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Plastics Biodegradation: The Situation Now and Its Potential Effects on Environmental Safety

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ABSTRACT: Plastics are made of polymers with a high concentration of petrochemical components derived from coal, oil, and natural gas and majority of fossil and bio-based plastics are not biodegradable. The aim of this paper is to provide a critical review of the current situation and potential environmental safety of plastic biodegradation by harvesting data and information from secondary sources. Data obtained show that there are several different kinds of plastics exists, including polypropylene (PE), polyethylene terephthalate (PET), polyvinyl chloride (PVC), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polystyrene (PS) and that the environment is seriously threatened by the widespread use of plastics, poor waste management, and careless community behaviour about proper disposal. In Nigeria, more than 88% of the plastic garbage produced is not recycled. In the absence of appropriate waste management and litter control techniques, the use of biodegradable plastics for specialised applications is a promising idea. *Ideonella sakaiensis* 201-F6 is a brand-new bacterial strain that has been discovered to be capable of breaking down PET. High-density polyethylene was found to be negatively impacted by *Achromobacter xylosoxidans*. Therefore, a lot of research is being done to create methods for degrading polymers composed of fossil and biological sources as excellent techniques and environmentally acceptable strategies for waste management.

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According to Saminathan *et al*. (2014), plastics are polymer products made from a variety of synthetic or semi-synthetic organic and inorganic substances. They contain significant amounts of petrochemical components obtained from coal, oil, and natural gas. Many polymer materials, such as polyvinyl chloride (PVC), polylactic acid or polylactide (PLA), polycaprolactone (PCL), polyethylene (PE), polyurethane (PUR), polyhydroxybutyrate (PHB), polyhydroxyalkanoate (PHA), polyethylene terephthalate (PET), polybutylene succinate (PBS), polypropylene (PP), and polystyrene (PS), are commonly used for various purposes (Muhamad *et al*., 2015; Yoshida *et al*., 2016). Today's most widely used plastics, including PE, PP, PS, and PVC, are mostly made of fossil and bio-based materials that do not decompose. Due to poor waste management and unchecked littering, these non-biodegradable plastics have accumulated in the environment in vast amounts and pose an imminent risk to our planet (Sharma and Dhingra, 2016). In addition to numerous other ecological and health issues, the long-term buildup of non-biodegradable polymers in the soil decreased soil fertility. According to estimates made at the global level, 57 million tonnes of plastic garbage are produced each year (Vijaya and Reddy, 2008).

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Additionally, aquatic birds and fish are at risk since there are six times as many plastic polymers in the oceans as plankton. Serious issues with human health are also being brought on by plastics and their additives (Comăniță *et al*., 2016). Because of this, non-biodegradable plastics have accumulated in the environment, and scientists and other partners are quite concerned about this problem (Tokiwa and Calabia, 2008).Bio-based biodegradable polymers are playing an increasingly important role in the packaging, health, and agriculture industries, although their impact on the plastics sector is still extremely small. Additionally, according to Rujni-Sokele and Pilipovi (2017), community training plans and efficient waste management are the foundations of both the technologies' environmental safety and applicability. Numerous studies have documented how certain microorganisms, such as bacteria and fungi, are able to degrade biodegradable polymers quickly under stress by creating exoenzymes and their byproducts (Ghosh *et al*., 2013). Proteases, lipases, and cutinases are significant microbial enzymes involved in the biodegradation of polymers (Muhamad *et al*., 2015). Aside from that, it has been demonstrated that complex polymers like poly(ethylene adipate) and PCL can be broken down by enzymes like esterases and lipases generated by *Rhizopus delmar*, *R. arrhizus*, *Achromobacter* sp., and *Candida cylindracea* (Lam *et al*., 2009). Due to their complex structure and lack of understanding about the ideal circumstances for rapid degradation, biodegradable plastic polymers make up a relatively small portion of commercial uses (Rujni-Sokele and Pilipovi, 2017). In order to ensure environmental safety, biodegradable plastics could eventually replace nonbiodegradable polymers in at least some applications, which might involve packaging, if policies like proper waste management, garbage control, community education, and the development of industrial biodegradation facilities are implemented. Microorganisms destroy complex polymers by a variety of processes, such as the direct use of plastic fragments as food or the indirect action of numerous microbial enzymes. *Pseudomonas fluorescens*, *P. aeruginosa*, and *Penicillium simplicissimum* are the most often employed bacterial and fungal strains for the biodegradation of polymers (Raziyafathima *et al*., 2016).

