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A Review of Plastic Pollution; Conventional and Recent Bioremediation Technologies

Chinedum Chukwuemeka UDEKWU,
University of the West of Scotland, UK; B00423075@studentmail.uws.ac.uk

Uchechukwu Chidiebere FRANCIS,
University of the West of Scotland, UK; Frankejikeme.jc@gmail.com

Mercy Mayowa OJETUNDE
West Virginia University, Morgantown, USA.

Joseph Chinemelu OKAKPU,
Michael Okpara University of Agriculture, Nigeria.

Favour Matthew AWAH
Michael Okpara University of Agriculture, Nigeria; awahfavour3@gmail.com

Omoniyi Babajide AWE*
University of Toledo, Ohio
aweomoniyi80@gmail.com

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Abstract - The discovery of the first artificial plastic in 1869, initially known as celluloid and invented by John Hyatt, aimed to replace ivory in ornaments and artistry, reducing the demand for elephant tusks. Hyatt's breakthrough involved dissolving camphor in nitrocellulose and alcohol under heat. While celebrated as a pioneering scientific achievement, little attention was paid to the long-term consequences of plastic proliferation. Today, the widespread use of plastics poses severe threats to marine and terrestrial ecosystems, including habitat competition, water contamination, and the release of environmental toxins, leading to widespread pollution. Developing countries, such as Nigeria, face disproportionate impacts due to the global surge in plastic production and consumption, which outpaces efforts in degradation and recycling. This article reviews the environmental effects of biodegradable (BPs) and non-biodegradable plastics (NBPs), focusing on disposal challenges and management strategies in such regions. It explores microbial degradation as a sustainable solution, synthesizing data from academic databases (PubMed, Scopus, Web of Science) spanning 2000 to 2023. Studies were screened based on relevance to plastic production, usage, disposal methods, and environmental outcomes, particularly in developing countries. The findings highlight that while developed nations manage plastic waste effectively through stringent regulations and innovative recycling, developing countries struggle with inefficient disposal methods, like landfilling and incineration, which contribute to soil and water contamination and greenhouse gas emissions. Microbial degradation is a promising, cost-effective approach to naturally breaking down plastics. The study advocates for enhanced research into microbial degradation and adopting bioremediation technologies globally, emphasizing knowledge sharing and best practices transfer from developed to developing nations. This review underscores the urgency of addressing plastic pollution through sustainable waste management practices, particularly in regions facing significant environmental and health challenges. Prioritizing microbial degradation aligns with environmental sustainability goals and offers a pragmatic solution for tackling plastic waste worldwide

Keywords: *Biodegradable plastics, Microorganisms, Bio-fragmentation, Polyhydroxy butyrate, Photo-degradation, Biodeterioration*

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1. Introduction

Thermoplastics and thermosets are the two main categories into which the complex polymers known as plastics fall [1]. Most plastics, like nylon and polyethylene, are NBPs, or non-biodegradable polymers. NBPs are produced from ethylene gas, a byproduct of petroleum. In contrast, BPs (biodegradable plastics) such as polybutylene succinate, polycaprolactone, polyhydroxy butyrate, polylactide, etc., are produced from biomass or fossils [2,3]. Production of plastics increased from 2 million metric tons in 1950 to 380 million metric tons in 2015 alone, driven by the ongoing surge in global demand for these materials [4]. An additional study on biodegradable plastics in Nigeria found that each person produces around 400 grams of non-biodegradable trash monthly [5]. Plastics are inexpensive and easy to work with, which is a major factor in their rising popularity and manufacturing. However, half of these plastics end up in aquatic bodies because people don't properly dispose of them after use, which means more marine garbage [6]. Nearly two-thirds of the trash that ends up in African countries' drainage systems—including along coastlines—is plastic, which isn't biodegradable. This means that it causes flooding, water contamination, and deaths [7]. Developed nations, on the other hand, have stepped up to the plate to address this NBP environmental problem [8]. These nations have turned to landfilling, different microbial degradation pathways, recycling, and producing biodegradable plastics from biomass and renewable sources (such as sugars, corn, potatoes, etc.). Developed nations have effectively dealt with the issue of NBPs, in contrast to emerging nations, thanks to the stringent implementation and compliance with environmental legislation [6]. Biodegradable and non-biodegradable plastic degradation pathways are covered extensively in this article. The focus is on microbial degradation pathways. The article also discusses the general safety of these pathways, offers suggestions on how developing nations like Nigeria can address their NBP problems, and looks ahead to future developments in plastic bioremediation.

2.0 Structural and Synthetic Composition of Plastics

Traditionally, plastics are produced by the process of petroleum cracking. Crude oil is initially subjected to elevated temperatures and pressure using a specific zeolite catalyst [10]. Subsequently, it is subjected to fractional distillation to obtain naphtha. The naphtha is subjected to additional catalytic cracking to produce ethylene gas, which is then used to manufacture polyethylene and polyvinyl chloride. These two substances are the main components of non-biodegradable plastics and are created by the processes of polymerization or polycondensation [11]. This process forms a lengthy sequence of carbon-to-carbon connections within intricate and condensed plastic structures that bacteria are unable to break down [12]. Biodegradable plastics, also known as biobased plastics, are made from biological sources and include carbon-to-nitrogen peptide linkages easily broken down by microbes (Figure 1). Nevertheless, it is important to note that not all bio-based plastics can naturally decompose. Some examples of materials are polyethylene and nylon.

