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Advanced synergistic remediation of diverse plastic pollutants using nano-enabled biocatalysts

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Abstract

Plastic, a highly malleable material once shown its role to alternate things like ivory, wood, and so on to reduce burden on nature, has become a rapidly rising global concern over the past few decades due to its legacy in every possible application, from spacesuits to socks, daily needful things to life-supporting medical things. Its vast accumulation has reached from polluting rivers to the human internal organs, posing severe threats to ecosystems, human health and the stability of our planet Earth. This review explores the history, applications, major impacts, alternatives and recycling of plastic and nanotechnology as a transformative solution, focusing on the promising potential of Nano-enabled Biocatalysts (NBs) for efficient plastic degradation. NBs, which integrate biological elements like enzymes or microorganisms with synthetic nanomaterials (e.g., silver, titanium, iron oxides), offer superior catalytic activity, stability, and selectivity compared to their individual components. Prominent studies demonstrating NBs' efficacy, including the use of Aspergillus oryzae with silver nanoparticles and Lactobacillus plantarum with titania nanoparticles for enhanced polyethylene degradation, as well as bacterial consortia augmented by iron oxide nanoparticles and other advanced nanomaterials are reviewed. These innovative approaches facilitate faster and more complete plastic breakdowns, significantly reducing microplastic and nanoplastic contamination. Research in this domain is still in its early stages. Further studies are essential to fully comprehend the characteristics of biological and nanoscale components, engineer new functional materials, assess their comprehensive risks and benefits, and rigorously test their effectiveness under real-world environmental conditions before widespread implementation.

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INTRODUCTION

Plastic, originally developed to conserve natural resources and democratize access to goods, has unfortunately evolved into a significant global environmental concern. Early innovations in plastics, such as cellulose, were designed as alternatives to valuable natural resources like ivory, which was used in products ranging from billiard balls to piano keys, thus reducing the pressure on elephant populations. Similarly, the invention of Bakelite provided a substitute for shellac, a resin harvested from lac insects, used in electrical insulation. In many ways, plastics

reduced the need for wood and paper products, which are widely used in packaging, furniture, and other applications, potentially saving forests. The unique properties of plastics made them incredibly versatile and attractive for a vast array of applications, leading to mass production and widespread consumption. According to reports, global plastic production reaches approximately 460 million tonnes annually, with India contributing 9.3 million tonnes. However, only around 9% of plastic waste is recycled globally, a process that requires significant energy and also results in global warming emissions [1]. The greatest concern lies not only in the accumulation of plastic waste but also in the depletion of valuable fossil fuels used in plastic production. Despite the many negative impacts of plastic on the environment and human health, the major drivers behind the ever-increasing growth of plastic waste are economic development, urbanization, and the continuously growing population [2]. Although numerous alternatives to plastic have been created, none are completely replaceable. Plastic waste is now ubiquitous, contaminating ecosystems worldwide, even entering the human body [3]. Therefore, effective plastic waste degradation is imperative. Various techniques, such as physical, chemical, and biological methods, exist to degrade plastics, but these methods consume a lot of energy and remain slow. Nanotechnology, which has extensive applications in various fields, holds great promise, from drug delivery and lighting technologies [4] to plastic degradation [5].

This paper explores the historical trajectory of plastic innovation, classifies various plastic types, discusses their environmental impacts, examines existing and emerging alternatives to conventional plastics, evaluates the current state of plastic waste recycling, highlights the need for effective degradation methods, and delves into the potential role of nanotechnology in addressing this global challenge.

The Rise and Versatility of Plastics

Plastic has been used for various purposes since ancient times, with natural polymers such as horn, amber, rubber, tortoiseshell, and shellac being utilized. In the 19th century, due to the scarcity of animal-derived materials, inventors created semi-synthetic materials from natural sources like milk, cork, and blood. In 1862, Alexander Parkes, a chemist and artisan from Birmingham, developed cellulose nitrate, one of the first synthetic polymers. Parkesine, regarded as the first manufactured plastic, democratized consumer goods and culture by lowering production costs. In 1907, Belgian chemist Leo Baekeland invented Bakelite, the first fully synthetic plastic. This invention, made from combining formaldehyde and phenol, sparked a consumer boom in affordable, desirable products. Bakelite's mass production made it ideal for introducing design trends like Art Deco.

