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Biodegradation of Microplastics: Mechanisms, Challenges, and Future Prospects for Environmental Remediation

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ABSTRACT: Microplastics are widespread environmental pollutants detected in aquatic, terrestrial, and atmospheric ecosystems. Their persistence, coupled with their potential to bioaccumulate and release toxic additives, raised serious concerns for both environmental and human health. This study aimed to assess microbial biodegradation as a viable strategy for reducing microplastic pollution. The research focused on the mechanisms through which microorganisms, particularly bacteria and fungi, degraded plastic polymers under various environmental conditions. Several microbial strains demonstrated the ability to degrade polymers such as polyethylene, polystyrene, and polyvinyl chloride, albeit at varying efficiencies. Environmental parameters such as temperature, pH, oxygen availability, and nutrient concentration, were found to significantly influence the rate and extent of microbial degradation. Despite these promising findings, the overall degradation rates observed in natural environments remained low. Moreover, challenges related to microbial specificity, metabolic limitations, and the scalability of degradation processes hindered the practical application of microbial treatments on a large scale. The complexity of polymer structures and the additives used in plastic manufacturing further complicated microbial breakdown. To overcome these barriers, future research should prioritize genetic engineering of microbial strains and the optimization of bioprocesses to improve degradation efficiency. Such advancements could pave the way for sustainable and effective biotechnological solutions to mitigate microplastic pollution.

KEYWORDS: Environmental pollution; microplastics; microbial biodegradation; enzyme mechanism; treatment technology

1. Introduction

Microplastics were defined as extremely small plastic particles, typically less than 5 mm in size, that fragmented from larger plastic items [1]. They consisted primarily of carbon and hydrogen atoms bonded together in long polymer chains. Plastics were extensively used in daily life and had become ubiquitous across various environments. Approximately 80% of global plastic usage consisted of polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polycarbonate (PC) [2]. The types of microplastic polymers, along with their structures and common applications, are presented in Table 1. Microplastics occurred in various forms, including fibres, fragments, films, foams, beads, and pellets. They entered the environment when they detached from original products and were found in diverse habitats, from terrestrial areas to aquatic systems. Typically, microplastics contained chemical additives and non-intentionally added substances (NIAS). Most of these substances were not chemically bonded to the polymer chains and could leach into the environment over time [3]. As a result, microplastics posed serious threats to wildlife, which often mistook them for food, leading to bioaccumulation within the food chain and eventual human exposure. Organisms that ingested microplastics experienced physical harm, toxicological stress, and, in severe cases, death.

Table 1. Common plastic polymers, their uses, and production characteristics.

Polymer	Production and Utilization	Typical Uses	Reference
PE	One of the most widely produced plastics globally; accounts for over 30% of total plastic demand	Used in food packaging, plastic bags, bottles, toys, and fishing nets	[2]
PP	High global production; valued for durability and chemical resistance	Common in automotive parts, kitchenware, textiles, and food packaging	[2]
PET	High production volume; widely recycled due to its use in packaging	Used in beverage bottles, synthetic fibers, electronics, and construction materials	[2]
PS	Moderately produced; commonly used in disposable and insulation products	Used in foam packaging, disposable utensils, insulation panels, and containers	[4]
PVC	Extensively produced for construction; durable and cost-effective material	Used in pipes, window frames, flooring, door panels, and cables	[2]
PC	Lower production volume than PE or PP; valued for transparency and impact resistance	Used as a glass alternative in eyewear, electronics, and protective equipment	[2]
PU	Broad industrial use; produced in various forms including foams and coatings	Applied in furniture, mattresses, coatings, adhesives, and automotive interiors	[2]
PHB	Biodegradable polymer; produced at a small scale for specialty biomedical uses	Used in internal surgical sutures and other medical applications	[2]
PCL	Biodegradable, specialty polymer; limited commercial use	Employed in sutures, drug delivery systems, and tissue engineering	[2]

There were several treatment technologies developed to remove microplastics from the environment, such as wastewater treatment, microalgae-based systems, bioinspired molecules, metal-organic frameworks (MOFs), and photocatalytic micromotors. However, industries often took the easier path by open-burning plastic waste, which released carbon monoxide and carbon dioxide, contributing to global warming. Various methods had been proposed to degrade microplastics, including thermal degradation, hydrolytic degradation, mechanochemical degradation, catalytic degradation, photodegradation, and biodegradation [5]. Among these, biodegradation was considered the most favorable due to its pollution-free mechanism and eco-friendly nature [6]. Biodegradation emerged as a promising microplastic treatment method in many industries, owing to the diversity and adaptability of microbial communities. In this process, microbes such as bacteria, fungi, and algae were capable of degrading the complex polymer structures of microplastics through enzymatic activity, utilizing the resulting carbon compounds for growth and metabolism [7]. The biodegradation process typically involved four main stages: biodeterioration, biofragmentation, assimilation, and mineralization. The rate of degradation was influenced by multiple factors, including environmental conditions, biological variables, and the structural properties of the microplastics themselves [8]. The advantages, limitations, current challenges, and future research directions in biodegradation technologies were also discussed to provide a comprehensive understanding. This essay focused on elucidating the mechanisms of biodegradation as a strategy to reduce microplastic pollution.

2. Current Status

Pollution has risen drastically in recent years, especially microplastic pollution, which poses a major threat to ecosystems, water sources, and human and wildlife health. Due to their tiny size, microplastics can easily spread through water, soil, and air. Research estimates that humans ingest 518 to 3,078 microplastic pellets annually through fish consumption [1]. Global plastic production increased by 4% in 2021, exceeding 390 million tonnes, and is projected to rise by 600 million tonnes per year by 2050 due to the COVID-19 pandemic [9]. In Malaysia, ranked the eighth-largest contributor to marine plastic pollution, 60% of plastic waste enters water bodies [10]. States such as Terengganu, Pahang, and Kelantan generate 0.71 kg of plastic waste per capita daily, with surface waters showing 0.0033 particles/m^3 of microplastics. Malaysian beaches like Seberang Takir and Batu Burok have 879 and 780 particles/m^2 of debris, respectively. In Europe, the Danube River releases about 1,500 tonnes of microplastics into the Black Sea annually. In Wuhan, China, microplastic levels in urban waters range from 1,660 to 8,925 particles/m^3, with most particles being colored and under 2 mm in size [11].

Table 2. Microplastic abundance on the water surface of several locations.