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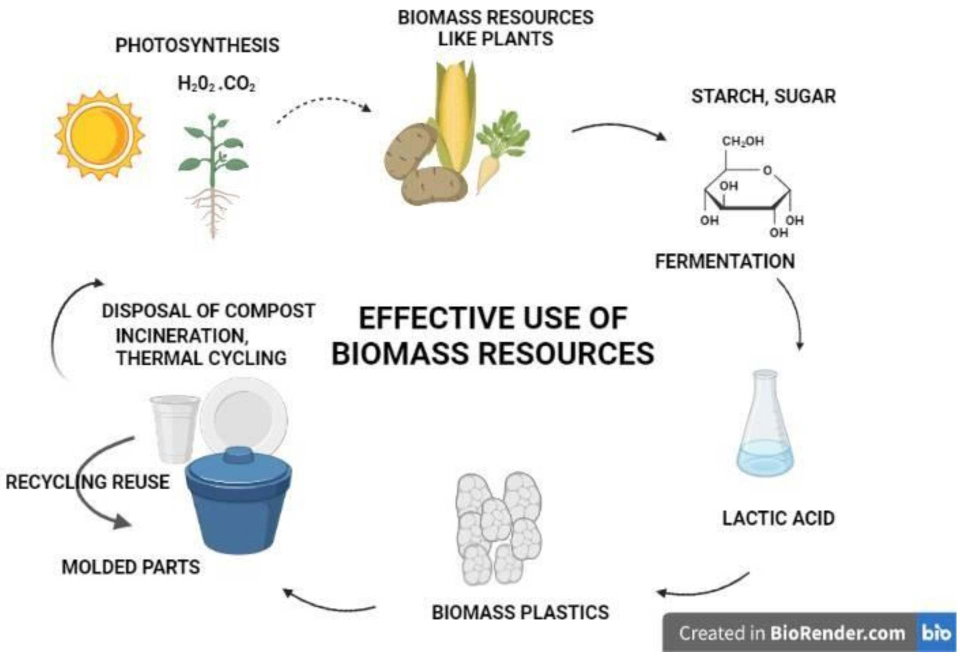

Figure 1: *Production of Bioplastics from biomass* (Created in BioRender.com)

2.1 Overview of Plastic Disposal and Degradation Pathways

Plastics are utilized in various fields such as pharmaceuticals, engineering, electrical, industrial, agriculture, and sports [13]. The widespread use of plastics has undeniably facilitated the discovery of plastic garbage, particularly in the absence of the three principles of waste management: reuse, recycling, and reduction in plastic waste creation. Developing countries continue to have challenges in dealing with non-biodegradable plastics, whereas developed countries have successfully implemented strategies to regulate and control the utilization and manufacturing of plastics [14]. The various methods of disposal have been emphasized as follows.

2.1.1 Landfill

According to the World Economic Forum, recycled plastics are far lower than discarded as trash or buried in landfills [15]. In the United States, a study indicated that 16% of plastic packaging trash underwent thermo-degradation, whereas 70% was disposed of in landfills [16]. Conversely, European countries record a landfilling rate of 30%, whereas underdeveloped countries report a landfilling rate of 100% [17,18]. Although landfilling is commonly used globally as a practical method for managing plastic trash, it faces the drawback of competing for space with other human activities, such as crop and livestock production [19]. Therefore, it is advisable to refrain from landfilling as it is incompatible with the circular economy of plastics and poses sustainability obstacles [20]. Landfilling poses the intrinsic difficulty of vying for valuable ground space with other crucial human activities, such as agriculture and livestock husbandry [19]. This competition may lead to conflicts and problems with limited land availability, highlighting the necessity for more sustainable and space-efficient waste management techniques. One major drawback of landfilling is that it is incompatible with the ideas of the circular economy for plastics. The circular

JDFEWS 5 (1): 11-33, 2024
ISSN 2709-4529

economy prioritizes the reduction, reuse, and recycling of materials in order to minimize waste and foster sustainability. Landfilling is an inherently linear and unsustainable technique of disposal since it does not facilitate the recovery and reintegration of plastics back into the production cycle. Landfilling has substantial sustainability issues due to its environmental impact and limited area availability. The consequences include persistent pollution of soil and water, disturbance of natural habitats, and heightened release of methane due to the decomposition of organic matter combined with plastics. Each of these variables contributes to the adverse environmental consequences of this disposal strategy.

