PLASTIC WASTE MANAGEMENT THROUGH BIOLOGICAL METHODS: AN APPROACH TOWARDS SUSTAINABLE DEVELOPMENT

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ABSTRACT

At present, the massive plastic pollution load into the environment has become an alarming issue in the world. Plastic wastes enter into the food chain through different ways and can cause serious health issues in aquatic animals and humans besides environmental pollution. Several techniques, including adsorption, coagulation, photocatalysis, and microbial degradation, as well as approaches such as reduction, reuse, and recycling, are currently popular. These techniques vary in their efficiency and the way they interact. Additionally, this review emphasizes the significant benefits and difficulties linked to these methods and strategies in order to comprehend the process of choosing viable paths toward a sustainable future. However, besides reducing plastic waste in the ecosystem, other alternative avenues have also been recently investigated to convert plastic wastes into value-added products for the circular economy. This review paper provides an overview of the currently documented methods and strategies focusing on the biological approaches used for the elimination of plastic trash and bioplastic development approaches. Furthermore, it is crucial to gain a comprehension of the key variables that must be highlighted while contemplating various methods and possibilities for bioplastic production, or insights into the potential utilization of these trashes as valuable resources or converting the plastic wastes into electricity, and transforming it into fuel. This review aims to offer readers a thorough summary of the current state of research about tactics and strategies to address the worldwide problem of plastic pollution.

KEYWORDS: Bioplastic, Waste, Biological approach, Plastic pollution, Sustainable

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Introduction

Plastic pollution has become a significant and urgent environmental problem in our era. Since the last few decades, there has been a significant increase in the manufacture and consumption of plastics, resulting in extensive environmental deterioration. Plastics are widely present in contemporary life, utilized in a multitude of areas including packaging, building, electronics, and healthcare. Nevertheless, the excessive use and incorrect disposal of these products have led to substantial environmental repercussions due to their longevity and affordability (Afshar et al., 2024, Ahamed et al., 2021). According to the current statistics, about 34 million tons of plastics have been produced in a year by humans, of which 7% are recycled, and the remaining 93% are dumped into the sea, oceans, and landfills, leading to its accumulation (Varghese et al., 2022). It is estimated that annually more than 300 million tons of plastic wastes are being produced worldwide (Dey et al., 2024) out of which only 9% can be recycled and the rest of it goes to the ocean (Bhattacharya and Singh, 2024).

Plastics are polymers derived from petrochemicals, with a wide range of properties and applications. Common types of plastics include polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET) (Bombelli et al., 2017). While plastics offer numerous benefits, their persistence in the environment poses serious risks to ecosystems and human health. Plastic waste can persist for hundreds of years, accumulating in landfills, waterways, and oceans. Wildlife ingestion and entanglement, habitat destruction, and leaching of toxic chemicals are some of the adverse effects associated with plastic pollution (Brandon et al., 2018). Factors such as insufficient infrastructure, inadequate recycling facilities, and lack of public awareness contribute to the persistence of plastic pollution. Moreover, the globalization of plastic production and consumption has led to the transboundary movement of plastic waste, exacerbating the problem for many countries (Gajendiran et al., 2016, Gewert et al., 2015).

Effective management of plastic waste presents a complex set of challenges. Despite growing awareness of the issue, current waste management systems are often inadequate to cope with the sheer volume of plastic waste generated worldwide (Chen et al., 2020). To tackle the plastic pollution challenge, a comprehensive strategy is needed that includes reducing trash, enhancing recycling strategies and recovery systems, promoting innovative materials conversion techniques and utilize the heat energy in other industry simultaneously (Figure 1). Effective cooperation among governments, industries, non-governmental organizations, and the public is crucial in order to devise sustainable solutions to this worldwide dilemma (Ghorbannezhad et al., 2020). By comprehending the extent and consequences of plastic pollution, we can strive for a future in which plastics are utilized ethically, recycled efficiently, and handled in a way that protects the environment for future generations (Gyung Yoon et al., 2012).