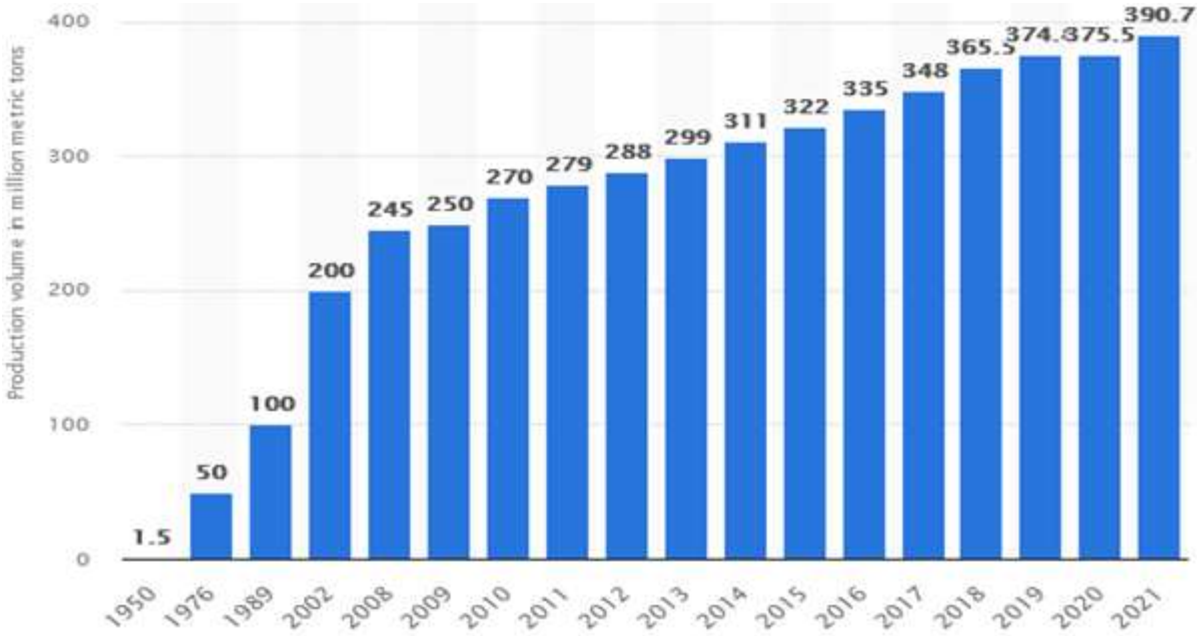

Fig 1: Annual production of plastics worldwide from 1950 to 2021 (Statista, 2023)

Types of Plastic

Polyethylene Terephthalate (PET): among the thermoplastics that are most frequently made worldwide. Due to its widespread use in the food and beverage industries, PET is the thermoplastic that generates the most garbage overall. PET is used to make salad trays, water bottles, and carbonated beverages. The thermoplastic polyester that goes by the name polyester most frequently is PET. PET is a thermoplastic substance that comes in amorphous (transparent) and semi-crystalline (opaque and white) forms. PET that is semi-crystalline exhibits good tensile, ductile, stiffness, and hardness properties. It barely absorbs any water. PET is ductile but less stiff and rigid than metal.

High Density Polyethylene (HDPE): By using the compression moulding technique, HDPE matrix composites augmented with chitosan particles were created. As reinforcement, chitosan particles from deep-sea squid were employed, which had a bulk density of 0.3g/cm3 and a particle size of 90 m. In the current era, polymer composites are a research material. They are employed in the manufacture of shampoo bottles, bleach bottles, and cleaning bottles.

Polyvinyl Chloride (PVC): They are employed in the fabrication of pipes, fittings, rigid PVC window and décor frames, PVC foam thermal insulation, and automobile components. PVC, a product of salt, oil, and gas, was one of the first plastics to be discovered (Chauhan *et al*., 2019). PVC is made from ethylene (43 wt%) and chlorine (57 wt%), which are created as byproducts of the chloralkali electrolysis of brime, which also produces sodium hydroxide, hydrogen, and chlorine. It is one of the chemical industry's most expensive goods. PVC, a stiff material, is softened and made more malleable by the addition of plasticizers, the most popular of which are phthalates.

*Low Density Polyethylene (LDPE)***:** The substance LDPE is malleable and flexible. The melting point is between 105 and 115 °C, and it is stable between 50 and 85 °C. LDPE is stable up to 290 °C without oxygen. Within 290 to 350 °C, it disintegrates, forming thermoplastic compounds with a decreased molecular weight. Above 350 °C, more gaseous products are produced, and butene rather than ethylene makes up the majority of these gases. Less stable in the presence of oxygen is LDPE. Thermal oxidation takes place while processing LDPE at high temperatures in the presence of air. UV radiation-induced photochemical oxidation of LDPE happens when it is exposed to the outdoors. Fine fractures develop on the surface of the products as a result of oxidation brought on by heat or light influences. They could degrade the mechanical and physical attributes. Light stabilisers are added to LDPE to help stop these undesirable phenomena. Practically minimal impact is felt by non-oxidising acids, bases, salts, and their solutions on polyethylene. But oxidising substances harm polymers. LDPE is insoluble at room temperature, but it dissolves in aliphatic, aromatic, and halogenated hydrocarbons at higher temperatures. Environmental stress splitting is a phenomenon that can occur when products manufactured from LDPE are subjected to the effects of chemical compounds as well as mechanical stress. LDPE offers superior permeability characteristics. While essentially impermeable to water and steam, it possesses good permeability to oxygen and carbon dioxide. These qualities are used specifically in packaging. With good dielectric characteristics and a high volume resistance, LDPE makes a great insulator. Because of its low dissipation factor, LDPE is well suited for usage at high frequencies, especially where very little dielectric loss is needed. The extensive range of uses for this polymer is made possible by its superb physical and mechanical qualities. For all processing processes, BRALEN+ and TIPOLEN are offered in a variety of grades as follows: blow moulding, extrusion, and injection moulding of plastic films. for the manufacture of packaging films, bin liners, and carrying bags.

Polypropylene: The thermoplastic polymer polypropylene is colourless and odourless, translucent in its natural condition, and can be dyed in a variety of colours and tones. First and foremost, all Tipplen and Tatren grades are distinguished by their high polymer purity and reliable quality. This is because Ziegler-Natta catalysts are produced via a very complex method. They are used to make microwaveable meal trays and margarine tubs, as well as fibres and filaments for carpeting, wall coverings, and car upholstery.