In the early 20th century, petroleum and chemical industries formed alliances with companies such as Dow Chemicals, ExxonMobil, DuPont, and BASF. In 1932, Imperial Chemical Industries (ICI) used ethylene gas derived from crude oil and natural gas to create Perspex. The world's most abundant plastic, polyethylene, was discovered in 1932 after a failed attempt to combine ethylene and benzaldehyde. In refineries, naphtha is produced by the fractional distillation of crude oil, a complex hydrocarbon mixture. This naphtha is then broken down into smaller monomer units, such as ethylene and propylene, through heat or catalytic processes. These monomers undergo polymerization, chemically joining to form long chains of polymers like polyethylene and polypropylene, which are used to make various plastic products through different shaping techniques [1].

CLASSIFICATION

Plastics, a diverse class of materials, are comprehensively categorized based on their physicochemical properties, applications, material origin, biodegradability, life cycle, and compliance with international standards. Based on thermal behavior, plastics are broadly classified into thermoplastics and thermosetting plastics. Thermoplastics soften upon heating and can be repeatedly melted and reshaped, while thermosetting plastics undergo irreversible chemical changes during curing, becoming rigid and non-recyclable in their cured state [6]. Further classification can be based on applications, distinguishing between general plastics, engineering plastics, and functional plastics, each with specific performance characteristics. Plastics are also categorized as fossil-based or bio-based, with bio-based plastics derived from renewable sources like corn and sugarcane. Bioplastics can be

biodegradable or non-biodegradable, depending on their chemical structure. Additionally, plastics are divided into biodegradable and non-biodegradable types [7]. The Society of the Plastics Industry (SPI) established the Resin Identification Code (RIC) system to facilitate plastic identification and recycling, assigning numbers 1 through 7 to common plastic types:

PET or PETE (Polyethylene Terephthalate) - commonly used for beverage bottles

HDPE (High-Density Polyethylene) - found in rigid containers like milk jugs

PVC (Polyvinyl Chloride) - used in pipes and window frames

LDPE (Low-Density Polyethylene) - flexible items like plastic bags and films

PP (Polypropylene) - used in robust applications like food containers and automotive parts

PS (Polystyrene) - foamed products like Styrofoam and disposable cutlery

OTHER or O - a catch-all category for resins not listed above, including materials like Polycarbonate (PC) and various specialty bioplastics

IMPACTS OF PLASTIC WASTE

The vast use of plastics in every sector, from birth to death, coupled with rapid urbanization and a growing human population, has led to large-scale production and accumulation of plastic waste. Improper plastic disposal harms the aesthetic beauty of natural environments and triggers broader ecological distress, including groundwater contamination, which affects agricultural productivity. Animals often ingest plastic debris or become entangled in it, impairing feeding, mobility, and reproduction, sometimes even leading to death. Plastics also serve as vectors for the colonization of invasive species. It is estimated that 20 million metric tons of plastic waste end up in the environment annually, significantly contributing to biodiversity loss, ecosystem degradation, and climate change [8].

Due to environmental exposure, plastics undergo weathering, a process involving mechanical, chemical, and biological actions that fragment them into smaller pieces, resulting in mesoplastics (5–25 mm), large microplastics (1–5 mm), small microplastics (20 μm–1 mm), and nanoplastics (1–100 nm) [9]. These smaller fragments persist in the environment for decades or even centuries [10] and can accumulate in both human and animal bodies, potentially leading to chronic health conditions. Recent evidence confirms the widespread presence of microplastics in male reproductive systems and breast milk [3]. Synthetic textiles like polyester, nylon, and acrylic release microplastic fibers during routine laundry [11], contributing to microplastic contamination, particularly in aquatic environments. It is estimated that 19 to 23 million metric tons of plastic enter aquatic ecosystems annually, which constitutes around 0.5% of the world's plastic waste. As of UNEP 2025, oceans already contain 75 to 199 million tonnes of plastic.

RECYCLING

Plastic waste is not just waste; it is a substantial and accessible resource fueling innovation across numerous technological domains. Research is demonstrating the potential of converting plastic waste into valuable products, from daily necessities to industrial-level applications. Techniques like hydrolytic depolymerization of PET using microwave irradiation and pyrolysis enable the upcycling of plastic waste into fuels and chemical feedstocks [12], thereby reducing reliance on finite resources.

