. Biodegradation can effectively lessen the negative impact of plastic additives and promote a healthier ecological system [21].

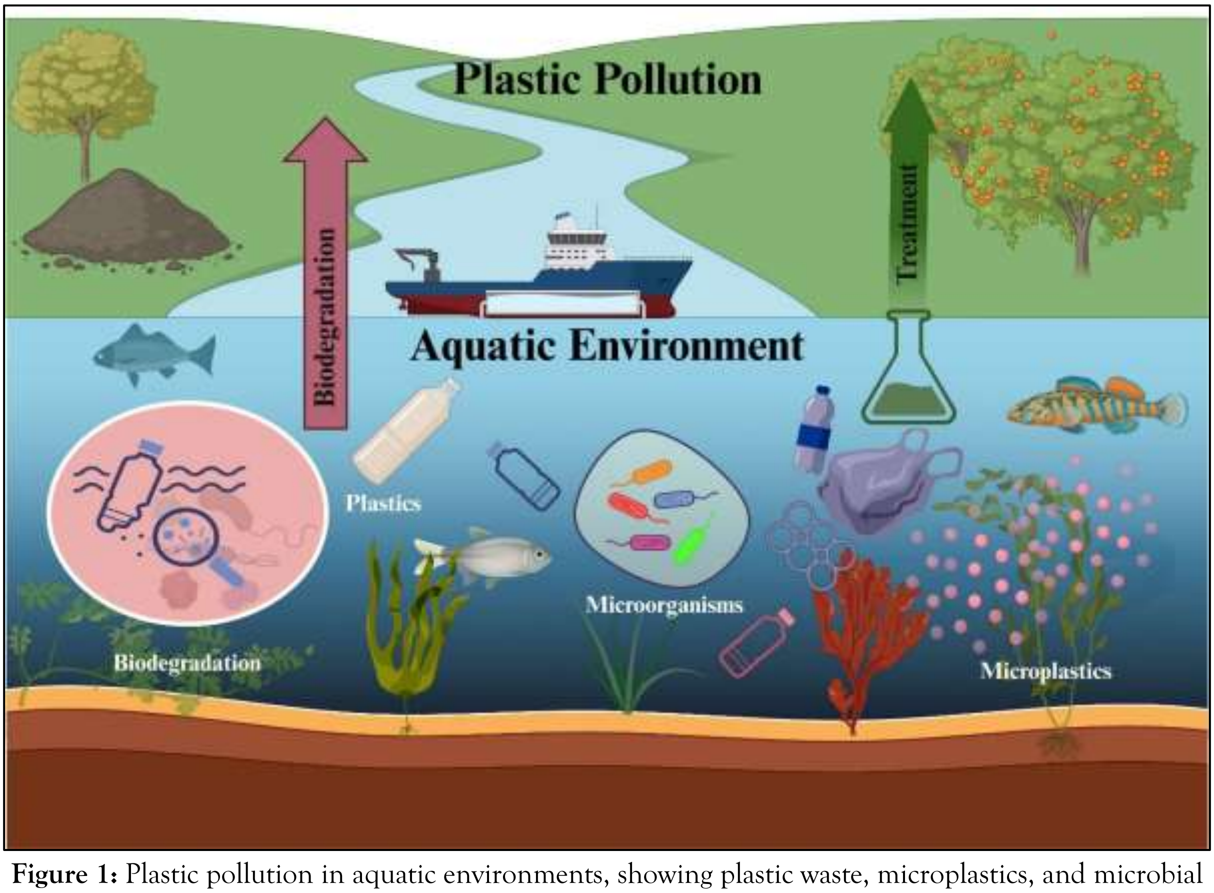


Figure 1: Plastic pollution in aquatic environments, showing plastic waste, microplastics, and microbial biodegradation as a treatment approach [21].

2. Plastic Degradation in Aquatic Ecosystems

In 2017, plastic production hit 348 million tons, raising the volume of plastic waste in the environment. Plastic debris dispersed on land will be transported by water flows to contaminate the marine ecosystems. The extensive use of plastic leads to a significant generation of plastic waste globally. Plastic waste that contaminates the environment comes in different types and sizes [22].