Locations	Microplastic concentration	References
Lake		
Lake Hovsgol, Mongolia	20265 particles/km^2	[11]
Laurentian Great Lakes, USA	466000 particles/km^2	[11]
Taihu Lake, China	340 – 25800 particles/m^3	[1]
Poyang Lake, China	5000 – 34000 particles/m^3	[1]
Veeranam Lake, India	13 – 54 particles/km^2	[1]
Lake Bolsena, Italy	0.82 – 4.42 particles/m^3	[1]
Lake Iseo, Italy	40000 particles/km^2	[1]
Lake Victoria, Africa	130 – 670 particles/m^3	[1]
Estuary		
Klang River Estuary, Malaysia	2.47 particles/l	[12]
Miri River Estuary, Malaysia	10.7 – 14.3 particles/l	[12]
Pearl River Estuary, China	42100 particles/m^3	[1]
Adour Estuary, France	0 – 3.88 particles/m^3	[1]
Chao Phraya River Estuary, Thailand	40 – 56 particles/m^3	[1]
River		
Sungai Dungun, Malaysia	102.8 items/m	[12]
Miri River, Malaysia	10.7 – 14.3 particles/l	[12]
Tebrau River, Malaysia	560 – 720 particles/kg	[12]
Skudai River, Malaysia	300 – 420 particles/kg	[12]
Chishui, China	1770 – 14330 particles/m^3	[1]
Zhangjiang River, China	50 – 725 particles/m^3	[1]
Vistula River, Poland	1600 – 2550 particles/m^3	[1]
Netravathi River, India	288 particles/m^3	[1]
Thames River, UK	14.2 – 24.8 particles/m^3	[1]

In Malaysia, several challenges persist in addressing microplastic pollution. Firstly, waste disposal facilities are not sustainable, with conventional landfilling being the most common method. This practice can lead to soil and water contamination through leachate production. Additionally, plastic recycling is limited, as recycling industries primarily focus on valuable plastics like PET, while less valuable plastics are often discarded, increasing landfill waste [10]. Furthermore, awareness of the harmful effects of single-use plastics remains low among Malaysians [12]. The frequent use of plastic bags for shopping and polystyrene boxes for takeaways is common. Although some stores have introduced fees for plastic bags and polystyrene containers over the past five years, this measure has had limited success, as many people continue to use them.

3. Source and Occurrence of Microplastics

Primary microplastics were tiny plastic particles specifically manufactured for certain purposes, especially for commercial use. Examples of primary microplastics included plastic pellets, plastic fibres, and microbeads. Plastic pellets are melted and used to produce larger industrial raw materials. Microbeads were commonly found in personal care products such as cosmetics, face washes, and toothpaste. Plastic fibres are used to make synthetic and optical fibres. During washing, washing machine effluent released more than 100 fibres per litre, with up to 1900 synthetic fibres released from a single synthetic garment [13].

Secondary microplastics are generated from the breakdown of larger plastic items like water bottles, bags, and fishing nets. These larger plastics degraded into smaller fragments due to exposure to environmental factors such as UV radiation from the sun, wind, and ocean waves [7]. Secondary microplastics are commonly found on beaches and coastal areas, where large amounts of plastics were discarded during tourism and leisure activities. Exposure to UV rays combined with mechanical abrasion from waves and sand further fragmented the plastics. Of the millions of tonnes of plastic produced worldwide, only 9% were recycled, 12% incinerated, and the remaining amount entered the environment, contributing to secondary microplastic pollution [13].

Primary microplastics from cosmetic products enter aquatic systems through sewage systems from households. Industries might also spill microbeads, plastic fibres and pellets during the manufacturing process of plastic products. Microplastics from industries and households are discharged into sewage systems which may accidentally flow into various water sources such as rivers, lakes, reservoirs, and oceans [11]. Plastic pipes such as PVC and PE pipes that channel wastewater further increases microplastic pollution due to the friction between the water and the inner surface of the pipe [14]. As most plastic products are used indoors, the indoor microplastic concentration is significantly higher than the outdoor microplastic concentration. It was found that the outdoor concentration is between 0.3 to 1.5 fibres/m^3, while the indoor concentration is 40 times the outdoor concentration [15]. Secondary microplastics may come from fishing nets released into the ocean due to the waves and ultraviolet light exposure. As time passes, the microplastics are spread to oceans and rivers worldwide. Besides water sources, dust is a suitable transport pathway for microplastics. It can travel long distances from one location to another side of Earth due to its low density. There is a possibility that humans and wildlife may inhale the airborne microplastics, causing health problems and death. The distribution pathways of microplastics into the environment is shown in Figure 1.

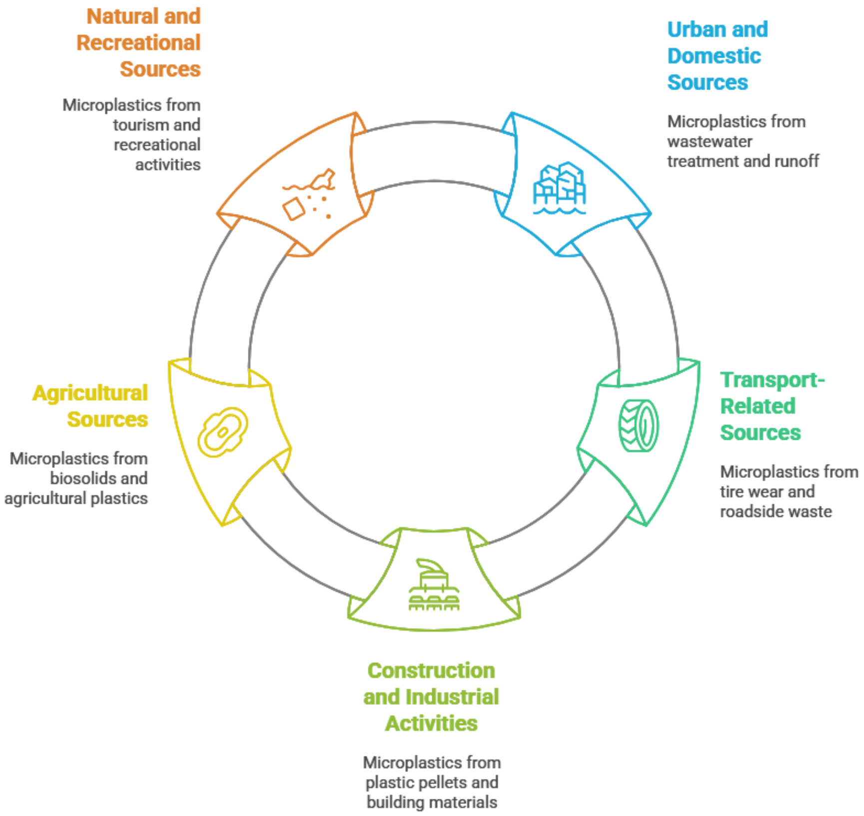

Figure 1. Mechanisms of microplastic release into the environment.

4. Environmental and Health Impact

4.1. Environmental impact.

Microplastics enter the soil through irrigation, littering, and sewage sludge application. Once in the soil, they can alter various soil properties, including bulk density, porosity, aggregation, fertility, nutrient cycling, and pH [16]. The presence of microplastics increases soil bulk density, leading to compaction and poor root growth. Additionally, microplastics occupy soil pore spaces, reducing porosity, which restricts air and water movement and may result in poor aeration and waterlogging. Microplastics can also disrupt natural soil aggregation by interfering with binding agents such as organic matter and microbial waste products, reducing the formation of stable soil aggregates [17]. Furthermore, microplastics increase soil pH due to the conversion of organic nitrogen to ammonia, which consumes hydrogen [18].

Beyond terrestrial ecosystems, microplastics also adversely affect marine and freshwater environments. Approximately 70% of marine plastic debris settles in sediments, 15% accumulates in coastal areas, and the rest floats in seawater [19]. Due to their small size, marine animals often mistake microplastics for food. Microplastics have been found in the digestive systems of whales, fish, turtles, and zooplankton. Birds and fish may accidentally ingest floating microplastics, mistaking them for prey. A study in Terengganu offshore waters detected microplastics in seawater and zooplankton [12]. Zooplankton either excrete microplastics as feces or retain them in their bodies; retained microplastics then move up the food chain, affecting animals and humans who consume them. Microplastics that are not ingested persist in the ocean and can take hundreds or thousands of years to degrade.