*Polystyrene:*Polystyrene, a hard thermoplastic with no flavour or odour, is also tasteless. Easily polymerizing to polystyrene, styrene does so by a reasonably common free radical chain process. Due to the brittleness of crystal polystyrene, styrene is routinely polymerized in the presence of dissolved polybutadiene rubbers to increase the strength of the polymer. These homopolymers of styrene are also known as general-purpose or crystal polystyrene. By production volume, polystyrene is the fourth-largest thermoplastic. It is applied in the key markets for packaging consumer and institutional items, electrical goods, furniture, building construction, industrial machinery, and transportation, in that order of consumption. To make plastic cutlery, foam hamburger boxes, foam egg cartons, protective packaging for toys and electrical products, and insulating material for use in construction and building projects.

Classification of Plastics Based on Biodegradability: In terms of biodegradability, plastics can be divided into two categories: non-biodegradable plastics and biodegradable plastics. The chemical structures of several plastic polymers, both biodegradable and not, are discussed, along with the stated mechanisms of their degradation in particular investigations.

Non-biodegradable plastics: Polymers derived from fossil fuels and biological sources are both non-biodegradable plastics. The majority of commonly used nonbiodegradable plastics are fossil-based synthetic polymers made from hydrocarbons and petroleum (petrochemical) derivatives. Due to the frequent repetition of tiny monomer units, their molecular weight is large (Ghosh *et al*., 2013). These polymers are very stable and do not easily interact with biosphere cycles that lead to deterioration (Vijaya and Reddy, 2008). The majority of commercial polymers used today are either non-biodegradable or degrade at rates that prevent total disintegration. Many commonly used plastics, such as PVC, PP, PS, PET, PUR, and PE, are non-biodegradable. They have built up in the surroundings in enormous proportions as a result of inadequate waste management and littering, and they are now a threat to the planet (Krueger *et al*., 2015). Nowadays, plastic films for different plastic objects, including sheets used for packaging, carry-on and shopping bags, and mugs, are made from polyolefin-derived plastics, such as PE. Limitations in waste management are a problem with polyolefins because of their durability and stability in the environment. The promotion of waste management methods for such non-biodegradable polymers is therefore important (Shah *et al*., 2008). Additionally, some of these polymers have starch and pro-oxidants added to them to aid in disintegration, which lessens their inflexibility and resistance to microbial attack (Vijaya and Reddy, 2008). However, due to a dearth of convincing proof of degradation, oxo-biodegradable polymers are thought to be non-biodegradable (Reddy, 2008).

Biodegradable plastics: Depending on the level of biodegradability and microbial assimilation, both bio-based and fossil-based polymers can be used in biodegradable plastics. Enzymatic and non-enzymatic hydrolysis occurs during the biodegradation of polymers (Wackett and Hershberger, 2001). The nature of the pretreatment, the type of organism, and the properties of the polymer are a few of the variables influencing how effectively biodegradation processes work. Additional essential factors for the degradation of plastics include mobility, crystallinity, functional group type, tactility, chemical components, molecular weight, and additives included in polymers (Artham and Doble, 2008). Microorganisms release exoenzymes during the degradation process, which breaks down polymer complexes into simpler molecules like dimers and monomers. As a result, tiny molecules must be much smaller to pass through a bacterial cell's semi-permeable membranes and be used as both the cell's source of energy and carbon (Jayasekara *et al*., 2005). Both aerobic and anaerobic processes are used in biodegradation reactions (Shah *et al*., 2008).

Bio-based biodegradable plastics: Renewable resources are used to create bio-based, biodegradable polymers. Due to their capacity for complete biological degradation, bio-based biodegradable polymers are desirable in several industrial applications from an environmental standpoint (Kale *et al*., 2007). Since enzymes lower their molecular weight extracellularly, bio-based biodegradable plastics like cellulose, starch, and starch-based polymers are directly digested by microbes. The most popular bio-based polymer for making biodegradable plastics is starch. Starch is widely used to create bio-based, biodegradable polymers because of its availability, affordability, abundance, and capacity to degrade under specific environmental circumstances (Nanda *et al*., 2010; Chattopadhyay *et al*., 2011). Since starch is made up of amylopectin and amylase polymers, it can be used as a replacement. Starch-based polymers are divided into two categories, along with a wide variety of other bio-based, biodegradable compounds used in packaging.

According to Jayasekara *et al*. (2005), starch-based polymers are an alternative to starch-filled polymers. Microorganisms (bacteria, fungi, and algae) and different environmental factors are able to completely decay these polymers (Kasirajan and Ngouajio, 2012). Various microorganisms (*Variovorax paradoxus*, *Comamonas* sp., *Aspergillus fumigatus*, *Acidovorax faecilis*, and *Paucimonas lemoignei*), isolated from soil, are reported to degrade bio-based polymers under both anaerobic and aerobic conditions (Tiwari *et al*., 2018). Polyethylene succinate, *Pseudomonas* sp., plastics industry, Shopping bags, Agriculture films (Tribedi and Sil, 2014) Polylcaprolactone, *Clostridium botulinum*, *C. acetobutylicum*, *Fusarium solani*, long-term items, Agricultural films, fibres, Aquatic weeds, and seedling containers (Abou-Zeid *et al*., 2001). Polymer blends Starch/polyester *Streptomyces*, *Phanerochaete chyrsosporium* present in fibres and engineering thermoplastics (Shah *et al*. 2008). Starch/polyethylene *Aspergillus niger*, *Penicillium funiculosm*, and *Phanerochaete chrysosporium* are Highly susceptible to environmental conditions (Shah *et al*. 2008). Starch/PVA Blends *Alcaligenes feacalis*+ Agricultural Applications, Packaging Materials (Pathak and Navneet, 2017)