2.1.2 Recycling

In this process, polymers are broken down either through mechanical means or chemical methods utilizing powerful engines and processes such as pyrolysis, gasification, depolymerization, and oxidation. The polymers undergo recycling processes to be transformed into smaller plastic materials, which are then dispersed again for reuse. Although this procedure is widely accepted, the drawback is that thermoset plastics cannot undergo mechanical recycling [21]. Recycling utilizes both mechanical and chemical methods to dismantle and reconstruct plastic products. From a mechanical standpoint, high-powered machines utilize shredding, melting, and reforming processes to transform plastics into smaller particles or shapes. Conversely, chemical techniques such as pyrolysis, gasification, depolymerization, and oxidation employ controlled chemical reactions to convert polymers into valuable chemicals. High-power engines, such as industrial shredders and extruders, are commonly used in the mechanical recycling process. These machines can disintegrate polymers into tiny fragments, which can subsequently be utilized as primary material for a multitude of items. This technique is highly efficient for a wide range of polymeric materials, especially thermoplastics. Chemical recycling procedures, such as pyrolysis and gasification, entail exposing plastics to elevated temperatures and controlled conditions to disintegrate them into their fundamental chemical constituents. This leads to the generation of valuable feedstock or raw materials that can be utilized to produce new polymers or other commodities. Although recycling is flexible, it encounters constraints when handling thermoset plastics. Thermoset plastics differ from thermoplastics in that they undergo a chemical curing process during production, rendering them non-reversible. Unlike thermoplastics, which may be melted and reshaped, thermoset polymers retain their shape permanently. Consequently, they cannot undergo mechanical recycling since they do not become soft when heated. The existence of this constraint highlights the necessity for the development of advanced chemical recycling methods to effectively tackle thermosets.

2.1.3 Thermo-Oxidative Degradation

This necessitates the incineration of plastic garbage at extremely high temperatures. Therefore, the production of liquid fuel, ash, and volatile dioxins can have harmful effects on the environment [22]. The practice of plastic degradation described here is widely used in developing nations and has had a substantial impact on the depletion of the ozone layer due to the release of greenhouse gases [23]. Therefore, this procedure is strongly discouraged due to the need for additional specialized detoxification treatment, resulting in higher costs and reduced environmental friendliness (refer to Table 1). Research has demonstrated that polymers can be used as sources of energy generation by catalytic thermal decomposition in a fluidized bed [24]. The process of converting plastics into gasoline is currently being suggested as a prominent and effective method to address plastic pollution [25]. However, the fundamental obstacle to its widespread implementation is the issue of scalability. Thermo-oxidative breakdown involves exposing plastic trash to exceptionally high temperatures, usually achieved through cremation. In this procedure, the polymers are subjected to high temperatures until they reach the point of burning, causing the complicated polymer chains to break down into simpler components. The final byproducts of this combustion process consist of liquid fuel, ash, and volatile

JDFEWS 5 (1): 11-33, 2024
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dioxins. The emission of volatile dioxins during the process of thermo-oxidative degradation is a major cause for worry. Dioxins are extremely poisonous substances that can cause severe environmental and health consequences. These substances can remain in the environment for a long time and build up in living species, harming ecosystems and human health [22]. Thermo-oxidative deterioration is associated with the reduction of the ozone layer. Plastics combustion emits greenhouse gases, including carbon dioxide and various pollutants, which contribute to global warming and ozone layer depletion [23]. The production of environmentally toxic byproducts during this process requires special detoxification treatment, making thermo-oxidative degradation a costly and less environmentally friendly method of plastic disposal. The requirement for rigorous emissions control and subsequent treatment after combustion contributes to the expenses and ecological consequences. Although the conversion of plastics into fuel is suggested as a major solution to plastic pollution, the capacity to scale up this process is still a substantial constraint. The implementation of this technology necessitates significant infrastructure and financial resources. Additionally, its accessibility and economic viability may vary across different places. Furthermore, the requirement for meticulous emissions control and waste management renders it an intricate undertaking to execute on a grandiose magnitude.

2.1.4 Photo-Degradation

This degrading process utilizes UV radiation. Plastic polymers absorb these rays to start the process, followed by propagation and termination steps to create depolymerized individual units or monomers of olefin, aldehyde, or ketone [26]. Although photo-degradation has a swift final phase, the overall process is prohibitively costly and not feasible for commercialization. Consequently, it lacks widespread acceptance as a feasible method for breaking down polymers. Photo-degradation depends on plastic polymers' capacity to assimilate ultraviolet (UV) radiation, usually derived from sunshine. When subjected to these intense radiation waves, the polymer chains inside the plastic substance experience a photochemical breakdown process. The initiation of this process occurs by absorbing ultraviolet (UV) energy, which stimulates the polymer molecules and initiates chemical processes. After the beginning step, the photochemical reactions spread throughout the plastic substance. This process entails a sequence of successive reactions that fragment polymer chains into smaller constituents. These reactions usually entail the creation of highly reactive substances, which can then interact with the polymer, causing it to break down into smaller units or monomers. The resultant units can have different compositions, such as olefins, aldehydes, or ketones, according to the precise chemical makeup of the plastic material [26]. Although photo-degradation benefits from a quick ending phase, it encounters notable obstacles that restrict its feasibility. A major obstacle is the requirement for a reliable and powerful source of UV radiation, which is not easily accessible in all settings. Moreover, this approach requires significant energy and incurs high costs, rendering it unfeasible for widespread commercial use. The need for regulated UV exposure and the upkeep of these settings can be a substantial obstacle. Photo-degradation is not commonly accepted or regarded as a feasible technology for degrading plastics due to its high prices and impracticality as a mass plastic waste management solution. Although it shows potential as a scientific notion, implementing it on a practical level is difficult.