4.2. Human health concerns.

The presence of microplastics in food sources such as seafood and crops raises concerns about food safety and potential health risks to humans and wildlife. Microplastics can enter the human body through skin contact, inhalation of airborne particles, and consumption of contaminated food and water. Over the years, microplastics have been commonly detected in tap water, bottled water, and even salt. One study found an average of 55.2 microplastic particles per kilogram of salt and sugar [20]. While many microplastics are excreted via the digestive system, some smaller particles can enter the circulatory system [21]. Once in the bloodstream, microplastics can be transported throughout the body and accumulate in major organs such as the heart, lungs, and liver.

Exposure to microplastics can cause inflammation, genotoxicity, immunotoxicity, and carcinogenesis [22]. Inhaled microplastics may lead to respiratory diseases such as chronic obstructive pulmonary disease (COPD) and asthma. The lung alveoli, with their large surface area and thin walls, allow inhaled microplastics to diffuse easily into the bloodstream. Ingestion of microplastics can cause gastrointestinal issues such as hemorrhoids, colitis, and irritable bowel syndrome (IBS), primarily through contaminated food and water. Seafood like fish and shellfish can accumulate microplastics from the ocean, and drinking water may be contaminated by microplastics that detach from pipe surfaces. In the intestines, the villi absorb nutrients along with microplastics, which then enter the gastrointestinal tract and bloodstream.

The presence of microplastics in food sources such as seafood, crops, salt, and drinking water raises serious concerns about food safety and potential health risks to both humans and wildlife. These microscopic particles can enter the human body through various pathways, including dermal absorption, inhalation of airborne microplastics, and ingestion of contaminated food and water. Studies have detected microplastics in everyday consumables such as tap water, bottled water, and condiments like salt and sugar, with one study reporting an average of 55.2 particles per kilogram in salt and sugar [20]. Although many of these particles are excreted via the digestive system, smaller microplastics can penetrate biological barriers, enter the circulatory system, and accumulate in organs such as the lungs, liver, and heart [21].

Prolonged exposure to microplastics has been linked to a range of health issues, including inflammation, genotoxicity, immunotoxicity, and even carcinogenesis [22]. Inhalation of microplastics, particularly in urban environments, can contribute to respiratory diseases such as asthma and chronic obstructive pulmonary disease (COPD), as their small size allows them to reach deep into the alveoli and enter the bloodstream. Ingested microplastics can also disrupt the gastrointestinal system, causing disorders like irritable bowel syndrome (IBS), colitis, and hemorrhoids.

Microplastics found in cosmetics and personal care products—especially those under 100 nm—can penetrate the skin, potentially triggering irritation, hormonal imbalances, and reproductive toxicity. Furthermore, microplastic surfaces provide a habitat for pathogens such as *Helicobacter pylori*, which form biofilms that enhance infection risks [23]. During the COVID-19 pandemic, SARS-CoV-2 was shown to survive and multiply on microplastic surfaces, increasing the potential for airborne transmission [24].

Plastic products are often manufactured with chemical additives like plasticizers, antioxidants, flame retardants, and pigments. These additives are typically not chemically bound to the polymer matrix and can leach into surrounding environments and organisms.

Many of these substances are toxic and associated with adverse health effects and mortality in living organisms [25]. Table 3 provides an overview of these additives and their documented impacts.

Table 3. Chemical additives found in microplastics and their harmful effects.

Additive Type	Purpose	Chemicals Involved	Adverse Effects on Health and Environment	Reference
Flame Retardants	Reduce flammability and inhibit fire spread	Tetrabromobisphenol A (TBBPA)	Carcinogenic effects in rodents	[25]
		Polybrominated diphenyl ethers (PBDEs)	Impaired neurodevelopment	[25]
		Hexabromocyclododecane (HBCD)	Disruption of endocrine and reproductive systems	[26]
Antioxidants	Prevent oxidative degradation	Bisphenol A (BPA)	Endocrine system disruption	[26]
		Nonylphenol compounds	Endocrine and reproductive harm in aquatic species	[26]
		Octylphenol compounds	Similar endocrine and reproductive disruption in fish	[26]
		Butylated hydroxytoluene (BHT)	Cancer risk in animals, skin sensitization	[26]
Plasticizers	Enhance plastic flexibility, especially PVC	Phthalates	Associated with cancer, cardiovascular, and respiratory illnesses	[25]
		Adipates	Reduction in body weight and bone density	[26]
Crosslinking Agents	Transform linear polymers into 3D networks	Formaldehyde	Neurological disorders, respiratory irritation, toxic metabolites	[26]
		Hydrazine	Respiratory irritation, convulsions, carcinogenic in animals	[26]
Pigments	Provide color to plastic products	Cobalt (II) diacetate	Irritation to respiratory tract	[26]
		Iron oxide	Metal fume fever, eye discoloration, contribution to atmospheric warming	[26]

5. Prevention and Treatments

5.1. Prevention.

Car tyres are a major source of microplastic pollution, as they are composed of both synthetic and natural rubbers. Synthetic rubber, derived from petroleum-based polymers, wears down due to friction during driving, releasing microplastics into the environment [27]. Promoting public transportation such as buses and trains can help reduce this emission. Therefore, governments should invest in expanding and improving public transit systems to make commuting more convenient. For short distances, individuals are encouraged to walk, cycle, or use scooters as alternatives to private vehicles [28].

Additionally, the textile industry contributes to microplastic pollution through the production of synthetic fabrics. A shift toward manufacturing clothing from natural materials like cotton, wool, and silk should be encouraged. To support this transition, the cost of synthetic garments could be increased to incentivize consumers to choose organic alternatives. While natural fabrics also shed microfibers, these are typically larger and less likely to contribute to microplastic pollution [28].

Single-use plastics—such as plastic bags, bottles, and straws—are another widespread source of plastic waste, as they are typically discarded after one use [29]. Their usage can be minimized by adopting reusable alternatives, including fabric shopping bags, bamboo straws, and refillable water bottles. Furthermore, avoiding plastic bags for small purchases that can be carried by hand is a simple yet effective step. The adoption of biodegradable plastics in manufacturing can also help reduce environmental impact, as these materials are more easily broken down by microorganisms.

5.2. Treatments.

5.2.1. Wastewater treatment.

Wastewater treatment consists of three main stages, primary, secondary, and tertiary, each employing specific methods and technologies to remove microplastics. Primary treatment focuses on removing large debris from incoming wastewater through screening, sedimentation, and flotation. Screening includes coarse screens (6–150 mm) for larger debris and fine screens (1.5–6 mm) which can capture smaller particles such as microplastics [30]. Sedimentation relies on gravity to settle suspended solids and some organic matter at the bottom of tanks, improving the efficiency of subsequent treatment. The settling rate depends on particle size, shape, and density, and optimal results require calm, laminar water flow [31]. Flotation removes suspended solids, fats, oils, and grease by attaching air bubbles to hydrophobic particles (such as microplastics), which are then floated to the surface and skimmed off. This method is particularly effective due to microplastics' hydrophobic nature [32].