Polyhydroxyalkanoates: It is naturally occurring biodegradable polyester made from sugars and lipids that are fermented by microorganisms (Shimao, 2001). Due to their biodegradability, PHA polymers can be employed in the pharmaceutical, medical, and packaging industries (Philip *et al*., 2007). Fast food service equipment, disposable medical devices, packaging materials, and various paints are further things created by PHA that are often utilised (Flieger *et al*., 2003). Under various soil and environmental circumstances, PHA is subject to varying degrees of microbial biodegradation. Microorganisms can break down PHA and use it as a carbon and energy source when there aren't enough available sources of those things (Chen and Patel, 2011). According to Boyandin *et al*. (2013), *Bacillus*, *Burkholderia*, *Nocardiopsis*, and *Cupriavidus* are a few representative bacterial taxa for PHA biodegradation. Similar to how fungal taxa like Mycobacterium and *Micromycetes* are known to digest PHA, they do so using both aerobic and anaerobic pathways (Boyandin *et al*., 2013).

Polylactic acid: The commercial production of polylactic acid, a biodegradable plastic, is carried out by NatureWorks in the USA. It is produced using renewable resources like sugarcane, tapioca roots, or maize starch. Because the polymer may be integrated into both human and animal bodies, it has been widely used in medicine (Ikada and Tsuji, 2000). Due to its availability, biodegradability, and outstanding mechanical qualities, PLA is the most significant among the biobased biodegradable polymers (Balla *et al*. 2001). Microorganisms have been shown to be able to entirely metabolise the PLA hydrolytic breakdown products (Fukushima *et al*., 2009). Since then, it has been discovered that soil-isolated *Amycolatopsis* sp. and *B. licheniformis* degrade PLA (Anderson and Shive, 2012). Lipase isolated from the fungus *Cryptococcus* sp. strain S-2 effectively degraded PLA and displayed a distant resemblance to proteins of the cutinase family (Masaki *et al*., 2005). Another bio-based biodegradable polymer used in the delivery of food and medication to host microorganisms is poly(lactic-co-glycolic acid) (Anderson and Shive, 2012).

*Fossil-based biodegradable plastics:*Fossil-based biodegradable plastics are used in a variety of applications, particularly in the packaging sector. The vast majority of fossil-based plastics, nevertheless, are nonbiodegradable and present a significant challenge for the management of their waste (Kehinde *et al*., 2020). One of the main challenges in the contamination control process is the scrap of non-biodegradable fossil-based plastics in humus (Goldstein, 2005). The packaging of pharmaceutical products, various foods, cosmetics, and chemicals uses these plastics extensively. Non-biodegradable polymers derived from fossil fuels degrade very slowly. The degradation process is aided by a variety of environmental factors, including bacteria and their enzymes (Chen and Patel, 2011; Mir *et al*., 2017). According to Vijaya and Reddy (2008), new findings on the degradation of plastics are concentrated on characterising the microorganisms that can break down fossil-based plastics in the atmosphere, developing new enzyme-based degradation strategies, and synthesising duplicates of the genes that encode biodegradation enzymes. However, for efficient and quick biodegradation, the microbe-based biodegradation processes must be tailored for different environmental circumstances. Additionally, effective waste management and litter prevention are crucial for a better use of these polymers in terms of environmental safety. Following are some instances of biodegradable polymers derived from fossil fuels:

Polyethylene succinate: One of the thermoplastic polyesters, polyethylene succinate (PES), is produced by copolymerizing ethylene oxide and succinic anhydride or by poly-condensing ethylene glycol and succinic acid (Hoang *et al*., 2007). PES is a material that the plastics industry uses to make agricultural films, paper coating agents, and shopping bags. A mesophilic bacterial strain known as *Pseudomonas* sp. AKS2 is said to breakdown this polymer effectively (Tribedi and Sil 2014). Contrary to the diversity of PCL-degrading microorganisms, there is a restricted distribution of PES-degrading microbes. The thermophilic *Bacillus* sp. TT96 strain, which also degrades PES, was obtained from soil (Tokiwa *et al*., 2009). In addition, certain mesophilic microorganisms that were isolated and have the potential to naturally break down PES are phylogenetically related to the genera *Bacillus* and *Paenibacillus* (Tokiwa *et al*., 2009).

Polycaprolactone: Aerobic and anaerobic microbes may quickly break down polycaprolactone, a biodegradable polymer derived from fossil fuels. Along with its application in packaging material, biomedical devices, catheters, and blood bags, this partly crystalline polyester is blended with other copolymers. It is costly, but because of its adaptability and biodegradability, it has attracted interest (Wu, 2005). Microbial lipases and esterases have the ability to break down PCL (Karakus. 2016). The *Bacillus* and *Paenibacillus* genera are home to many bacteria that are known to degrade PCL (Tokiwa *et al*., 2009).