2.1.5 Biodegradation

Microorganisms have evolved over thousands of years to transform and break down various substances, such as xenobiotics, and are crucial for maintaining several environmental processes. They have played a crucial role in limiting the buildup of certain substances by breaking them down and repurposing their chemical components into reusable molecules, such as water, carbon dioxide, and methane [27]. Microbial communities undergo genetic modifications through evolution to incorporate new chemical compounds into their metabolic pathways, enabling them to adapt to different environmental challenges. Microorganisms, such as bacteria and fungi, have evolved for

JDFEWS 5 (1): 11-33, 2024
ISSN 2709-4529

millions of years to effectively break down and convert a wide range of chemicals, including synthetic or foreign substances, such as many types of synthetic polymers. These microbes possess enzymes and metabolic pathways that enable them to degrade intricate chemical structures present in plastics. A key advantage of biodegradation is its ability to minimize the buildup of synthetic materials in ecosystems, therefore mitigating the process of bioaccumulation. Microorganisms act as the primary defense mechanism by breaking down and reusing the chemical constituents of plastics, converting them into simpler, organic molecules that can be reintroduced into the environment. This encompasses the transformation of plastic trash into water, carbon dioxide, and even methane [27]. Biodegradation facilitates the recycling and reintegration of the chemical constituents of plastics into natural biogeochemical cycles. This approach emulates the natural process of cycling and reusing materials. Microorganisms play a crucial role in preserving the balance of vital components such as carbon and nitrogen in ecosystems by decomposing manmade products. Microbial communities are extremely flexible and have demonstrated the capacity to undergo genetic changes and alter their genomes to adapt to environmental constraints. Over time, these organisms can acquire the ability to incorporate novel chemical compounds, such as those present in plastics, into their metabolic processes. The capacity of microorganisms to adapt and break down plastics in the environment indicates a significant potential for enhanced biodegradation efficiency. Microbes actively breakdown big polymer molecules found in plastics. These microorganisms' function by releasing three primary enzymes: lipase, proteinase k, and dehydrogenase [28]. Table 2 showcases instances of these microbes and the specific types of polymers they break down. *Aspergillus tubingensis*, a kind of fungal, secretes more enzymes than bacteria [29]. Conversely, yeasts (*Pseudozyma antarctica*) exhibit a faster development rate and can flourish in environments characterized by low pH, high salt levels, and cold temperatures. These conditions naturally impede the growth of numerous bacteria [30]. Significantly, yeasts can produce specialized enzymes that assist in the breakdown of various foreign substances known as xenobiotic pollutants [31].

JDFEWS 5 (1): 11-33, 2024
ISSN 2709-4529

Table 1: *A comparison of the different plastic disposal and degradative pathways*

Pathway	Active agent	Degradation Speed	Eco-friendly	Cost efficiency	Reference
Landfill	-	125days	No, it competes for space and leads to land deterioration	Yes, it is costefficient	[32]
Recycling	Corrosive Chemicals	-	Yes	No, (high cost of chemical disposal)	[21]
Thermo-oxidative degradation	Oxygen and heat	Less than 24hrs	No, due to the emission of greenhouse gases	No, it consumes a lot of fuel energy	[33]
Photodegradation	Ultra-violet radiation	50-100yrs	No, the slow rate of degradation allows more accumulation of plastic waste	No, it is highly costly	[34]
Biodegradation	Microorganisms and enzymes	16-100days	Yes	Yes ($5-$25 per kg of cellulose enzyme required for 1 ton of plastic waste)	[35,36]

JDFEWS 5 (1): 11-33, 2024
ISSN 2709-4529

3.0 Mechanism of Plastic Degradation by Microorganisms

Microorganisms break down plastics both outside and inside their cells via five specific processes: colonization, biodeterioration, bio-fragmentation, assimilation, and mineralization [37]. Microorganisms adhere to plastic polymers and establish pore spaces to facilitate penetration while simultaneously forming colonies in the vicinity of the plastics. The process of biodeterioration begins when bacteria, such as Nitrosomonas spp., release compounds, such as sulfuric acid, which weaken the robust carbon-carbon bonds that bind plastic polymers together. In addition, microbes secrete specialized enzymes, including esterases, proteases, and ureases, to degrade more intricate compounds [38]. Following the biodeterioration stage, the fragmentation stage involves microbes' secretion of peroxide and superoxide onto the plastic. This secretion enhances the polarity of the plastic by introducing functional groups, such as hydroxyl and carboxyl groups. These functional groups aid in the microbial colony's ability to break down the polymer into monomers and dimers [40]. Subsequently, the microbe engulfs these smaller units by phagocytosis to break them down into beneficial natural components. This process can occur through either aerobic or anaerobic catalytic pathways, as depicted in Figure 3.

3.1 Colonization: Colonization is the initial stage of plastic breakdown. Microorganisms, such as bacteria and fungi, adhere to the surface of plastic polymers. The microbes form colonies on and around the plastic, forming a microbial community that collaboratively decomposes the plastic substance. Microorganisms utilize many techniques to adhere to plastic surfaces, frequently through direct physical contact facilitated by features such as pili, flagella, or sticky appendages. They have developed the ability to distinguish between various types of plastics, demonstrating a high level of selectivity in their capacity to inhabit surfaces based on surface charge, hydrophobicity, and chemical composition. This acknowledgment could result in the favoritism of plastic materials by specific bacterial and fungus populations.