Secondary treatment, also known as biological treatment, utilizes microorganisms like bacteria and fungi to degrade organic pollutants and nutrients. These microbes metabolize organic matter, producing carbon dioxide, water, and energy [33]. Key technologies include the anaerobic-anoxic-aerobic (A2O) process, activated sludge systems, biofiltration, trickling filters, and solids contact tanks. The A2O method involves three separate tanks: in the aerobic tank, oxygen is supplied to support microbial activity that breaks down organic matter; the anaerobic tank operates in the absence of oxygen, relying on anaerobic microbes for degradation; and the anoxic tank enables denitrification, converting nitrogen compounds into nitrogen gas with limited or no oxygen, often through trickling filters or suspended growth systems [34].

In the activated sludge process, oxygenated tanks facilitate the formation of microbial flocs that capture microplastics, which settle in a secondary clarifier for removal. This sludge is often recirculated. In trickling filters, wastewater trickles over a bed of rocks, where microbial biofilms consume organic contaminants [33]. Tertiary treatment further removes residual microplastics through filtration and disinfection [35]. Filtration methods such as activated carbon, disc filtration, and sand filtration are physical processes. Slow sand filters allow microbial action to degrade microplastics, whereas rapid sand filters trap them through adsorption due to faster flow [36]. Activated carbon functions similarly, using carbon surfaces to capture microplastics. Disinfection methods include chlorination, ozonation, UV filtration, and advanced oxidation processes (AOPs), which are chemical treatments [37]. These techniques generate reactive species like hydroxyl radicals (OH•), which degrade microplastics by initiating a chain reaction that breaks down their polymer structures [38]. Table 4 provides an overview of the treatment technologies and their microplastic removal efficiencies.

Table 4. Technologies used in wastewater treatment and its efficiency in removing microplastics.

Treatment stage	Technology	Removal Efficiency (%)	Reference
Primary	Skimming	50 – 70	[39]
	Grit and grease removal	45	[40]
	Primary settling tank	33.75	[41]
	Pulse clarification	63	[42]
	Aerated grit chambers	16.5	[43]
	Coagulation/Flocculation	90	[44]
Secondary	Activated sludge process	7 - 20	[43]
	Biofiltration	19	[43]
	Trickling filter and solids contact tanks	7	[40]
	Secondary settling tank	97	[40]
	Anaerobic-anoxic-aerobic (A2O)	15	[43]
	Conventional activated sludge	98.3	[43]
Tertiary	Electrocoagulation	90 – 99.2	[43]
	Membrane bioreactor (MBR)	99.9	[43]
	Reverse osmosis (RO)	90.5	[43]
	Membrane disc filter	99.1	[41]
	Dissolved air flotation	95	[43]
	Rapid sand filtration	70 – 97	[43]
	Granular activated carbon filtration	82.1 – 88.6	[37]
	Chlorination	20 – 68	[37]
	Ozonation	90	[43]
	UV filtration	10	[37]
	Advanced oxidation processes (AOPs)	90	[37]

5.2.2. Bioinspired molecules.

Researchers have developed bioinspired molecules to remove microplastics from water. These molecules combine organic and inorganic components and consist of two main parts: an inclusion unit (IU) and a capture unit (CU), together forming an inclusion compound (IC). The CU has the ability to bond with various functional groups. When microplastics are captured by the IC, the water molecules surrounding them are displaced. These displaced water molecules interact with nearby water through Van der Waals forces, creating voids that microplastic particles can occupy. This mechanism enables the efficient removal of microplastics from water [45].

5.2.3. MOFs.

MOFs, also called porous coordination polymers (PCPs), are crystalline materials with a nanoporous structure, making them ideal for adsorbing microplastics. They offer several advantages such as high surface area, strong coordination bonds, and excellent adsorption capacity [46]. A recent innovation involves the use of zirconium-based MOF foams, which exhibit high mechanical strength and a network of interconnected pores. The performance of these foams can be enhanced by increasing MOF content or modifying their surfaces with functional groups like $-OH$, $-NH_2$, $-NO_2$, and $-Br$. Microplastics interact with MOF foams through several mechanisms: attachment to interlinked pore structures, electrostatic attraction between negatively charged microplastics and positively charged MOFs, and through Van der Waals forces and hydrogen bonding [47].

5.2.4. Photocatalytic micromotor.

Photocatalytic micromotors are microscopic devices that use photocatalytic materials to convert light energy into mechanical motion, enabling them to autonomously move through liquids to perform specific functions. Common photocatalytic materials include TiO_2, AgCl, and Cu_2O, which generate gradients or bubbles under light exposure. These reactions drive micromotors via mechanisms such as bubble recoil, self-diffusiophoresis, and self-electrophoresis. TiO_2 is the most widely used material due to its high photocatalytic activity, stability, and ease of fabrication [40]. Micromotors remove microplastics through two main mechanisms: phoretic interaction, where microplastics adhere to micromotors via Van der Waals and electrostatic forces, and shoveling, where micromotors actively collect and transport microplastics [45].

5.2.5. Biodegradation mechanism.

Biodegradation of microplastics involves four fundamental mechanisms: biodeterioration, biofragmentation, assimilation, and mineralization, which occur in both soil and aquatic environments. The first stage, biodeterioration, begins when microorganisms adhere to the microplastic surface, forming a layer of microbial colonies known as a biofilm [49]. This biofilm facilitates further interaction between the microbes and the polymer surface. During this phase, the physical and chemical characteristics of the polymer, such as its surface texture, shape, and molecular composition, begin to change. Several environmental factors, including temperature, surface tension, porosity, and moisture content, significantly influence the efficiency of microbial adhesion and biofilm formation. The second stage is biofragmentation, in which the microorganisms secrete extracellular enzymes that break down the complex polymer chains into smaller fragments such as monomers, dimers, and oligomers, through hydrolysis and oxidative processes [50]. These breakdown products become small enough to be taken up by microbial cells. The specific type of microbes and enzymes involved in degrading different types of polymers are summarized in Table 5.

Following biofragmentation, the third stage in the biodegradation process is assimilation. In this phase, the smaller degradation products such as monomers, dimers, and oligomers, produced during biofragmentation are absorbed by microorganisms through the cell membrane [51]. This uptake is crucial, as these molecules serve as sources of carbon, energy, and nutrients. Once inside the microbial cell, the compounds undergo further metabolism through various biochemical pathways depending on environmental conditions. In aerobic environments, oxygen serves as the terminal electron acceptor, enabling the complete oxidation of organic materials into simpler compounds. In anaerobic environments, where oxygen is absent, other molecules such as nitrate, sulfate, or carbon dioxide act as alternative electron acceptors, supporting microbial respiration and energy production [52]. The final stage, mineralization, completes the biodegradation process. It involves the full conversion of organic intermediates into inorganic compounds. Under aerobic conditions, the primary end products are carbon dioxide, water, and microbial biomass. In contrast, anaerobic mineralization generates methane, in addition to carbon dioxide, water, and biomass [53]. These end products are then released back into the environment, signifying the complete microbial degradation of microplastics.