The deterioration of plastic waste in water bodies is due to different environmental elements linked to certain microorganisms. The initial stage or primary degradation phase occurs via mechanical degradation, photodegradation triggered by UV light from sunlight, oxidation, and hydrolysis, along with the aid of various organisms. This method generates smaller pieces of plastic or microplastics. Incomplete plastic breakdown from different environmental influences results in small plastic particles, ranging from 1 to 5000 μM, referred to as microplastics, which can subsequently be converted into nanoplastics via additional mechanical degradation. Nano-plastics are the type of plastic that is difficult to recognize directly in aquatic environments, which often leads to its consumption by marine organisms and its movement through the food chain [23]. Synthetic polymers may also be broken down by various microbial processes involving bacteria, fungi, and algae, which generally require a considerable amount of time and include certain specific enzymes [22]. Biodegradation is regarded as a superior method. It is carried out with a range of plastic-degrading microorganisms, which are facilitated by different enzymes that degrade plastics. Microorganisms that degrade plastics will use this resistant polymer as their energy and carbon source [24].

2.1 Types of plastics most commonly found in aquatic ecosystems

The plastics most frequently encountered in aquatic environments are widely utilized polymers like high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polyethylene terephthalate (PET), polylactic acid (PLA) [25] [26] [27]. These substances can build up in various environmental matrices, specifically in aquatic habitats, resulting in the emergence of meso -, micro-, or nano-plastics during their breakdown, typically referred to as secondary particles [28]. Pre-formed microplastics are examined here in the form of particles created in sizes below one millimetre for particular applications, and particles derived from macroplastic products significantly enhance the level of pollution. This presents serious challenges for worldwide ecosystems and calls for awareness [29].

According to Meng *et al.*, (2024), polyethylene is noted for being the most common and widespread polymer category in the marine ecosystem and exists in far greater amounts and mass concentrations than other plastics[30]. Polyethylene is categorized into low-density polyethylene (LDPE) and high-density polyethylene (HDPE) due to variations in chemical resistance, toughness, clarity, and flexibility. HDPE primarily consists of linear chains, whereas LDPE features a significant level of branching. Polyethylene is viewed as a persistent material, which has led to its widespread presence and excessive buildup in the environment. HDPE is usually noted for its high density-to-strength ratio; it exhibits intermolecular forces that are robust and can withstand various solvents. LDPE withstands acids, alcohols, and bases, yet it becomes unstable when exposed to strong oxidizing agents along with both aromatic and aliphatic hydrocarbons [31].

According to several researchers, poly (ethylene terephthalate) is a polyester with a crystalline structure that is chemically stable and colorless. It is also frequently utilized in making containers and packaging for food and beverages, along with electronic parts. PET exhibits significant resistance to elevated temperatures, alcohol, and solvents, and upon orientation, it demonstrates exceptionally robust mechanical strength, particularly against wear and tear [32] [33].

Oliveria *et al.*, (2020) demonstrated that polyvinyl chloride (PVC) is a non-crystalline polymer with thermoplastic properties produced in two forms: a flexible type for films and a rigid type for structural applications. PVC is a chemically stable polymer that resists acids along with inorganic substances, yet it is susceptible to ultraviolet light. PVC is a stiff and fragile substance that requires modification. PVC demonstrates outstanding resistance to oils as well as fats. The level of permeability to gases and water vapour relies on the plasticizer quantity, which is incorporated during production [27].

According to Qi *et al. (2018), PLA, or polylactic acid, belongs to the class of aliphatic polyesters* generated through fermentative biotechnological methods utilizing agricultural sources as raw materials, such as corn, wheat, and sugarcane. Although PLA is not easily biodegradable, it can be recycled and becomes biodegradable in industrial composting environments. Nonetheless, the complete capability of this polymer can only be realized through the establishment of appropriate facilities for separation, recycling, followed by composting PLA plastics [34] [35] [36].