Upon attachment, microbes often commence the development of biofilms, which are organized populations surrounded by an extracellular matrix. Microorganisms within these biofilms cooperate in a coordinated manner, offering stability and resistance to the microbial population under the demanding environment posed by plastics. The colonization stage demonstrates the wide range of microorganisms present, with each contributing distinct enzymatic capability. The presence of diverse microorganisms allows the microbial community to effectively degrade polymers with different chemical compositions. Collective activity is a defining characteristic of colonization, when microorganisms collaborate and work together in harmony. They secrete extracellular enzymes and participate in internal mechanisms to degrade the plastic polymer, highlighting the significance of collaboration in the plastic breakdown process.
Adaptation plays a vital role in the process of colonization, necessitating alterations in gene expression and metabolic pathways. Microorganisms enhance their capacity to consume plastics as a carbon source and adapt to overcome the environmental difficulties presented by plastics. The colonization of microorganisms on and in the vicinity of plastics initiates a prolonged and ongoing interaction between these organisms and artificial substances. As the microbial community undergoes development and expansion, it actively aids in the gradual decrease of plastic waste and its corresponding ecological consequences.

3.2 Biodeterioration: The biodeterioration process commences when microorganisms start to interact with the plastic polymer. Specific strains of Nitrosomonas spp release compounds, including sulfuric acid, into their surroundings. These compounds have a vital function in weakening the robust carbon-carbon bonds that maintain the

JDFEWS 5 (1): 11-33, 2024
ISSN 2709-4529

integrity of the plastic polymer. The deterioration of the polymer begins with the weakening of its structure. Simultaneously, microorganisms secrete specialized enzymes such as esterases, proteases, and ureases, which aid in further degrading intricate chemical compositions present in the plastic material [38]. Biodeterioration is a crucial step in the microbial decomposition of plastics. It signifies the transition from the early stages of colonization to the deliberate and ongoing process of deterioration. During this stage, microbes interact with the plastic polymer, initiating the process of decomposition. Microorganisms release substances such as sulfuric acid that weaken the carbon-carbon bonds of plastic, making it more prone to deterioration. In addition, they utilize specialized enzymes, including esterases, proteases, and ureases, that are crucial in dismantling intricate chemical compositions included in the plastic substance.

The chemical secretions and enzymatic activities work together to break the chemical bonds in the plastic, causing it to break down into smaller and less complex components. This technique decreases the dimensions and intricacy of the plastic polymer, rendering it more susceptible to subsequent deterioration. Biodeterioration increases the susceptibility of the plastic material to future degradation processes. Microorganisms facilitate the deterioration of plastic by destabilizing the polymer structure and destroying the intricate chemical linkages, thereby preparing it for further degradation phases, such as bio-fragmentation. This stage is crucial in the overall process of plastic degradation by microbes.

3.3 Bio Fragmentation: During the bio fragmentation stage, bacteria release substances such as peroxide and superoxide onto the plastic. These compounds enhance the polarity of the plastic by introducing functional groups, such as hydroxyl and carboxyl groups, into the polymer's structure. The incorporation of these additional functional groups enhances the plastic's susceptibility to microbial breakdown. The microbial colony functions to degrade the plastic polymer into smaller components, such as monomers and dimers. This phase is vital in the process because it converts the plastic material into simpler and easier to handle components [40]. Microorganisms have a vital function in the release of chemicals such as peroxide and superoxide onto plastic material. These chemicals are used to increase the surface polarity of the plastic. This modification incorporates functional groups, such as hydroxyl and carboxyl groups, into the structure of the polymer. The incorporation of these functional groups is crucial since it makes the plastic material more prone to microbial breakdown. The enhanced polarity and integration of hydroxyl and carboxyl groups alter the plastic, rendering it more attractive to the microorganisms present in the colony. Microbial activity can easily reach plastic, making it more susceptible to breakdown. This alteration in the chemical composition of the plastic represents a pivotal advancement in enabling the material to degrade efficiently.

During the process of bio fragmentation, the microbial population works together to break down the plastic polymer. Microorganisms utilize their enzymatic capabilities and metabolic pathways to specifically interact with the changed plastic surface. Their main goal is to break the polymer's bonds, causing the plastic to break down into smaller pieces. The polymeric polymer undergoes a significant alteration through the combined activities of microorganisms. The transformation occurs as the structure transitions from a bigger, cohesive form to smaller, fragmented components. These units are composed of monomers and dimers, which are simpler and more controllable constituents. This change is a crucial breakthrough in the entire breakdown process, as it simplifies the complexity of the plastic material, making it ready for further absorption by microbes.

3.4 Assimilation: Following the bio-fragmentation phase, microorganisms ingest the smaller components of the plastic, such as monomers and dimers. This absorption frequently occurs via phagocytosis, a mechanism wherein the microorganism engulfs and internalizes these entities. After entering the microbial cells, these units generated from plastic serve as substrates for further breakdown.