Table 5. Microbes with their enzymatic capability for degradation of polymers.

Microbes		**Enzymes**	**Polymers**	**Reference**
Bacteria	*Azotobacter beijerinckii*	Hydroquinone peroxidase	PS	[51]
	Bacillus cereus	Laccase, Lipase, Esterase	PET, PS	[7]
	Brevibacillus borstelensis	Lipase	PE	[50]
	Comamonas testosteroni	PETase	PET	[54]
	Ideonella sakaiensis	Cutinase, PETase	PET	[50]
	Pseudomonas putida	Lipase, Esterase, Alkane hydroxylase, Dehydrogenase	PS, PU, PVA	[53]
	Pseudomonas vesicularis	Esterase	PVA	[53]
	Rhodococcus ruber	Styrene monooxygenase, Dehydrogenase, Laccase, Oxidase	PS, PE, PVA	[50]
	Thermobifida fusca	Cutinase, Lipases	PVC, PET	[50]
Fungi	*Anthrobotrys oligospora*	Protease	PLA	[50]
	Aspergillus niger	Laccase	PE, PP	[6]
	Cladosporium cladosporioides	Esterase, Lipase	PU	[4, 50]
	Cochliobolus sp.	Laccase	PVC	[6]
	Fusarium graminearum	Peroxidase	PE	[6]
	Fusarium solani	Cutinase, Esterase, Lipase, Serine hydrolase	PET, PU, PCL	[6]
	Humicola insolens	Cutinase	PET	[6], [4]
	Penicilliumfuniculosum	Unknwon	PHB	[6]
	Phanerochaete chrysosporium	Manganese peroxidase, Lignin peroxidase	PE, PVC, PS	[53]
	Pichia pastoris	Lipase	PET	[7, 50]
	Trametes versicolor	Laccase	PE	[4]
	Xepiculopsis graminea	Esterase, Lipase	PU	[6]
Algae	*Chlamydomonas reinhardtii*	Unkown	PP	[6]
	Chlorella vulgaris	Unknwon	PVC	[55]
	Navicula pupula	Exopolysaccharide enzymes	PS	[55]
	Karenia mikimotoi	Unknown	PVC	[55]
	Scenedesmus dimorphus	Oxidoreductase	PE	[7]
	Skeletonema costatum	Unknown	PVC	[55]

Abbreviations: PE: Polyethylene; PET: Polyethylene terephthalate; PHB: Polyhydroxybutyrate; PS: Polystyrene; PVC: Polyvinyl chloride; PU: Polyurethane; PLA: Polylactic acid, PCL: Polycaprolactone; PVA: Polyvinyl alcohol.

6. Factors Affecting Microplastic Biodegradation

6.1. Environmental Factors.

Environmental conditions in soil and water such as pH, temperature, oxygen availability, nutrient concentration, and moisture content, play a critical role in regulating microbial activity and thus influence the rate of microplastic degradation [56]. A neutral to slightly alkaline pH, particularly around 7.5, is considered optimal for promoting enzymatic activity in microbes, thereby enhancing the biodegradation process. Temperature also significantly affects microbial metabolism and enzyme function. At low temperatures, the formation of ice crystals near microbial cell membranes can impair membrane fluidity, slowing down enzymatic reactions. Conversely, excessive heat can lead to protein denaturation, nucleic acid degradation, and increased membrane vulnerability to hydrocarbon toxicity. Microorganisms have varying temperature tolerances: psychrophiles thrive below 20°C, mesophiles between 15°C and 45°C, thermophiles from 50°C to 80°C, and hyperthermophiles endure extreme heat ranging from 80°C to 110°C [57]. Soil moisture facilitates microplastic swelling, reduces molecular weight, promotes deformation, and acts as a medium for nutrient transport, collectively accelerating hydrolysis and microbial enzymatic reactions [58]. However, excessive moisture can saturate soil pores, reducing oxygen diffusion and thus inhibiting the activity of aerobic microorganisms [59]. Nutrient availability, especially phosphorus and nitrogen compounds like ammonium and nitrate, supports microbial growth and enhances degradation efficiency [60]. Nonetheless, an overabundance of nutrients may disrupt microbial community balance and introduce competition, ultimately diminishing microplastic degradation rates.

6.2. Biotic factors.

Biotic factors such as microbial community structure, population density of degraders, biofilm formation, and redox potential significantly affect the degradation of microplastics. Microorganisms often rely on metabolic cooperation, such as cross-feeding and syntrophy, to exchange metabolites. For instance, syntrophic interactions are critical for the degradation of complex compounds like monoaromatic and polyaromatic hydrocarbons, with some microbes producing methane as a by-product [61]. Since microplastics are composed largely of hydrocarbon chains, hydrocarbon-degrading bacteria play a central role in their breakdown. These microbes can enzymatically degrade hydrocarbons into simpler compounds, thereby enhancing overall biodegradation efficiency [62].

6.3. Structural properties of microplastics.

The physicochemical characteristics of microplastics strongly influence their susceptibility to microbial degradation. Important factors include molecular weight, surface area, functional groups, presence of impurities, and degree of crystallinity [63]. Polymers with high molecular weight, indicating longer chain lengths, are generally more resistant to degradation, as they require more energy and enzymatic effort to break down [64]. Conversely, microplastics with more functional groups and weaker chemical bonds are more amenable to microbial attack. Crystallinity also plays a crucial role. In crystalline regions, the polymer chains are tightly packed, limiting enzyme penetration and thus resisting degradation. In contrast, amorphous regions have loosely arranged molecules that are more accessible to enzymatic activity, resulting in faster breakdown [2].

7. Pros and Cons of Biodegradation and Future Research

Biodegradation is recognized for its environmental sustainability, offering a green solution for microplastic removal. Unlike physical or chemical methods, it generates non-toxic end products such as carbon dioxide, water, methane, and biomass [51]. Another advantage lies in the specificity of microbial enzymes, which target particular polymer types without affecting surrounding materials. For example, Pseudomonas species produce alkane hydroxylase, which targets polyethylene, and polymerase, which degrades polystyrene [50]. Additionally, biodegradation is cost-effective, particularly when compared to the high operational and maintenance expenses associated with chemical and physical treatments.

However, biodegradation has limitations. It is time-consuming and heavily reliant on microbial activity, making it slower than chemical treatments [7]. Under natural conditions, microplastic degradation can take around six months, and in marine environments, this process may span centuries, during which harmful additives can leach into ecosystems [65]. To improve the efficiency of biodegradation and mitigate plastic pollution, further research is essential in several areas. These include development of alternative biodegradable materials and enhancement of microbial efficiency through genetic engineering that modified microbes can secrete more effective enzymes, improving their ability to degrade microplastics [66].

Moreover, biodegradation by-products can be converted into value-added compounds. For instance, terephthalic acid and ethylene glycol—produced from PET degradation—can be transformed into polyhydroxyalkanoate (PHA) by engineered Pseudomonas putida. PHA has commercial applications in textiles and food packaging industries [51, 67]. Pretreatment techniques, such as pyrolysis, can also enhance biodegradation by reducing polymer rigidity and increasing enzyme access [2]. Lastly, more studies are needed on the fungal degradation of polypropylene (PP) and polystyrene (PS), as current research in this area remains limited [4].