Spoerk *et al.*, (2020) suggested that polypropylene (PP) is denser and robust than PE, and it is usually transparent in its original state. In comparison to polymers aside from PE, it has the minimum density and is comparatively inexpensive. It also possesses other desirable characteristics, such as acting as a water vapor barrier and exhibiting resistance to fats and oils. Due to its elevated melting point, it is appropriate for uses like microwave packaging [37].

Microplastics or MPs are plastic fragments 1 μM to 5 mm and belong to a category of macromolecular polymers characterized by significant heterogeneity. These microplastics are extensively found in both aquatic and terrestrial environments, posing possible dangers to ecosystems and humans via inhalation, ingestion, skin contact, and the food chain [38].

Low-density polyethylene (LDPE) ranks among the most highly utilized plastic materials owing to its adaptability and efficiency and is commonly utilized in manufacturing plastic bags [39]. Low-density polyethylene (LDPE), representing 20% of worldwide plastic production, is released in large amounts within the ocean, endangering marine organisms and ecosystems. Nonetheless, LDPE emerged as a notable pollutant in marine settings. Various research studies showed that marine bacteria efficiently break down LDPE film, potentially decreasing plastic pollution in the ocean [40] [41]. LDPE identified a notable source of pollution in the ocean. Various research studies have shown that the marine bacteria can effectively degrade LDPE film, highlighting their potential in plastic waste reduction. Therefore, the marine ecosystem may act as a possible source for native plastic-degrading microbes [42]. Previously, it has been stated that marine microorganisms has the ability to breakdown the LDPE plastics [40].

The different types of polymers used in plastics possess distinct characteristics that can affect their performance in various settings. An essential element in the ocean ecosystem is the concentration of plastics present in seawater. For example, PE, primarily LDPE, usually shows a density of under 1 $kg.m^{-3}$, enabling this kind to remain buoyant in both salt and freshwater. The reason behind this is that it is among the most frequently encountered kinds of plastics when samples are taken from surface waters [43].

2.2 Factors Influencing Plastic Degradation

Veerappapillai *et al.,* (2015) showed that the breakdown of a polymer is influenced by various factors such as humidity, temperature, oxygen, stress, sunlight, microorganisms, and impurities [44].

Andrady *et al.* (2003) demonstrated that factors like weather conditions, location, and different contaminants may affect the methods and breakdown rate of plastics [45]. Sunlight is among the most vital elements that influence plastic breakdown. As the light intensity rises, the pace of the photooxidation process accelerates, leading to a rise in the pace of plastic breakdown [46]. Furthermore, the rate of abiotic degradation increases as temperature rises [47], with the process rate doubling for a rise of 10 °C. The temperature may influence the motion of the polymer chain, which in turn impacts its enzymatic function through microbial breakdown. It also impacts the rate of the hydrolysis reaction by altering the generation of free radicals, the oxygen diffusion rate, and humidity [48].

The chemical and physical characteristics of plastic materials are essential to the degradation process. The vulnerability of PWs to both biotic and abiotic degradation is influenced by the polymer chain length and the composition of the plastic polymer backbone; thus, longer carbon chains can enhance the polymer's resistance to degradation [49] [50].

Typically, UV-B sunlight radiation refers to the primary trigger for the (photooxidative) light-induced oxidation breakdown of frequently used plastic polymers such as HDPE, PP, LDPE, and nylons when exposed to conditions of the marine environment. Next, the deterioration process persists with the thermo-oxidative reaction for some time, lacking further exposure to UV radiation [51].

3. Mechanisms of Plastic Degradation in Water Sources

Plastics break down in the ecosystem through four mechanisms: thermooxidative degradation, photodegradation, biodegradation by microorganisms, and hydrolytic degradation. In general, the natural breakdown of plastic starts with photodegradation, followed by thermooxidative degradation [20]. Abiotic degradation, often referred to as non-biological degradation, involves the breakdown of plastic due to physical weathering, hydrolysis, and photochemical processes. Temperature, sunlight (UV radiation), chemical processes, and physical stress are among the factors that can lead to abiotic degradation [52]. Andrady *et al.,* (2011) demonstrated that Abiotic degradation (AOPs) typically happens before biotic degradation and is triggered by exposure to heat, water, or ultraviolet light in the environment [51].