JDFEWS 5 (1): 11-33, 2024
ISSN 2709-4529

3.5 Mineralization: Mineralization is the ultimate stage in the process of deterioration. Microorganisms utilize plastic-derived compounds as a carbon and energy source. They utilize either aerobic or anaerobic catalytic processes to further decompose these units into natural, biodegradable constituents consisting of carbon dioxide, water, and other environmentally harmless molecules.

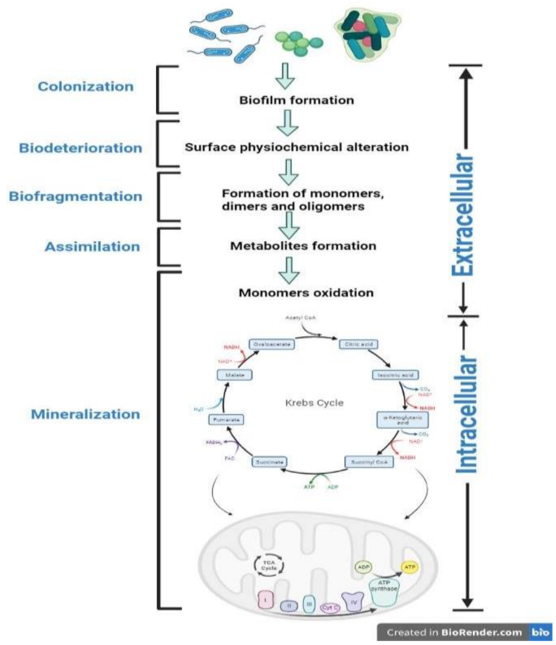

Figure 3: *Mechanism of degradation of plastic polymer by microbes* (Biorender.com)

JDFEWS 5 (1): 11-33, 2024
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***Table 2**: Showing the different microorganisms and the type of plastics they degrade*

MICROORGANISM	PLASTIC TYPE	DEGRADATIVE PRODUCT	REFERENCE
Phanerochaete chrysasporium	PP	Octane, Acrylonitrile, 3-hexanol, etc	[41]
Cochiliobolus sp.	PVC	Diethyl[(phenyl sulfonyl)methyl]phosphate, Dimethylguanidine, etc	[42]
Mucor spp.	PS	n-Hexane, 1,3,5Cycloheptatriene, Benzene, Pyridine	[43]
A. oryzae	PE	4,6-Octadiyn-3-one, 2-methyl	[44]
Aspergillus flavus	PVC	Unspecified lower molecular weight oligomers	[45]
A. fumigatus	PE	Unspecified lower molecular weight oligomers	[44]
Aspergillus nomius	PE	Phenol, 3,5-bis (1,1-dimethylethyl), etc	[46]
Aspergillus terreus	PE	1,2-Bis(Trimethylsilyl)benzene: Hexasiloxane and Hexadecanoic acid	[47]
Aspergillus sydowii	PE	Dodecahydropyrido [1,2-b] isoquinolin-6-one, etc	[47]
Cephalosporium sp.	PS	pyridine, Benzene; Chloro-2,4-Diphenyl-4-methyl-2(E)pentene, etc	[43]
Actinomycete Stryptomyces Scabies	PET	Terephthalic acid	[48]
Cladosporium cladosporioides	PU	2,2-Dimethyl-1,3-propanediol, hexane-1,6-diol, etc	[49]
P. protegens	PU	Unspecified Impranil hydrolysis products	[50]
Stenotrophomonas pavanii	PE	4,6-Octadiyn-3-one, 2-methyl	[44]
Streptomyces sp.	PET	Ethyl benzene, o-xylene	[51]
Streptomyces sp.	PE	Phthalic acid, Heneicosane, Benzene acid, etc	[52]
Streptomyces sp.	PE	1,4-Epoxynaphthalene-1(2h)-methanol, etc	[46]
Amoxybacillus rupiensis	Nylon	6-Aminohexanoic acid	[53]
Achromobacter Denitrificans	PE	Benzene, Tetrachloroethylene, Eicosane, Octane, Hexadecanoic acid	[54]
Bacillus spp.	PET	4,4-dimethyl-2-pentene, carboxylic acids, alcohols	[44]
Enterobacter sp.	PE	Monobenzyl phthalate	[55]
Lysinibacillus fusiformis	PE	1,2,3,4-Tetramethyl benzene and Hexadecanoic acid, etc	[56]

JDFEWS 5 (1): 11-33, 2024
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4.0 Comparative Study of Microorganisms

Table 2 revealed that, in addition to Aspergillus flavus, other species of Aspergillus were discovered to break down plastics exclusively, including polyethylene. On the other hand, bacillus, Streptomycete, and Actinomycete species were identified to specifically degrade polyethylene terephthalate. Additionally, it was revealed that Streptomycete bacteria can create biofilms and achieve optimal degradation at lower temperatures ranging from 18 ºC to 28 °C. In contrast, bacillus and Aspergillus build their biofilms at temperatures between 30 ºC and 35 °C, and at a pH of 9.5 [51]. The study on microbial soil isolates that break down polyethylene terephthalate revealed that the size of the plastic particles and the duration of the reaction play a crucial role in determining the percentage of degradation [47]. Similarly, fungi (*Cochliobolus sp.*) and bacteria (*Amoxybacillus rupiensis*) found in soils contaminated with plastic waste exhibited a preference for polyvinyl chloride polymers and nylon, respectively. *Cochliobolus sp*. produces laccase enzyme and thrives best at a temperature of 30 °C, while *Amoxybacillus rupiensis* degrades most effectively at a temperature of 65°C when grown in a defined chemical medium [42, 53].