Biodegradable polymer blends: Blending multiple elements is an affordable and effective way to manufacture biodegradable polymers with the desired properties. In comparison to copolymerization, this approach is simpler, quicker, and more affordable (Tokiwa *et al*., 2009). The component that is instantly biodegradable determines how quickly polymer blends degrade (Jayasekara *et al*., 2005). Polymer blends are preferred over fossil-based biodegradable polymers in several applications due to their advantages on a commercial scale (Garg and Jana, 2007). Blends made from starch-based biodegradable polymers include starch-PVA and starch-polyester blends. Due to the complete disintegration of each component, they are thought to be completely biodegradable. The main mechanism of degradation causes the polymer's structural integrity to collapse, increasing the surface area available for enzyme action. Research on the microbiological mechanisms of polymer blend breakdown and diverse degradation products has been on the rise (Jayasekara *et al*., 2005). The assimilation of the starch and PVA mixtures by diverse bacteria is claimed to result in complete biodegradability. The processing parameters of starch and PVA mixes have been extensively researched (Thakore *et al*., 2001).

Starch/polyester blends: The nature of the materials they are made of makes starch and polyester mixes biodegradable. Artificial polyester and starch blends are economical because starch is widely available, inexpensive, and renewable (Tokiwa *et al*., 2009). Increasing the starch concentration speeds up the degradation of polyesters like PCL in the blend (Ratto *et al*., 1999). Blends of straight-chain polyester and starch exhibit better properties when functionalized anhydride polyesters are added in tiny amounts, according to Mani and Bhattacharya (2001). These blends, which have ductile intensities and a 70% level of starch by weight, are relatively akin to synthetic polyester. The majority of thermoplastics used in engineering are made from polyesters, which are also versatile polymers (Fradet and Tessier, 2003). According to Tokiwa and Calabia (2007), mixes of polyester can be hydrolyzed by lipase enzymes produced by a variety of microorganisms, particularly the *R. arrhizus* and *R. delemar* strains.

PVA/starch mixtures: PVA is a biodegradable, water-soluble polymer derived from fossil fuels; adding starch to PVA makes it more competitive. These mixtures are widely utilised in agriculture and packaging because they have improved film-forming properties (Tang *et al*., 2008). Enzymatic hydrolysis has been found to be used by several bacteria to break down starch and PVA mixtures. Depolymerase, for instance, is known to effectively breakdown these blends and is released by *Alcaligenes feacalis* T1 (Tokiwa *et al*., 2009).

Current Status of Plastic Pollution: The amount of plastic produced increased dramatically from 2 million metric tonnes in 1950 to 348 MT in 2017 (Nairobi, 2022). With more plastic being produced, there is a considerable increase in plastic trash, much of which ends up in landfills and the ocean. There are now significant efforts being made to decrease plastic usage and improve recycling because of the negative environmental effects of plastic trash. Every year, 11 metric tonnes of plastic trash enter the ocean. By 2040, this could have tripled (Kibria *et al*., 2023). The seas' plastic garbage is dangerous to marine life and may have negative effects on human health. To prevent additional harm to our seas, it is crucial to take steps to minimise plastic usage and properly dispose of plastic debris. Microplastics build up in the ocean as a result of the hundreds of years it might take for plastic debris to disintegrate. These tiny plastic particles can find their way into the food chain and then onto our plates. As a result, it is imperative that both individuals and corporations embrace sustainable practises and support programmes that advance a circular economy.

In 2020 alone, an estimated 367 MT (367 billion kg) of plastic will be manufactured. Compared to the 1.5 million MT (1.5 billion kg) produced in 1950, this is a huge increase. Most of this plastic garbage is dumped in landfills or the environment, harming ecosystems and wildlife. In fact, it is predicted that there will be more plastic in the ocean by weight by 2050 than there will be fish. This emphasises how vital it is for both citizens and governments to take action to cut back on their use of plastic and properly dispose of their plastic waste. Every second that year, about 12 metric tonnes (12,000 kg) of plastic waste were created (Dawodu *et al*., 2023). This shocking quantity of plastic waste is the same as a truckload of trash being dumped into the ocean every minute. Our oceans are becoming overrun with plastic debris, which is harming marine life and upsetting entire ecosystems.

Around 2.5 MT of plastic garbage are produced in Nigeria each year; according to Dumbil and Henderson (2020), Nigeria is the ninth-highest contributor to global plastic pollution. Given that it frequently ends up in landfills and waterways, where it causes pollution and other environmental concerns, this plastic trash poses a serious risk to both the environment and human health. To lessen the effects of plastic pollution, Nigeria must adopt efficient waste management plans and encourage environmentally friendly behaviours. Unfortunately, approximately 88% of Nigeria's plastic garbage is not recycled. Rather, a large portion of it finds its way to bodies of water like rivers, drains, lakes, lagoons, and the ocean. As a result, there is now a serious environmental and health issue since dying marine species mistake the plastic for food. Additionally, during rainy seasons, the plastic debris causes flooding by clogging up streams. According to Aligbe (2021), Lagos produces 870,000 metric tonnes of plastic waste per year. As a result, it ranks as one of the major sources of global plastic pollution. The government must put policies in place to lessen this waste, such as outlawing single-use plastics and encouraging recycling initiatives. But there have been obstacles, such as a lack of infrastructure and resources for effective waste management. In order to stimulate attitude change towards minimising plastic trash, there is also a need for greater public education and awareness efforts.