8. Conclusion

Microplastic pollution has emerged as a persistent global issue, posing significant risks to both environmental and human health. Despite growing awareness, the global demand for plastics continues to rise, exacerbating the problem. Microorganisms play a critical role in the degradation of microplastics, particularly those that enter the environment without prior treatment. These pollutants are now ubiquitous, being detected in diverse environments ranging from marine ecosystems and urban infrastructure to remote forested regions. To address this widespread contamination, a variety of mitigation strategies have been proposed and implemented. These include reducing the use of plastic products, improving wastewater treatment processes, increasing public awareness, and promoting the development and use of eco-friendly or biodegradable alternatives. Among the available solutions, microbial biodegradation stands out as a promising, pollution-free approach. However, its broader application is currently limited by challenges such as low degradation efficiency, scalability constraints, high maintenance costs, and slow processing speeds. To alleviate these limitations, industries should be encouraged to adopt and produce biodegradable plastics as substitutes for conventional plastics in items such as bottles, containers, garbage bags, and even single-use tea or coffee bags. Additionally, as wastewater treatment plants are recognized as major sources of microplastic release, advancing new or existing technologies within these facilities could offer significant potential for microplastic reduction through biodegradation. Nevertheless, the current understanding of microbial degradation of microplastics remains in its infancy. Critical aspects such as the impact of microplastics on microbial communities and the potential for enzyme reuse require further investigation. Future research should focus on enhancing degradation rates and developing more efficient, scalable, and cost-effective biodegradation technologies. With sustained efforts and scientific innovation, these advancements could contribute substantially to sustainable development within the coming years.

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Competing Interests

The author declares that there are no competing interests, financial or otherwise, that could influence or bias the content of this review article. No funding was received for the preparation of this manuscript.

Author Contribution

Novlina Finayeva: conceptualization, methodology, data curation, writing original draft. Risky Ayu Kristanti: supervision, project administration, writing review & editing. Kong Rachana: investigation, formal analysis, validation. Ummi Mardhiah Batubara: resources, visualization, writing review & editing. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

As a review article, this study analyzed and synthesized existing data from previously published studies. All data discussed in this review are properly cited and can be found in the reference list. No new datasets were generated during this study. For access to specific articles referenced, readers are directed to the original publications or can contact the corresponding authors of those studies.

References

[1] Zhang, T.; Jiang, B.; Xing, Y.; Ya, H.; Lv, M.; Wang, X. (2022). Current status of microplastics pollution in the aquatic environment, interaction with other pollutants, and effects on aquatic organisms. *Environmental Science and Pollution Research*, *29*, 16830–16859. https://doi.org/10.1007/s11356-022-18504-8.

[2] Cai, Z.; Wang, J.; Li, Y.; Chen, Q.; Zhang, Y.; Liu, H. (2023). Biological Degradation of Plastics and Microplastics: A Recent Perspective on Associated Mechanisms and Influencing Factors. *Microorganisms*, *11*(7), 1661. https://doi.org/10.3390/microorganisms11071661.

[3] Bridson, J.H.; Abbel, R.; Smith, D.A.; Northcott, G.L.; Gaw, S. (2023). Release of additives and non-intentionally added substances from microplastics under environmentally relevant conditions. *Environmental Advances*, *12*, 100359. https://doi.org/10.1016/j.envadv.2023.100359.

[4] Temporiti, M.E.E.; Nicola, L.; Nielsen, E.; Tosi, S. (2022). Fungal Enzymes Involved in Plastics Biodegradation. *Microorganisms*, *10*(6), 1180. https://doi.org/10.3390/microorganisms10061180.

[5] Zeenat; Elahi, A.; Bukhari, D.A.; Shamim, S.; Rehman, A. (2021). Plastics degradation by microbes: A sustainable approach. *Journal of King Saud University - Science*, *33*(6), 101538. https://doi.org/10.1016/j.jksus.2021.101538.

[6] Srikanth, M.; Sandeep, T.S.R.S.; Sucharitha, K.; Godi, S. (2022). Biodegradation of plastic polymers by fungi: a brief review. *Bioresources and Bioprocessing*, *9*(1), 42. https://doi.org/10.1186/s40643-022-00532-4.

[7] Jain, R.; Kumar, S.; Singh, P.; Sharma, A.; Gupta, V. (2023). Microplastic pollution: Understanding microbial degradation and strategies for pollutant reduction. *Science of The Total Environment*, *905*, 167098. https://doi.org/10.1016/j.scitotenv.2023.167098.

[8] Tania, M.; Vijaya Anand, A. (2023). The implementation of microbes in plastic biodegradation. *Journal of Umm Al-Qura University for Applied Sciences*, *11*, 208–218. https://doi.org/10.1007/s43994-023-00077-y.

[9] Sulaiman, R.N.R.; Ahmad, S.; Lim, K.T.; Wong, C.Y.; Tan, L.L. (2023). Microplastics in Malaysia's Aquatic Environment: Current Overview and Future Perspectives. *Global Challenges*, *7*(8), 2300047. https://doi.org/10.1002/gch2.202300047.

[10] Jiang, J.Q. (2018). Occurrence of microplastics and its pollution in the environment: A review. *Sustainable Production and Consumption*, *13*, 16–23. https://doi.org/10.1016/j.spc.2017.11.003.

[11] Noor, N.S.; Ismail, A.; Mohd, K.; Hassan, R.; Abdullah, S. (2024). Microplastic Pollution in Malaysia: Status and Challenges - A Brief Overview *Malaysian Journal of Analytical Sciences*, *28*(3), 569–585.

[12] Ziani, K.; Ioniță-Mîndrican, C.B.; Mititelu, M.; Neacșu, S.M.; Negrei, C.; Moroșan, E. (2023). Microplastics: A Real Global Threat for Environment and Food Safety: A State of the Art Review. *Nutrients*, *15*(3), 617. https://doi.org/10.3390/nu15030617.

[13] Yang, X.; Zhou, Y.; Xia, R.; Liao, J.; Liu, J.; Yu, P. (2024). Microplastics and chemical leachates from plastic pipes are associated with increased virulence and antimicrobial resistance potential of drinking water microbial communities. *Journal of Hazardous Materials*, *463*, 132900. https://doi.org/10.1016/j.jhazmat.2023.132900.

[14] Arpia, A.; Chen, W.H.; Ubando, A.T.; Naqvi, S.R.; Culaba, A.B. (2021). Microplastic degradation as a sustainable concurrent approach for producing biofuel and obliterating hazardous environmental effects: A state-of-the-art review. *Journal of Hazardous Materials*, *418*, 126381. https://doi.org/10.1016/j.jhazmat.2021.126381.

[15] Chen, Y.; Li, X.; Wang, Z.; Zhang, L.; Wu, J. (2024). Effects of microplastics on soil carbon pool and terrestrial plant performance. *Carbon Research*, *3*(1), 1–23. https://doi.org/10.1007/s44246-024-00124-1.

[16] Liang, Y.; Lehmann, A.; Yang, G.; Leifheit, E.F.; Rillig, M.C. (2021). Effects of Microplastic Fibers on Soil Aggregation and Enzyme Activities Are Organic Matter Dependent. *Frontiers in Environmental Science*, *9*, 650155. https://doi.org/10.3389/fenvs.2021.650155.