In India, businesses like Shree Ranga are setting the standard by recycling millions of plastic bottles daily into polyester for clothing, while entrepreneurs like Aditya process large amounts of plastic waste. International companies like Amble Outdoors integrate recycled polyester into their products, and sustainable fashion brands like Unirec and Oceanness prove the viability of making clothing from recycled plastics. The growing trend of converting plastic waste into clothing [13] highlights the changing perception of plastic waste as a valuable resource.

RECYCLABILITY RATE

A major challenge in effective plastic waste management lies in the highly varying recyclability rates of different plastic types. Highly crystalline plastics like HDPE exhibit sharper melting points (around 130-137 °C) and higher stiffness, while amorphous plastics like polystyrene (PS) lack a distinct melting point, softening over a broader temperature range (around 100 °C). Semi-

crystalline plastics such as polyethylene terephthalate (PET) have a melting point of around 250-260 °C, while LDPE melts at around 110-115 °C [14]. This disparity in melting points significantly impedes the recycling of mixed plastic waste. Attempting to melt such mixtures at a single temperature often leads to material degradation, phase separation, and poor-quality recyclates [15]. Consequently, not all plastic types can be efficiently or completely recycled. It is estimated that only 9% of all global plastic waste is recycled, which is alarmingly low [1]. However, recycling rates vary considerably depending on the polymer type and region.

PET and HDPE are highly recyclable due to polymer degradation and contamination across successive cycles. PET is largely downcycled, limiting its potential for high-value, closed-loop recycling. PVC, once commonly used, has declined due to the presence of hazardous additives. Its recycling process poses environmental risks due to its heterogeneous composition and the hazardous byproducts generated during reprocessing. As a result, its recyclability rate remains extremely low, often below 1%. LDPE, characterized by its thin, flexible, low-density nature and propensity for contamination, is highly challenging and energy-intensive to collect and reprocess, yielding limited high-quality recycled products. Similarly, PP, despite its widespread production, has very low global recycling rates—often below 1%—mainly due to its vast range of applications, particularly in multilayer packaging, which complicates separation and reprocessing. For these difficult-to-recycle plastics, specialized collection and sorting programs, such as those offered by TerraCycle, are often necessary.

PS, commonly used in Styrofoam or thermocol, consists of air-puffed beads. Its low density, high bulk, and high volume-to-weight ratio make it economically unviable for transportation and recycling. Large quantities of PS consume considerable energy and yield little material. As such, PS recycling is highly limited, often below 1% via conventional methods. The 'OTHERS' category encompasses mixed plastics, polycarbonates (PC), and various bioplastics or less common types. These diverse compositions and the limited infrastructure for recycling them contribute to their very low recyclability rates, typically below 1% [15].

Considering that only a small portion of generated plastic waste is recycled, with some types requiring high energy input but yielding limited returns, it is evident that alternative and more fundamental solutions are needed to manage plastic waste that cannot be efficiently recycled.

Addressing the limitations of recycling and conventional degradation methods, which vary significantly in efficacy, is crucial. Many approaches inadvertently contribute to microplastic and nanoplastic pollution. Nanotechnology has emerged as a powerful tool offering faster degradation rates while significantly reducing the formation of residual microplastic and nanoplastic pollution.

NANO-ENABLED BIOCATALYSTS

The world is facing an urgent environmental crisis as pollution levels rise, threatening human health, ecosystems, and the planet itself. While several methods exist to control pollution and recover resources, the need for affordable and effective solutions is growing globally. In response, scientists and researchers are dedicating their efforts to developing sustainable and efficient technologies to address pollution and waste, resulting in the creation of integrated, innovative strategies.

Among these, Nano-enabled Biocatalysts (NBs) represent a novel class of materials that combine biologically derived elements with synthetic components. The biological components can include biomolecules such as proteins, DNA, tissues, living cells, or entire organisms. On the synthetic side, NBs may incorporate inorganic materials like silver, gold, titanium, cadmium, iron oxide, carbon-based substances, or silica oxide, as well as organic materials like lipids and polymers. Additionally, composite materials such as metal-organic frameworks (MOFs) and metal-phenolic networks (MPNs) may also be included.

The integration of biological systems with nanomaterials allows NBs to perform advanced functions that neither component could achieve independently. These functions include enhanced catalytic activity, stability, and selectivity, attributed to the unique properties of NBs, such as biodegradability, large surface area, and magnetic or electrochemical characteristics.