Effects of Plastics on Environmental Microbiome: According to Paredes and Lebeis (2016), plastics have direct chemical effects on several types of ambient microbial communities in addition to having an impact on microbial communities physically. It has a number of unanticipated biological consequences, according to Bray and Wicking (2019). A few examples of these effects include changes in the types of microorganism present, altered metabolic processes, and increased antibiotic resistance. Plastics may also be used to transport dangerous germs and toxins, which could harm the microbiomes of the environment. Furthermore, the accumulation of plastic garbage in the ecosystem has a physical impact on species and their habitats. This highlights how important it is to develop effective waste management strategies and progress towards plastic substitutes that are less harmful to the environment. A further factor in greenhouse gas emissions and global warming is the production of plastic. Thus, reducing the use of plastic and adhering to the principles of the circular economy can greatly enhance both the environment and human health. Plastics may be affected by changes to the composition and population of microbial communities as well as changes to their metabolic activity. Plastic pollution can cause the environment to accumulate harmful substances that can be harmful to both human and microbial health. Studies have shown that plastic pollution can disturb the usual balance of microbial populations in aquatic environments, which may have adverse ecological implications. Additionally, the spread of bacteria that are resistant to antibiotics might be aided by the presence of microplastics in the environment, jeopardising public health. Furthermore, pollution from plastic may have a negative impact on people's health. Microplastics created from plastic waste have the potential to contaminate the seafood we eat and get into the food chain. Consuming dangerous chemicals as a result could have negative health effects. Paredes and Lebeis (2016) claim that a range of environmental microbial communities are directly impacted by chemicals. Given that they are crucial to maintaining the health and balance of ecosystems, it is important to comprehend the consequences of chemical exposure on the diversity of these communities. A domino effect on other organisms and ecological processes can also result from changes in the diversity of microbial communities. A decrease in microbial diversity, for instance, could impact soil fertility and nutrient cycling. A small number of microbial species may also have essential symbiotic relationships with plants, and changes in their diversity or abundance may have an effect on the growth and well-being of plants. Microbial diversity is critical for maintaining the overall health and resilience of ecosystems because it can help with disease control and increase resistance to environmental shocks. Additionally, knowing how microbial communities function in ecosystems can assist in direct conservation efforts and lessen the negative consequences of human activities on natural systems. For instance, by studying the microbial communities in the soil, scientists can develop strategies to improve soil health and fertility, which are crucial for agriculture and food security. Additionally, knowing the microbial communities in aquatic ecosystems can assist in direct efforts to restore damaged habitats and safeguard biodiversity.

Microbes and their mechanisms for plastic biodegradation: According to Shah *et al.* (2014), extracellular enzymes produced by microbes mostly bacteria and fungi are frequently used to aid in the breakdown of several kinds of bio- and fossil-based polymers. These polymers are broken down by bacteria and fungi into CO_2 and H_2O using a variety of metabolic and enzymatic processes. Depending on the microbiological species and even within the strains, different enzymes have different characteristics and catalytic activities. A variety of enzymes are known to breakdown distinct forms of polymer due to this selectivity. For instance, proteases produced by *Bacillus* spp. and *Brevibacillus* spp. are engaged in the degradation of different polymers (Sivan, 2011). In order to catalyse the oxidation of aromatic and non-aromatic chemicals, laccases are typically found in fungi that physiologically breakdown lignin (Mayer and Staples, 2002). These microbial enzymes have an effective and environmentally friendly impact on the rate at which polymers degrade. It has been observed that different bacteria and their enzymes are linked to both biodegradable and non-biodegradable polymers, such as PHA, PLA, PET, PHB, PVC, PCL, and PBS (Muhamad *et al.*, 2015). There is a list of microorganisms and the enzymes they produce that cause different types of plastic to degrade. Microbes adhering to polymers and then colonising surfaces is the main mechanism of plastic biodegradation. Two processes are involved in the hydrolysis of plastics using enzymes: Prior to hydrolytic division, the enzymes first connect to the polymer substrate (Figure 2). Polymer degradation products such as oligomers, dimers, and monomers have substantially lower molecular weights and are finally mineralized into CO_2 and H_2O (Tokiwa *et al*., 2009). Under aerobic conditions, the bacteria use oxygen as an electron acceptor before synthesising smaller organic molecules, which results in the production of CO_2 and water as byproducts (Priyanka and Archana, 2012). Microorganisms break down polymers in anaerobic environments when there is no oxygen present. Anaerobic bacteria utilise sulphate, nitrate, iron, carbon dioxide, and manganese as electron acceptors (Priyanka and Archana, 2012). In order to improve the circumstances that allow polymers to be decomposed effectively, innovative microbial enzymes and routes must be investigated. Fossil- and bio-based polymers that are thought to be non-biodegradable may actually be fully degradable once novel microbial strains and their mechanisms to do so have been fully elucidated. To be used in packaging and the healthcare sector in a sustainable and environmentally friendly way, new polymers must be added to the category of biodegradable polymers.