3.1 Chemical and Physical Processes in Water Sources

Polymers may experience radiation degradation and photodegradation when subjected to wavelengths within the UV, visible, and gamma radiation, and infrared (IR) spectrum. Photodegradation can happen without O2 (photooxidative degradation) and O2 (photolysis), resulting in chain scission, rearrangement, and cross-linking. The extent of photodegradation relates to the wavelengths present in sunlight: ultraviolet (UV) radiation, infrared (IR) radiation, and visible light. In photolysis, the absorption of light directly results in chemical processes that result in deterioration. For polyamides and polyesters, the process of photolysis involves two separate photolytic reactions [53].

Sharma *et al.,* (2008) showed that thermal breakdown results from subjecting a polymer to heat over a prolonged duration and is termed thermo-oxidative degradation when oxygen (O2) is present. The first stage of thermal decomposition entails the rupture of macromolecular bonds, leading to the formation of radicals or monomeric segments that can interact with O2 to produce peroxide radicals [54]. Thermal degradation is the primary process at high temperatures because its rate surpasses that of hydrolysis, mechanical degradation, and photodegradation.

Lucas *et al.,* (2008) indicated that for biodegradable polymers, the thermal degradation occurs within the melting temperature range, which encompasses temperatures significantly above the range where biodegradation predominantly takes place under thermophilic as well as mesophilic conditions (20–60 °C). The melting temperature (Tm) of PLA is approximately 155 °C, and for poly(hydroxy butyrate) (PHB) is 175 °C, suggesting that thermal degradation will neither influence nor speed up the biodegradation process [55].

Bher *et al.,* (2022) indicated that chemical hydrolytic degradation is a main abiotic breakdown route for compostable polymers, particularly for polyesters that are aliphatic and aromatic [53].

As stated by Lucas *et al.* (2008), mechanical degradation refers to the decline in mechanical characteristics exhibited by a polymer's functionality due to the effects of mechanical stresses and exposure to harsh conditions. Mechanical degradation can occur due to compression, tension, and shear stresses applied to a polymer [55]. Conversely, physical forces like cooling, heating, drying and wetting, as well as surface turbulence generated by air or water, could result in mechanical degradation due to stress fractures [56].

According to Devi *et al.,* (2016), regarding environmental factors, an increase in the humidity as well as temperature speeds up the process of chemical hydrolysis [57]. The mobility of polymer chains rises with the temperature rise. Consequently, the susceptibility of hydrolysable bonds to chain cleavage increases. The water's chemical potential in the environment greatly affects the polymer hydrolysis [58]. Hydrolysis in acidic or basic environments may happen via various mechanisms, resulting in different reaction byproducts [59]. Ultimately, catalysts can enhance the speed up hydrolytic reaction rate [60][61]. Regarding polymer characteristics, Hydrophilic polymers show more susceptibility to hydrolytic breakdown than hydrophobic polymers [56].

Larrañaga *et al.,* (2019) demonstrated that PLA serves as an instance of breakdown of chemically hydrolysable polymers. In this regard, the conditions surrounding the material, along with variables like temperature, pH, and moisture, significantly influence the rate of hydrolytic degradation, either hastening or slowing it down [62].

3.2 Role of Microbial Activities in Degradation

Shah *et al.,* (2008) proposed that microorganisms' capacity to biologically break down polymers reduces with the rise in the molecular weight of the polymer. As the molecular weight increases, the solubility of the polymer decreases, making it less vulnerable to microbial attack, since the polymer must be integrated within the cell membrane of bacteria and broken down by cellular enzymes [63]. Furthermore, Singh *et al.,* (2008) showed that photo-oxidation, abiotic hydrolysis, and physical breakdown improve biodegradation [54].

Cai *et al.,* (2023) have documented, through various studies, the application of bacterial biofilms, individual bacterial cultures, and bacterial consortia for plastic degradation [64].