The use of NBs in pollution control and resource recovery offers a promising solution to some of the most pressing environmental challenges today. However, the selection of biological and nanomaterial components is crucial, as it influences the overall functionality of NB systems [16].

Numerous studies have demonstrated the efficacy of nano-enabled biocatalysts in plastic degradation, utilizing the synergistic properties of microorganisms and nanoparticles. A summary of key findings is presented in **Table 1**, with detailed discussions provided below.

Table 1 Summary of Nano-enabled Biocatalysts for Plastic (LDPE/HDPE) Degradation

S.No	Study (First Author, Year)	Microorganism(s) / Consortium	Nanoparticle(s) Used	Plastic-Type Degraded	Key Outcome / % Degradation (Timeframe)	Notes / Mechanism
1	Jayaprakash & Palempalli (2019)	*Aspergillus oryzae*	Silver Nanoparticles (AgNPs)	LDPE & HDPE	64.5% LDPE, 44.4% HDPE in 5 weeks	Weakening of C-H bonds, formation of smaller compounds (esters, alcohols, alkenes, aldehydes, ketones, cyano compounds)
2	Dave & Chauhan (2021)	*Lactobacillus plantarum*	Titania Nanoparticles (TNPs)	LDPE	59% degradation, 51% elongation in 21 days	TNPs oxidized LDPE surface under visible light, making fragments amenable to bacterial degradation.
3	Cada et al. (2019)	*Bacillus pseudofirmus*, *Bacillus agaradhaerens* (Alkaliphilic Bacterial Consortium)	Iron Oxide Nanoparticles (IONPs)	LDPE	Up to 18.3% weight reduction in 60 days	Increased bacterial growth, enhanced hydrophobicity, chemical bond shifting, surface disruption.
4	Kapri et al. (2009)	*Microbacterium species strain MK3, Pseudomonas putida strain MK4, Bacterium Te68R strain PN12* (Bacterial Consortia)	Nanobarium Titanate (NBT) (38nm)	LDPE	Accelerated λmax shift (209-224.11 nm in 2 days vs 4 days without NBT)	Influences bacterial growth cycle (shortens lag, prolongs exponential/stationary phases), supportive nutritional component.
5	Sah et al. (2010)	Two distinct bacterial consortia Consortium I: Microbacterium sp. strain MK3 (DQ318884), Pseudomonas putida strain MK4 (DQ318885), Bacterium Te68R strain PN12 (DQ423487); Consortium II: Pseudomonas aeruginosa strain PS1 (EU741797), P. putida strain PW1 (EU741798), and P. aeruginosa strain C1 (EU753182)	Fullerene 60 Nanoparticles (F60 NPs) (0.01% w/v)	LDPE	Accelerated λmax shift (209-224.97 nm on Day 1 vs Day 3)	Enhances enzymatic action on LDPE.

Table 1 Summary of Nano-enabled Biocatalysts for Plastic (LDPE/HDPE) Degradation(Continued)

6	Kapri et al. (2010)	Bacterial Consortium I (Microbacterium sp. strain MK3 (DQ318884), Pseudomonas putida strain MK4 (DQ318885), Bacterium Te68R strain PN12 (DQ423487)	Superparamagnetic Iron Oxide Nanoparticles (SPION) (10.6 nm)	LDPE	Sharp λmax shift (209-222.6 nm in 1 day), >8% weight loss (4-step degradation)	Accelerated degradation, formation of C-O frequencies (oxygen inclusion).
7	Mehmood et al. (2016)	*Stenotrophomonas pavanii* (CC18)	Dye-sensitized Titania + Starch blend	LDPE	Approx. 11% weight loss in 56 days	Synergistic effect of nano-modified plastic and microbial activity, photodegradation.
8	Olajire & Mohammed (2019)	(Not a microorganism-driven biodegradation, but photocatalytic)	Palladium Nanoparticles (Pd NPs) (from pineapple extract)	LDPE	~49% degradation in 30 days	Photocatalytic degradation under solar light, formation of carbonyl groups.
9	Pathak & Kumar (2017)	*Bacillus sp. strain V8, Pseudomonas sp. strain C 2 5* (and others identified)	SiO_2 Nanoparticles (20nm)	LDPE	Improved bacterial growth and enhanced biodegradation efficiency (λ-max shifts, FT-IR)	Improves bacterial growth, formation or alteration of chemical structure.