[17] Zhao, T.; Lozano, Y.M.; Rillig, M.C. (2021). Microplastics Increase Soil pH and Decrease Microbial Activities as a Function of Microplastic Shape, Polymer Type, and Exposure Time. *Frontiers in Environmental Science*, *9*, 675803. https://doi.org/10.3389/fenvs.2021.675803.

[18] Lamichhane, G.; Acharya, A.; Marahatha, R.; Modi, B.; Paudel, R.; Adhikari, A. (2022). Microplastics in environment: Global concern, challenges, and controlling measures. *International Journal of Environmental Science and Technology*, *20*(4), 4673–4694. https://doi.org/10.1007/s13762-022-04261-1.

[19] Makhdoumi, P.; Pirsaheb, M.; Amin, A.A.; Kianpour, S.; Hossini, H. (2023). Microplastic pollution in table salt and sugar: Occurrence, qualification and quantification and risk assessment. *Journal of Food Composition and Analysis*, *119*, 105261. https://doi.org/10.1016/j.jfca.2023.105261.

[20] Li, Y.; Tao, L.; Wang, Q.; Wang, F.; Li, G.; Song, M. (2023). Potential Health Impact of Microplastics: A Review of Environmental Distribution, Human Exposure, and Toxic Effects. *Environment & Health*, *1*(4), 249–257. https://doi.org/10.1021/envhealth.3c00052.

[21] Ghosh, S.; Sinha, J.K.; Ghosh, S.; Vashisth, K.; Han, S.; Bhaskar, R. (2023). Microplastics as an Emerging Threat to the Global Environment and Human Health. *Sustainability*, *15*(14), 10821. https://doi.org/10.3390/su151410821.

[22] Tong, X.; Wang, X.; Li, J.; Liu, S.; Zhang, W. (2022). Polyethylene microplastics cooperate with Helicobacter pylori to promote gastric injury and inflammation in mice. *Chemosphere*, *288*, 132579. https://doi.org/10.1016/j.chemosphere.2021.132579.

[23] Yang, W.; Gao, X.; Wu, Y.; Wan, L.; Tan, L.; Yuan, W. (2022). Impacts of microplastics on immunity. *Frontiers in Toxicology*, *4*, 956885. https://doi.org/10.3389/ftox.2022.956885.

[24] Campanale, C.; Massarelli, C.; Savino, I.; Locaputo, V.; Uricchio, V.F. (2020). A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health. *International Journal of Environmental Research and Public Health*, *17*(4), 1212. https://doi.org/10.3390/ijerph17041212.

[25] Hahladakis, J.N.; Velis, C.A.; Weber, R.; Iacovidou, E.; Purnell, P. (2018). An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *Journal of Hazardous Materials*, *344*, 179–199. https://doi.org/10.1016/j.jhazmat.2017.10.014.

[26] Kole, P.J.; Löhr, A.J.; Van Belleghem, F.; Ragas, A.M. (2017). Wear and Tear of Tyres: A Stealthy Source of Microplastics in the Environment. *International Journal of Environmental Research and Public Health*, *14*(10), 1265. https://doi.org/10.3390/ijerph14101265.

[27] 9 Ways To Reduce Your Microplastic Pollution & Consumption (accessed on 1 January 2024) Available online: https://www.perchenergy.com/blog/lifestyle/reduce-microplastic-pollution-consumption.

[28] Rabiu, M.K.; Jaeger-Erben, M. (2024). Reducing single-use plastic in everyday social practices: Insights from a living lab experiment. *Resources, Conservation and Recycling*, *200*, 107303. https://doi.org/10.1016/j.resconrec.2023.107303.

[29] Types of Screening in Wastewater Treatment. (accessed on 1 January 2024) Available online: https://aosts.com/types-wastewater-screening/.

[30] What Is Sedimentation in Water Treatment (accessed on 1 January 2024) Available online: https://aosts.com/what-is-sedimentation-in-water-treatment-types-settling-tanks/.

[31] Kyzas, G.; Matis, K. (2018). Flotation in Water and Wastewater Treatment. *Processes*, *6*(8), 116. https://doi.org/10.3390/pr6080116.

[32] Wastewater treatment - Primary treatment. (accessed on 1 January 2024) Available online: https://www.britannica.com/technology/wastewater-treatment/Primary-treatment.

[33] Abualhail, S.; Mohammed, R.N.; Xiwu, L. (2017). Integrated real-time control strategy in multi-tank A2O process for biological nutrient removal treating real domestic wastewater. *Arabian Journal of Chemistry*, *10*, S1041-S1054. https://doi.org/10.1016/j.arabjc.2013.01.009.

[34] Thorat, B.N.; Sonwani, R.K. (2022). Current technologies and future perspectives for the treatment of complex petroleum refinery wastewater: A review. *Bioresource Technology*, *355*, 127263. https://doi.org/10.1016/j.biortech.2022.127263.

[35] Chabi, K.; Rocha-Santos, T.; Duarte, A.C.; Lopes, I.; Pereira, R. (2024). Rapid sand filtration for <10 μm-sized microplastic removal in tap water treatment: Efficiency and adsorption mechanisms. *Science of The Total Environment*, *912*, 169074. https://doi.org/10.1016/j.scitotenv.2023.169074.

[36] Miino, M.C.; Galafassi, S.; Zullo, R.; Torretta, V.; Rada, E.C. (2024). Microplastics removal in wastewater treatment plants: A review of the different approaches to limit their release in the environment. *Science of The Total Environment*, *930*, 172675. https://doi.org/10.1016/j.scitotenv.2024.172675.

[37] Dos Santos, N.de O.; Busquets, R.; Campos, L.C. (2023). Insights into the removal of microplastics and microfibres by Advanced Oxidation Processes. *Science of The Total Environment*, *861*, 160665. https://doi.org/10.1016/j.scitotenv.2022.160665.

[38] Singh, S.; Kalyanasundaram, M.; Diwan, V. (2021). Removal of microplastics from wastewater: available techniques and way forward. *Water Science and Technology*, *84*(12), 3689–3704. https://doi.org/10.2166/wst.2021.472.

[39] Mastropietro, T.F. (2023). Metal-organic frameworks and plastic: an emerging synergic partnership. *Science and Technology of Advanced Materials*, *24*(1), 2189890. https://doi.org/10.1080/14686996.2023.2189890.

[40] Dey, T.K.; Hou, J.; Sillanpää, M.; Pramanik, B.K. (2023). Metal-organic framework membrane for waterborne micro/nanoplastics treatment. *Chemical Engineering Journal*, *474*, 145715. https://doi.org/10.1016/j.cej.2023.145715.

[41] Lin, J.; Zhang, Y.; Zhao, L.; Li, W.; Liu, J. (2022). TiO2@carbon microsphere core-shell micromotors for photocatalytic water remediation. *Optical Materials*, *124*, 111989. https://doi.org/10.1016/j.optmat.2022.111989.

[42] He, Y.; Li, H.; Xiao, X.; Zhao, X. (2021). Polymer Degradation: Category, Mechanism and Development Prospect. *E3S Web of Conferences*, *290*, 01012. https://doi.org/10.1051/e3sconf/202129001012.