Biodegradation refers to the process in which microorganisms break down organic matter, producing carbon dioxide and water. Incomplete mineralization leads to biotransformation, which produces organic and inorganic metabolites or transformation products. Microbes secrete extracellular enzymes responsible for most biodegradation activities involving biopolymers [57, 58]. According to a prior investigation conducted by [37], it has been demonstrated that bacteria and fungus can break down plastics. Fungi were employed to degrade highly resistant polymers, such as low-density polyethylene (LDPE), due to their capacity to release hydrophobic proteins that facilitate interaction with other organisms for colonization [59]. *Aspergillus Niger* effectively broke down plastic carry bags, retaining 25% of their weight after 32 weeks under shaking conditions [60]. In addition, [61] conducted a study to determine the rate of biodegradation of Low-density polythene (LDPE) utilizing *Aspergillus sp*. and versicolor. The study indicated that the maximum rate of biodegradation was 4.1594 gCO_2/l/week. During a one-month period in a laboratory setting, *A. niger* caused a deterioration of LDPE (low-density polyethylene) by up to 5.8%, but *A. japonicas* damaged it by up to 11.11%. Contrarily, *A. niger* degraded at a pace that was 38% faster than a. flavus (31%) over a period of 60 days [34]. Additionally, it has been documented that penicillium is capable of decomposing both LDPE and HDPE, with the involvement of *P. chrysogenum* and *P. oxalicum*. After a 90-day incubation period, HDPE and LDPE underwent decomposition, reducing 55.598% and 34.35%, respectively. This decomposition was accompanied by a decrease in pH. This suggests that the culture is producing metabolic byproducts during its growth in the LDPE or HDPE substrate. These species are expected to possess enzyme(s) that may catalyze alkene bond oxidation, resulting in carboxylic acids and carbonyl compounds. This eliminates the requirement for early oxidation.

Approximately 90 bacterial species have been identified to be capable of plastic breakdown [63]. The biodegradation of LDPE films was assessed using weight, tensile strength, scanning, and GC-MS techniques, in the presence of four bacterial strains: *Pseudomonas aeruginosa*, *Pseudomonas putida*, and *Pseudomonas syringae*. The results indicated a biodegradation rate of 20% [64]. Rhodococcus ruber demonstrated a biodegradation rate of 7.5% in branching low density polyethylene after an incubation period of 8 weeks. *Rhodococcus sp*. 36, found in soil sediments, had superior polypropylene (PP) degradation capabilities compared to Bacillus sp. during a 40-day incubation period [65]. One study [66] found that *Rhodococcus sp*. had a lower Polyethylene (PE) degradation rate than Pseudomonas and *Brevibacillus* *sp*.
Nevertheless, research using an extended incubation period demonstrated elevated breakdown rates for all categories of microorganisms. After 6 months of being kept under controlled conditions, the extent of natural breakdown was measured to be 46.16% by Actinomycetes, 37.09% by *Aspergillus flavus*, and 20.63% by the bacteria Pseudomonas

JDFEWS 5 (1): 11-33, 2024
ISSN 2709-4529

sp. [67]. [58] introduced a theoretical framework to forecast the rates at which chemically altered biopolymers, commonly employed as bioplastics, undergo biodegradation. Modifications in the chemical composition of biopolymers, such as the acetylation of cellulose to produce cellulose acetate, result in alterations in the process of biodegradation. Consequently, biodegradation occurs through the action of cellulases and acetyl esterases.

5.0 Factors Affecting the Biodegradation of Plastics

Environmental conditions, including temperature, humidity, nutrition availability, pH levels, and various other parameters, can influence the growth of microorganisms and their impact on polymers. Microbes release enzymes that are only able to operate within a specified temperature range. If the temperature exceeds this range, the enzymes can become denatured [68]. The temperature at which polymers undergo degradation and disintegrate into smaller molecules, such as oligomers or dimers, is commonly known as the softening temperature. Moreover, the softening temperature serves as an indicator of the polymers' resistance to biodegradation. At elevated temperatures, the enzymes responsible for degradation may undergo denaturation, resulting in the loss of their structural integrity. Lipase efficiently breaks down polycaprolactone (PCL) at low temperatures by hydrolysis [3].

Recent research indicates that certain bacteria, such as Bacillus, Rhodococcus, and Pseudomonas, can build biofilms on plastic surfaces, enhancing their degradative powers. In contrast, streptomyces fungal species do not possess this capability [69]. For instance, the bacillus bacteria release surfactant to reduce the hydrophobicity of the surface. This allows them to enter the plastic polymer and access the carbon-carbon structures in the backbone. On the other hand, fungal hyphae lack this ability, affecting their plastic degradation rate [70]. These biosurfactants enhance the process of biodegradation in challenging environmental conditions, such as elevated temperatures or pH levels [71,72].