Aspergillus oryzae and AgNPs:

Aspergillus oryzae, a fungus historically significant in food production, is now emerging as a key player in environmental sustainability. Its potential extends beyond traditional food applications to include novel roles in plastic degradation through nanoparticle synthesis. Silver nanoparticles (AgNPs) from *Aspergillus oryzae* were synthesized. In combination with the culture broth these AgNPs effectively degraded 64.5% of LDPE and 44.4% of HDPE in 5 weeks. The degradation mechanism involved the weakening of C-H bonds in HDPE, leading to the formation of smaller compounds like esters, alcohols, and alkenes. Similarly, LDPE degradation resulted in the formation of smaller compounds, including aldehydes, ketones, cyano compounds, esters, and alkanes. Notably, the degradation products from AgNPs were significantly less toxic to *Allium cepa* than polyethylene wax emulsion [17].

Lactobacillus plantarum and TNPs:

The biodegradation of LDPE is generally time-consuming. However, researchers developed Titania nanoparticles (TNPs) using sol-gel technique. In the presence of visible light these TNPs oxidized the surface of LDPE film resulting in the fragmentation of polymer chains. These LDPE fragments become more amenable to bacterial degradation by *Lactobacillus plantarum*. Further, LDPE was photo-catalytically biodegraded, resulting in an improvement in degradation rate and elongation 59% and 51% within 21 days, respectively. These results surpass previous studies, which reported a 49% weight loss and 12% elongation after 45 days. This proved the enhanced degradation of LDPE was due to the combination of TNPs and *Lactobacillus plantarum* [18].

Alkaliphilic Bacterial Consortium and IONPs:

In 2019, four researchers investigated the enhanced in-vitro biodegradation of LDPE using an alkaliphilic bacterial consortium isolated from a hyperalkaline spring in the Philippines, supplemented with iron oxide nanoparticles (IONPs). The researchers first isolated and identified two efficient LDPE-degrading alkaliphilic bacterial strains, *Bacillus pseudofirmus* and *Bacillus agaradhaerens*. To assess the impact of

IONPs, they monitored the growth of individual isolates and the consortium in a synthetic medium with LDPE, observing a significant increase in bacterial growth and altered growth phases in the presence of IONPs, characterized by a shortened lag phase and a prolonged stationary phase. The biodegradation efficiency was quantified by measuring the weight loss of pre-weighed LDPE strips after 60 days of incubation with the bacterial isolates and the consortium, both with and without IONP supplementation. The results revealed that the bacterial consortium, when supplemented with IONPs, achieved a maximum weight reduction of the residual polymer up to 18.3 ± 0.3%, compared to 13.7 ± 0.5% in the absence of IONPs. This enhanced degradation was further supported by a bacterial adhesion to hydrocarbon (BATH) test, which indicated higher hydrophobicity of the consortium in the presence of IONPs, corroborated by an increased protein content of the cells adhered to the LDPE films. End-product analysis using Fourier transform infrared (FTIR) spectroscopy revealed chemical bond shifting in the treated LDPE, and scanning electron microscopy (SEM) images showed pronounced disruption of the surface texture of the LDPE films exposed to the consortium with IONPs, collectively confirming the accelerated biodegradation process facilitated by the interaction between the alkaliphilic bacterial consortium and the iron oxide nanoparticles [19].

Nanobarium Titanate (NBT) and Bacterial Consortia

NBT is supplemented in minimal broth to influence the growth cycle of LDPE-degrading bacterial consortia. It affects the lag phase, exponential phase, and stationary phase, acting by reducing the duration of the lag phase and increasing the duration of the exponential and stationary phases. As a supportive nutritional component, NBT accelerates the growth of bacterial consortia, thereby assisting in plastic waste biodegradation. The preferred particle size is 38 nm, with bacterial consortia consisting of *Microbacterium* species strain MK3, *Pseudomonas putida* strain MK4, and *Bacterium Te68R* strain PN12. The experiment was conducted with both positive and negative controls, with and without nanoparticles. The nanoparticles were sonicated at 50-60 Hz for 2.5 minutes with 0.3-second cycles. UV spectrophotometry was used to monitor the bacterial growth cycle. The degraded LDPE residue was separated from the bacterial consortia by centrifugation, followed by evaporation to remove water. The dried residue was then analyzed and characterized using FTIR and TG-DTG-DTA, with LDPE used as a control. As the polymeric structure changes, a shift in λmax from 209–225.3 nm was observed, which took 4 days in the absence of NBT. In the presence of NBT, the spectrum shifted from 209–224.11 nm within 2 days, indicating an improved degradation action [20].