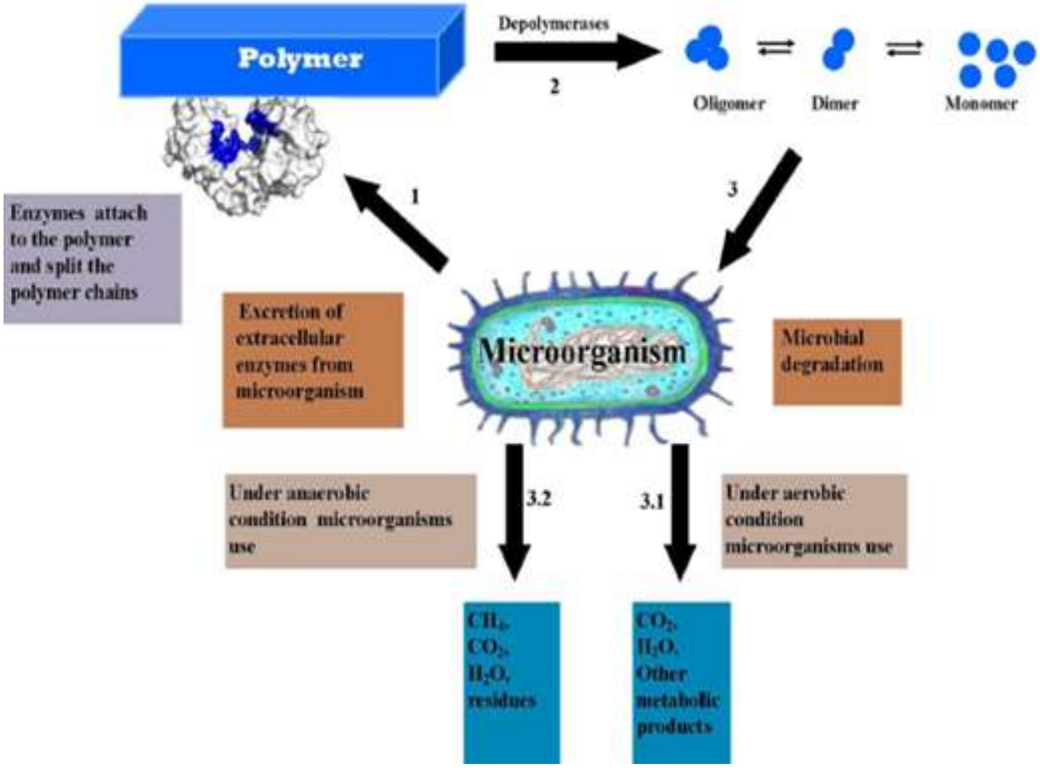

Fig 2: Plastic biodegradation mechanisms in aerobic and anaerobic environments (Ahmed *et al*., 2018)

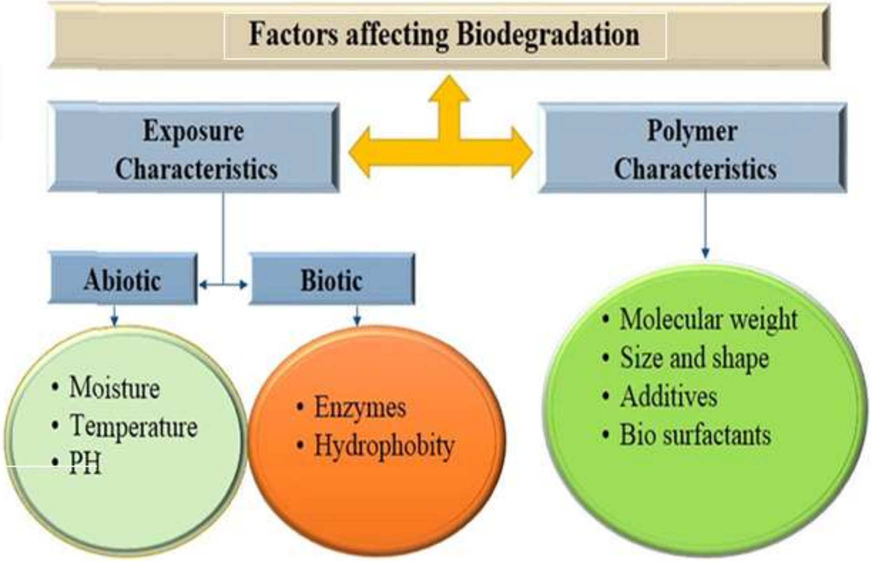

Fig 3: Factors affecting the rate of biodegradation of plastics (Ahmed *et al*., 2018)

Factors affecting plastic biodegradation: Several factors affect the biodegradation process, including the polymer properties, the exposure conditions, and the enzyme characteristics (Figure 3). Some of these factors are listed below:

Exposure conditions

Moisture: Given that bacteria need water to thrive and reproduce, moisture can have a variety of effects on polymer biodegradation. As a result of quick microbial action, polymer degradation speed is increased in the presence of enough moisture (Ho *et al*., 1999). Furthermore, moisture-rich environments promote the hydrolysis process by increasing the number of chain scission processes.

pH and temperature: By altering the acidic or basic circumstances, the pH can change how quickly hydrolysis events occur. For instance, the rate of PLA capsule hydrolysis is best at pH 5 (Henton *et al*., 2005). Different polymer breakdown products change the pH levels, which thus affect the rate of degradation and microbial development. The softening temperature of the polymer also has a substantial impact on its capacity to be broken down by enzymes. A lower chance of biodegradation exists in polyester with a higher melting point. As temperatures rise, potential enzymatic degradability declines. For example, purified *R. delemar* lipase successfully hydrolyzed polyesters with low melting points, such as PCL (Tokiw *et al*. 2009).

*Enzyme characteristics:*A variety of polymers can be biodegraded by different enzymes since each one has a different active site. In contrast to straight-chain polyesters made from any other monomer, enzymes generated by the fungi *A. flavus* and *A. niger* breakdown straight-chain polyesters formed from diacid monomers with 6 to 12 C-atoms more quickly (Kale *et al*., 2007). It was discovered that the extracellular enzymes (depolymerases) engaged in the depolymerization of PHB degrade PHB in various ways and are dependent on the particular depolymerase produced by the particular microbial species (Yamada-Onodera *et al*., 2001). Petrochemical-derived plastics are resistant to environmental degradation because of their hydrophobicity and three-dimensional (3D) structure (Yamada-Onodera *et al*., 2001). In addition, PE's hydrophobic property interferes with the development of a biofilm of microorganisms to slow down biodegradation (Hadad *et al*., 2005).