As stated by Zhai *et al.,* (2023), bacterial strains promote metabolic activities that assist in the adsorption, desorption, and degradation of plastics [65]. However, these microorganisms utilize polymer substances as their exclusive carbon source in nutrient-scarce environments, leading to a reduction in dry weight, molecular distribution of polymers, and average molecular weight while also inducing changes in chemical structures and morphology. This indicates that, in truth, these microorganisms may aid in diminishing microplastic and plastic contamination in the ecosystem [66].

Cao *et al.,* (2022) showed that bacterial consortia, which consist of two or more than two bacteria coexisting symbiotically, were also utilized to investigate plastic degradation. Employing bacterial consortia provides a reliable microbial community, removing the effects of detrimental metabolites generated by particular strains into the consortia [67].

4. Challenges in Plastic Degradation in Aquatic Environments

Many efforts have been undertaken to assess the extent of plastic contamination in aquatic ecosystems, with most concentrating on the accumulation of waste along shorelines [20]. This is probably because plastics tend to float and, consequently, frequently accumulate on coastlines [68]. The bulk of the debris observed on the analyzed beaches, in terms of quantity, is made up of plastic materials; often, three-fourths of the overall waste found on the coastline is of plastic origin [20] [69]. The notable abundance of plastic debris in the surroundings is associated with the extensive availability of plastic products and their longevity within the ecosystem [70] [71].

4.1 Environmental and Ecological Barriers in Water Systems

Numerous ecological and environmental factors impede the breakdown of plastic in water environments. The efficiency of biodegradation is reduced in freshwater and deep-sea habitats because to the low oxygen levels and low temperature, which act as a barrier for microbial activity [48]. Furthermore, biofilms that are commonly formed by plastics have the potential to either inhibit or alter the pace of breakdown by shielding the material from microbial harm. Variations in salinity in marine ecosystems additionally influence microbial communities, obstructing their capacity to decompose synthetic polymers [27]. In addition to that, UV radiations may also trigger photodegradation; however, this process is time taking and mainly impacts plastic exposed to the surface, with waste under the water remaining mostly unchanged. Another issue to be addressed is plastic getting converted into microplastics, as these tiny particles of plastic remain in the ecosystem without full mineralization, which results in prolonged environmental build-up [72]. All these elements together result in the longevity of plastics in water bodies, making it more challenging for waste management and ecosystem restoration.

4.2 Limitations in Current Research Approaches

Many significant advancements have been made till now for understanding plastic degradation; despite that, current research faces several limitations. Notable research has been carried out in regulated laboratory settings, which have failed to accurately replicate aquatic environments' complex and dynamic nature. Factors such as variable temperature, salinity, microbial diversity, and hydrodynamic conditions are often neglected, which leads to differences between laboratory findings and real-world degradation rates [73]. Also, standardized methods for estimating plastic biodegradation have been somewhat lacking, which makes it difficult to compare results across studies. This research also focuses on particular microbial strains or enzymes, whereas real-world situations are completely different, consisting of all sorts of microbial consortia, making interactions very unpredictable [74]. It is very crucial to address these gaps to develop effective and scalable plastic waste management strategies in aquatic ecosystems.

Conclusion

The persistence of plastics in aquatic ecosystems poses a significant challenge for the environment, making it necessary to understand their degradation mechanisms in detail. Abiotic degradation processes initiate polymer breakdown, while microbial biodegradation plays a crucial role in further decompositions. Research has demonstrated the potential of bacterial strains, biofilms, and consortia in conducting plastic degradation; however, environmental factors like temperature variations, salinity fluctuations, and oxygen limitations hinder the efficiency of these processes. Additionally, the lack of standardized methodologies and the difference between lab results and actual real-world situations present further obstacles to effective plastic waste management. In the future, the research should be more focused on the development of bioaugmentation strategies, optimizing microbial consortia, and implementing real-world degradation studies to enhance plastic bioremediation. A multidisciplinary approach that can sum up all the efforts from microbial ecology, polymer science, and environmental engineering is vital for devising effective strategies to reduce plastic pollution and promote ecosystem restoration.

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