Fullerene 60 Nanoparticles

The impact of Fullerene 60 nanoparticles on the in-vitro biodegradation of LDPE by two distinct bacterial consortia was investigated. Consortium I: *Microbacterium* sp. strain MK3 (DQ318884), *Pseudomonas putida* strain MK4 (DQ318885), *Bacterium Te68R* strain PN12 (DQ423487); Consortium II: *P. aeruginosa* strain PS1 (EU741797), *P. putida* strain PW1 (EU741798), and *P. aeruginosa* strain C1 (EU753182). The nanoparticles, supplied at an optimal concentration of 0.01% (w/v) in a minimal broth with 5 mg/ml LDPE, accelerated the degradation process, although higher concentrations were detrimental to bacterial growth. The study revealed that Fullerene 60 enhances enzymatic action on LDPE, leading to an improved degradation rate, which was monitored through bacterial growth curve analysis using a UV spectrophotometer and characterized by FTIR and TG-DTG-DTA. In the presence of Fullerene 60, the λmax shift (indicating polymeric structure changes) occurred from 209 nm to 224.97 nm on the first day, demonstrating a significantly faster rate compared to the controls without nanoparticles, which showed shifts to 220 nm after 3 days [21].

Supermagnetic Iron Oxide Nanoparticles (SPION)

Researchers conducted a comparative analysis of SPION and NBT for enhancing LDPE biodegradation by bacterial consortia, building on their previous work with Fullerene 60. Using SPION (10.6 nm, synthesized by co-precipitation) with Consortium I (*Microbacterium* sp. strain MK3 (DQ318884), *Pseudomonas putida* strain MK4 (DQ318885), and *Bacterium Te68R* strain PN12 (DQ423487)) [21], they observed accelerated degradation. UV spectrophotometry revealed a sharp λmax shift from 209 nm to 222.6 nm within

one day, progressing to 225.62 nm within two days in SPION-treated LDPE. Thermal analysis showed over 8% weight loss in four-step degradation for SPION-treated LDPE, compared to a one-step loss in pure LDPE. FTIR analysis indicated the formation of C-O frequencies (e.g., 1101.1 cm^{-1}) in the presence of SPION and consortia, signifying oxygen inclusion in the hydrocarbon chain, aided by consortial enzymes. The study also extended to in situ biodegradation processes, though FTIR and thermal profiles showed minimal changes, possibly due to degradation being a surface phenomenon. Significant molecular mass changes were observed, and SEM micrographs depicted surface alterations, confirming the enhanced degradation by SPION and bacterial consortia [22].

Dye-Sensitized Titania and Starch Blend with *Stenotrophomonas pavanii* (CC18)

The study on dye-sensitized titania and starch blend with *Stenotrophomonas pavanii* (CC18) involved modifying LDPE films by incorporating a mixture of dye-sensitized titania nanoparticles and starch. The dye sensitization was achieved by adsorbing a suitable organic dye onto the titania surface. These modified LDPE films were incubated in a mineral salt media culture of *Stenotrophomonas pavanii* (CC18) for 56 days. The degradation process was monitored by measuring the weight loss of the films over time. Surface morphology changes were observed using SEM, and chemical alterations in the LDPE polymer were analyzed using FTIR to detect the breakdown of long-chain hydrocarbons and the formation of oxidized products. Collectively, these analyses confirmed the successful degradation of the LDPE films. The most effective combination, involving photodegraded LDPE with dye-sensitized titania, starch, and CC18, resulted in approximately 11% weight loss of the LDPE films within 56 days. This demonstrated the synergistic effect of the nano-modified plastic and microbial activity [23].