[43] Gilani, E.; Sayadi, S.; Zouari, N.; Al-Ghouti, M.A. (2023). Plastic waste impact and biotechnology: Exploring polymer degradation, microbial role, and sustainable development implications. *Bioresource Technology Reports*, *24*, 101606. https://doi.org/10.1016/j.biteb.2023.101606.

[44] Jaduan, S.; Bansal, S.; Sonthalia, A.; Rai, A.K.; Singh, S.P. (2022). Biodegradation of plastics for sustainable environment. *Bioresource Technology*, *347*, 126697. https://doi.org/10.1016/j.biortech.2022.126697.

[45] Reineke, W. (2001). Aerobic and Anaerobic Biodegradation Potentials of Microorganisms. In: Biodegradation and Persistence. The Handbook of Environmental Chemistry; Beek, B., Eds.; Springer, Berlin, Heidelberg. https://doi.org/10.1007/10508767_1.

[46] Rana, I. (2019). Usage of Potential Micro-organisms for Degradation of Plastics. *Open Journal of Environmental Biology*, *4*(1), 7–15. https://doi.org/10.17352/ojeb.000010.

[47] Chinaglia, S.; Esposito, E.; Tosin, M.; Pecchiari, M.; Degli Innocenti, F. (2024). Biodegradation of plastics in soil: the effect of water content. *Polymer Degradation and Stability*, *222*, 110691. https://doi.org/10.1016/j.polymdegradstab.2024.110691.

[48] Temperature Effects on Bacterial Growth. (accessed on 1 January 2024) Available online: https://bio.libretexts.org/Courses/Prince_Georges_Community_College/PGCC_Microbiology/08%3A_Microbial_Growth/8.02%3A_Factors_that_Affect_Bacterial_Growth/8.2.01%3A_Temperature_Effects_on_Bacterial_Growth.

[49] Titone, V.; Correnti, A.; La Mantia, F.P. (2021). Effect of Moisture Content on the Processing and Mechanical Properties of a Biodegradable Polyester. *Polymers*, *13*(10), 1616. https://doi.org/10.3390/polym13101616.

[50] Bahmani, F.; Ataei, S.A.; Mikaili, M.A. (2018). The Effect of Moisture Content Variation on the Bioremediation of Hydrocarbon Contaminated Soils: Modeling and Experimental Investigation. *Journal of Environmental Analytical Chemistry*, *5*(2), 1000236. https://doi.org/10.4172/2380-2391.

[51] Lang, S.; Tarayre, C.; Delvigne, F.; Druart, P.; Ongena, M.; Thonart, P. (2016). The Effect of Nutrients on the Degradation of Hydrocarbons in Mangrove Ecosystems by Microorganisms. *International Journal of Environmental Research*, *10*(4), 583–592. https://ijer.ut.ac.ir/article_59903_0f6fe585f445848410e56417ff3eb191.pdf.

[52] Cavaliere, S.; Feng, S.; Soyer, O.S.; Jiménez, J.I. (2017). Cooperation in microbial communities and their biotechnological applications. *Environmental Microbiology*, *19*(8), 2949–2963. https://doi.org/10.1111/1462-2920.13767.

[53] Kebede, G.; Tafese, T.; Abda, E.M.; Kamaraj, M.; Assefa, F. (2021). Factors Influencing the Bacterial Bioremediation of Hydrocarbon Contaminants in the Soil: Mechanisms and Impacts. *Journal of Chemistry*, *2021*(1), 1–17. https://doi.org/10.1155/2021/9823362.

[54] Patway, A.S.; Surid, S.M.; Gafur, M.A. (2020). Properties and Applications of Biodegradable Polymers. *Journal of Research Updates in Polymer Science*, *9*(9), 32–41. https://doi.org/10.6000/1929-5995.2020.09.03.

[55] Jiang, R.; Lu, G.; Yang, H.; Wang, P.; Dang, Z. (2023). Insight into the degradation process of functional groups modified polystyrene microplastics with dissolvable BiOBr-OH semiconductor-organic framework. *Chemical Engineering Journal*, *470*, 144401. https://doi.org/10.1016/j.cej.2023.144401.

[56] Silva, R.R.A.; Marques, C.S.; Arruda, T.R.; Teixeira, S.C.; de Oliveira, T.V. (2023). Biodegradation of Polymers: Stages, Measurement, Standards and Prospects. *Macromol*, *3*(2), 371–399. https://doi.org/10.3390/macromol3020023.

[57] Joutey, T.; Bahafid, W.; Sayel, H.; El Ghachtouli, N. (2013). Biodegradation: Involved Microorganisms and Genetically Engineered Microorganisms. *Biodegradation-Life of Science*, *1*, 289–320.

[58] Uddin, M.K.; Novembre, L.; Greco, A.; Sannino, A. (2024). Polyhydroxyalkanoates, A prospective solution in the textile industry - A review. *Polymer Degradation and Stability*, *219*, 110619. https://doi.org/10.1016/j.polymdegradstab.2023.110619.

[59] Kwon, H.J.; Hidayaturrahman, H.; Peera, S.G.; Lee, T.G. (2022). Elimination of Microplastics at Different Stages in Wastewater Treatment Plants. *Water*, *14*(15), 2404. https://doi.org/10.3390/w14152404.

[60] Iyare, U.; Ouki, S.K.; Bond, T. (2020). Microplastics removal in wastewater treatment plants: a critical review. *Environmental Science: Water Research & Technology*, *6*(10), 2664–2675. https://doi.org/10.1039/D0EW00397B.

[61] Kurt, Z.; Clayton, P.; James, A. (2022). Effectiveness of microplastics removal in wastewater treatment plants: A critical analysis of wastewater treatment processes. *Journal of Environmental Chemical Engineering*, *10*(3), 107831. https://doi.org/10.1016/j.jece.2022.107831.

[62] Sarkar, D.J.; Das, S.; Das, K.; Das, P.; Chowdhury, A. (2021). Microplastics removal efficiency of drinking water treatment plant with pulse clarifier. *Journal of Hazardous Materials*, *413*, 125347. https://doi.org/10.1016/j.jhazmat.2021.125347.

[63] Tang, K.H.D.; Hadibarata, T. (2021). Microplastics removal through water treatment plants: Its feasibility, efficiency, future prospects and enhancement by proper waste management. *Environmental Challenges*, *5*, 100264. https://doi.org/10.1016/j.envc.2021.100264.

[64] Mandal, M.; Roy, A.; Popek, R.; Sarkar, A. (2024). Micro- and Nano- Plastic Degradation by Bacterial Enzymes: A Solution to 'White Pollution.' *The Microbe*, *3*, 100072. https://doi.org/10.1016/j.microb.2024.100072.

[65] Priya, K.; Kumar, S.; Verma, R.; Sharma, P.; Singh, J. (2022). Algal degradation of microplastic from the environment: Mechanism, challenges, and future prospects. *Algal Research*, *67*, 102848. https://doi.org/10.1016/j.algal.2022.102848.

[66] Nasir, M.S.; Abdullah, S.; Ismail, M.; Rahim, N.F.; Mohd, K. (2024). Innovative technologies for removal of micro plastic: A review of recent advances. *Heliyon*, *10*(4), e25883. https://doi.org/10.1016/j.heliyon.2024.e25883.