The type and number of additives employed in the pre-treatment of plastics can impact the rate at which microorganisms break down the plastics in a bioreactor. Plastics with a high molecular weight necessitate a greater number of chemical additions, such as cobalt and nickel, to enhance the microorganisms' ability to digest the plastics more rapidly and effectively [73]. Polymers with greater molecular weight and larger dimensions exhibit increased resistance to breakage. Enzyme activity enhances polymers' properties with a reduced surface area and a decreased molecular weight [74]. It increases the probability of direct interaction between the enzyme and the substrate. To improve biodegradability, a standardized requirement regarding shape and size exists. Additionally, the degradation of plastics can be influenced by the specific functional groups included in the plastic polymer. When selecting bacteria for biodegradation, it is crucial to consider the precise type of plastic they may digest and the functional groups present. This information is emphasized in Table 2.

JDFEWS 5 (1): 11-33, 2024
ISSN 2709-4529

6.0 Integration of 4ir Technologies to Mitigate the Adverse Effects of Plastic Pollution

The 4th Industrial Revolution (4IR) introduces advanced technologies that have the potential to significantly mitigate the adverse effects of plastic pollution through innovative approaches to waste management and environmental remediation.

6.1 Artificial Intelligence (AI): AI algorithms can revolutionize waste sorting processes by accurately identifying and sorting different types of plastics based on their composition and recyclability. This precision enhances recycling efficiency, reduces contamination in recycled materials, and maximizes resource recovery rates. Real-time data analytics provided by AI systems also enable dynamic adjustments to waste management strategies, optimizing collection routes and improving overall operational efficiency [75].

6.2 Internet of Things (IoT): IoT devices are crucial in real-time environmental monitoring and management. Sensors embedded in waste collection bins and recycling facilities can track fill levels, monitor waste composition, and detect potential environmental hazards. This data-driven approach enables proactive interventions to prevent plastic waste leakage into ecosystems and enhances the effectiveness of waste management practices [76, 77].

6.3 Advanced Robotics: Robotics technology automates complex waste sorting and processing tasks, improving throughput and quality in recycling operations. Robotic systems equipped with AI can handle delicate operations such as sorting mixed plastics and dismantling electronic waste, thereby increasing recycling rates and reducing the environmental footprint of plastic disposal [78, 79].

6.4 Bioremediation Technologies: Beyond conventional recycling methods, recent advancements in bioremediation technologies offer sustainable solutions to plastic pollution. Microbial degradation processes can break down plastics into biodegradable components, contributing to the reduction of plastic waste accumulation in landfills and marine environments [80, 81]

7.0 Future Directions

Scientists are diligently researching natural microbes that can more effectively break down plastics in challenging situations that normally inhibit their activity. These microorganisms must possess the ability to undergo exponential growth by utilizing plastic as their primary source of carbon energy. To achieve this, scientists are currently investigating the possibility of genetically modifying the Rhodobacterales, Oceanospirillales, and Burkholderiales orders by cloning the cutinase gene. This genetic manipulation aims to improve their ability to build biofilms and enhance their hydrolytic powers [82]. However, this research extends beyond bacteria and includes larger creatures. It has been recently found that a kind of worm known as the "yellow mealworm" can effectively break down plastics quickly [83]. Recent research has revealed that dark and super worms have the microbiological capacity to break down plastics [84]. In addition, researchers are developing innovative methods for creating modified natural polymers that have improved mechanical and physical characteristics. This is being done to address the issue of greenhouse gas emissions that occur when plastics are incinerated as a means of degradation [85].

8.0 Conclusion

Ultimately, the widespread utilization of plastics, namely non-biodegradable plastics (NBPs), has resulted in a worldwide environmental catastrophe with significant repercussions for both marine and terrestrial ecosystems. Given the increasing prevalence of plastics in our everyday existence, it is crucial to prioritize implementing efficient waste management systems and remediation technology. This review has conducted a thorough examination of several methods for disposing and breaking down plastic, paying close attention to both traditional and new bioremediation

JDFEWS 5 (1): 11-33, 2024
ISSN 2709-4529

techniques. Nevertheless, the transition towards biodegradation through microbial degradation pathways offers a hopeful prospect for a sustainable resolution to plastic pollution. Microorganisms, including bacteria and fungi, have evolved for millions of years to effectively metabolize and break down synthetic polymers. The microbial degradation route, which involves colonization, biodeterioration, bio-fragmentation, assimilation, and mineralization, offers a feasible and environmentally benign option. The analysis of various plastic disposal and degradation paths highlights the significance of adopting environmentally friendly approaches. Microbial degradation is notable for its rapid decomposition rate, environmentally friendly nature, and economic effectiveness, making it an attractive option for impoverished countries grappling with substantial obstacles in plastic waste management. To effectively tackle the challenge of plastic pollution, it is crucial for future efforts in bioremediation to prioritize the enhancement of microbial degradation processes, the exploration of microbial diversity, and the development of innovative technologies. Furthermore, global cooperation and the sharing of knowledge can aid in transmitting effective waste management strategies from more advanced areas to less developed countries.

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