Polymer characteristics

Molecular weight: In terms of biodegradability, molecular weight is a key factor in determining many polymer qualities. The lower the degradability, the higher the molecular weight. As opposed to low-molecular-weight polymers, higher-molecular-weight PCL (> 4000) was slowly digested by a strain of *R. delemar* lipase. Microbial enzymes find it easier to attack a substrate with a low molecular weight (Auras *et al*., 2004).

Shape and size: The degradation process is significantly influenced by the polymer's characteristics, such as its size and form. Compared to polymers with a limited surface area, those with a large surface area can deteriorate more quickly (Kijchavengkul and Auras, 2008).

Additives: The capacity to degrade is impacted by non-polymeric impurities such as colours (waste or debris of catalysts employed for the polymerization and additive conversion products) or filler. According to certain reports, as the amount of lingo-cellulosic filler in a sample grows, the thermal stability decreases, which is followed by an increase in the ash content. The thermoplastic polymer and lingo-cellulosic filler's dispersion and interfacial adhesion are the main variables affecting the composite system's heat stability (Yang *et al*., 2005). Similar to this, metals work well as pro-oxidants in the production of polymers susceptible to thermo-oxidative breakdown from polyolefins.

Biosurfactants: Amphiphilic substances called biosurfactants are primarily formed on surfaces with living things. Due to their low toxicity and great biodegradability, the inclusion of a biosurfactant accelerates the biodegradation of polymers (both fossil-based and bio-based) (Orr *et al*., 2004). Because they include particular functional groups that aid in the biodegradation process, biosurfactants enable action even in very acidic, alkaline, and saline environments (Kawai *et al*., 2004).

Current Insights of Research on Plastic Biodegradation: The use of environmentally friendly, biodegradable, and fossil- and bio-based plastics is on the rise. In the presence of effective waste management and litter control techniques, the use of biodegradable plastics for specialised purposes to create a sustainable community is a beneficial idea (Iwata, 2015). PET, a non-biodegradable polymer derived from fossil fuels, is used in plastic products all over the world, and environmental concerns have been raised over its accumulation. *Ideonella sakaiensis* 201-F6 is a unique bacterial strain that has recently been discovered to be capable of decomposing PET by utilising it as an energy and carbon source. According to Yoshida *et al*. (2016), the strain produces two enzymes that hydrolyze PET and its mono (2-hydroxyethyl) terephthalic acid into two environmentally safe monomers, ethylene glycol and terephthalic acid. To uncover its many other environmentally acceptable applications, further optimisation of the PET degradation process in cells or under industrial facilities is also important. Another study (Skariyachan *et al*., 2016) shows that the microbial consortia formed by *Pantoea* spp. and *Enterobacter* spp. have the potential to degrade the LDPE. Additionally, scientists have identified several bacteria that can transform organic styrene, a byproduct of the industrial plastics industry, into PHA. *P. putida* NBUS12, a recently discovered strain, is a powerful styrene-degrading bacterium (Tan *et al*., 2015). *Achromobacter xylosoxidans*, a different recently identified bacterial strain, was discovered to have an impact on the structure of high-density polyethylene (Kowalczyk *et al*., 2016). Similar to this, the thermophilic *Anoxybacillus rupiensis* Ir3 (JQ912241) bacterium was discovered in soil in Iraq that had been contaminated by hydrocarbons. It showed a good ability to use aromatic chemicals as carbon sources before degrading them (Mahdi *et al*., 2016). Therefore, a lot of research is being done to create methods for degrading polymers composed of fossil and biological sources in order to discover new environmentally acceptable uses for them and strategies for waste management.

Future prospects: The most creative and ecologically friendly solution to the issues surrounding the disposal of plastic waste created from diverse sources is to use biodegradable polymers in specific applications like packaging, agriculture, and the health industry. If used, bio- and fossil-based biodegradable polymers efficiently breakdown in the environment, within cells, or in well-maintained industrial settings. The environment is currently greatly threatened by nonbiodegradable petrochemical materials used in the production of plastics, especially in the absence of waste management facilities and litter control. In some applications, the need for environmentally friendly polymers is always rising. Future efforts should concentrate on making use of these materials, particularly for the production of packaging materials, food item packaging, and disposable medical supplies. Utilising biodegradable plastics for agricultural films, fishing nets, medicines, surgical frameworks, and sterile goods is also advantageous for the environment. Additionally, biodegradable plastics should be used in situations where there is a high risk of diffusion into the environment or when it is difficult to segregate the trash. On the other hand, to utilise such polymers in the community, efficient waste management and litter control are necessary. For particular uses, the next generation of bio-based biodegradable plastics will pledge to create a more sustainable society. To enable their reuse, these polymers should also be biodegraded and recycled in a balanced manner. As a result, in order to create environmentally friendly materials and increase society's sustainability, we must have competence both individually and collectively. by making small structural changes to polymers. Microbiologists, synthetic chemists, process engineers, and biomass researchers should all pool their resources to develop environmentally friendly products that will increase society's sustainability.

Conclusion: Plastic pollution affects microbiomes, affecting their health and ecosystems. To ensure long-term environmental safety, waste management, litter reduction, and the use of biodegradable materials are crucial. Microbial communities can convert plastic polymers into simpler molecules using aerobic and anaerobic methods. Characterizing new microbial strains and developing biobased biodegradable polymers is essential. Increased use of biodegradable materials in industrial applications and optimized degrading facilities are also necessary.

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