Palladium Nanoparticles from *Ananas comosus* Extract

The study on palladium nanoparticles from pineapple extract investigated the green synthesis of Pd nanoparticles using *Ananas comosus* (pineapple) leaf extract as the reducing and stabilizing agent. The synthesized nanoparticles were characterized by UV-vis spectroscopy, X-ray diffraction (XRD), FTIR, high-resolution transmission electron microscopy (HRTEM), and energy dispersive X-ray spectroscopy (EDX). For photocatalytic degradation, LDPE films coated with these nanoparticles were exposed to solar light in open air at ambient conditions for up to 30 days. The degradation was assessed by measuring the photo-induced weight loss, and surface morphology changes were observed by Transmission Electron Microscopy (TEM). FTIR spectroscopy was used to monitor changes in molecular structure and identify the production of carbonyl groups, indicating oxidation and degradation of the polyethylene. Specifically, LDPE films with 1.0% PdNPs showed around 49% degradation under solar light irradiation over 30 days [24].

SiO_2 Nanoparticles with *Bacillus* and *Pseudomonas*

The implications of SiO_2 nanoparticles on the in-vitro biodegradation of LDPE were investigated. The study involved isolating and identifying bacterial strains from waste disposal sites capable of degrading LDPE. Out of ten initial isolates, five potential strains were identified: *Bacillus* sp. strain V8, *Paracoccus* sp. strain B1 4-, *Pseudomonas* sp. strain C2 5, *Pseudomonas* sp. strain V1, and *Acinetobacter* sp. strain V4. *Bacillus* sp. V8 and *Pseudomonas* sp. C2 5 were found to be the most effective strains for polymer degradation. The study utilized SiO_2 nanoparticles with a particle size of 20 nm, added at a concentration of 0.01% w/v. The biodegradation experiments involved incubating LDPE samples (strips of 2 cm in diameter) in a minimal broth medium containing the screened bacterial isolates, both with and without the addition of SiO_2 nanoparticles. The cultures were incubated at 30°C in a shaking incubator (150 rpm) for 7 days. The degradation was assessed primarily by measuring the λ-max shifts of the LDPE samples and analyzing chemical modifications using FTIR spectroscopy. FTIR analysis revealed the formation or alteration of the chemical structure of the degraded polymer, showing absorption frequencies corresponding to C-H stretching, O-H stretching, and C≡H stretching. Additionally, the impact of the treatments (LDPE, bacteria, and bacteria with nanoparticles) on the growth parameters of *Vigna mungo* seedlings was assessed through a pot experiment. This assessment involved measuring shoot height, leaf length, and root length, and calculating the seed

germination percentage after 10 days. The study highlighted that SiO_2 nanoparticles improved bacterial growth and enhanced the biodegradation efficiency of the bacterial strains [25].

CONCLUSION

Plastic is ubiquitous, from the womb to the coffin, and its complete elimination is not only impossible but would also result in a loss to the nation's economy. While alternative materials are emerging, they cannot fully replace the vast range of plastic applications and often introduce their own environmental and public health challenges. Recycling is not suitable for all types of plastics. Plastic pollution has spread from atmospheric contamination to microplastic accumulation within the human body, affecting everything from testicles to breast milk. Although traditional methods for degrading plastic waste exist, they are often slow and incomplete, contributing to the spread of microplastics. Nanotechnology, with its applications spanning agriculture to wastewater treatment, presents a promising avenue to address plastic pollution through Nanoenabled Biocatalysts (NBs). These NBs enable a faster and more complete, eco-friendly degradation process that reduces microplastic pollution. A significant advantage of NBs is their potential for recovery and reuse across multiple degradation cycles, enhancing their economic viability and sustainability.

FUTURE RECOMMENDATIONS

Research into the development of NBs is still in its early stages, requiring a comprehensive understanding of both biological and nanoscale components. Additionally, there is a need to engineer these components into new, functional materials. A critical research gap is that current studies are largely confined to laboratory-scale experiments.

Further extensive research is necessary to fully comprehend the risks, challenges, and benefits of NBs and to improve their efficiency for large-scale, practical applications. It is also vital to optimize the recovery methods for NBs and rigorously assess their maximum cycles of reuse without significant loss of activity under varying environmental conditions. Finally, it is essential to test new inventions and innovations in real-world environmental conditions before large-scale implementation.

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Ethical Approval

No ethical approval was necessary for this study.

Author Contribution

All authors made substantial contributions to the conception, design, acquisition, analysis, or interpretation of data for the work. They were involved in drafting the manuscript or revising it critically for important intellectual content. All authors gave final approval of the version to be published and agreed to be accountable for all aspects of the work, ensuring its accuracy and integrity.

Conflict of Interest

The authors declare no conflict of interest, financial or otherwise.

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