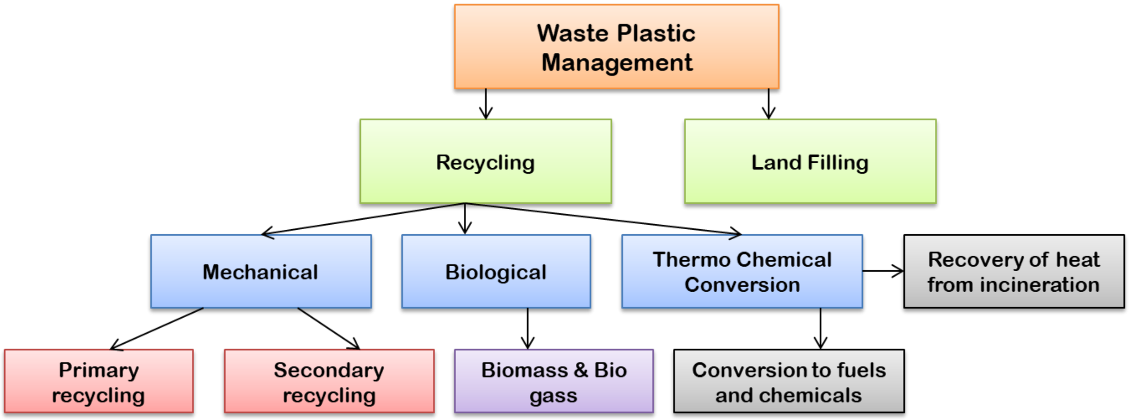

Figure 1. Strategies of plastic waste management by various approaches e.g., mechanical, biological, and thermochemical process.

Biological Degradation of Plastics

Plastics are commonly regarded as enduring pollutants in the environment because they are resistant to breakdown by conventional methods (Jeon and Kim, 2013, Kawai, 2010). However, recent research has uncovered that specific microbes have the capability to break down plastics using biological mechanisms. Further investigation is required to explore the methods, microorganisms, and factors that impact the biological breakdown of plastics. This review will provide insights into the possibility of utilizing nature's powers to reduce plastic pollution. A marine bacterial population has been studied for its ability to degrade poly (ethylene terephthalate) and polyethylene (Gao and Sun, 2021).

Plastic pollution poses a significant threat to ecosystems worldwide, but bioremediation offers a promising approach to mitigate its environmental impact (Rahmatiah Al Faruqy and Liew, 2016, Prieto, 2016). It has been reported in many articles about the concept of bioremediation for plastic pollution, including techniques in terrestrial, aquatic, and marine environments, successful case studies, and the challenges and future prospects of bioremediation for plastic waste management (Ahn et al., 2011). Bioremediation involves the use of biological agents, such as microorganisms, plants, or enzymes, to degrade or detoxify pollutants in the environment. In the context of plastic pollution, bioremediation strategies aim to break down plastic polymers into simpler compounds that can be assimilated by microorganisms or incorporated into natural nutrient cycles (Ahn et al., 2011, Marjadi et al., 2010). Bioremediation techniques can be applied in various environmental settings, including soil, freshwater bodies, oceans, and coastal habitats, to address different types of plastic waste (Lomwongsopon and Varrone, 2022, Rahmatiah Al Faruqy and Liew, 2016).

Bioremediation techniques for plastic pollution vary depending on the environmental conditions and the type of plastic waste present. In terrestrial environments, techniques such as composting, soil amendment with microbial inoculants, and phytoremediation using plastic-degrading plants can facilitate the decomposition of plastic litter and enhance soil health (Afshar et al., 2024). In aquatic and marine environments, bioremediation approaches include microbial degradation, biofilm formation on plastic surfaces, and the use of marine organisms such as bacteria, algae, and invertebrates to break down plastic debris. Several successful bioremediation projects have demonstrated the effectiveness of biological approaches in mitigating plastic pollution. Examples include the use of plastic-degrading bacteria to treat wastewater contaminated with microplastics, bioaugmentation of marine environments with plastic-degrading enzymes (Figure 2.) and the development of biodegradable mulches for agricultural plastic waste management (Roosen et al., 2021, Ronkay et al., 2021). These case studies highlight the potential of bioremediation techniques to remediate plastic pollution in diverse environmental settings.

While bioremediation shows promise as a sustainable solution to plastic pollution, several challenges must be addressed to realize its full potential (Patrício Silva, 2021). Factors such as the complexity of plastic polymers, variability in environmental conditions, and limited understanding of microbial plastic degradation mechanisms pose obstacles to the development and implementation of bioremediation strategies. Additionally, scaling up bioremediation technologies to address large-scale plastic pollution requires interdisciplinary collaboration, innovative bioprocess engineering, and integration with existing waste management infrastructure (Omondi and Asari, 2021).

Despite these challenges, bioremediation offers a cost-effective and environmentally friendly approach to mitigating plastic pollution, complementing traditional waste management practices. Future research efforts should focus on improving our understanding of microbial plastic degradation pathways, optimizing bioremediation processes for different environmental contexts, and exploring synergies between bioremediation and other plastic waste management strategies (Lokesh et al., 2023). By harnessing the power of nature to remediate plastic pollution, we can work towards a cleaner, healthier, and more sustainable environment for current and future generations.

Biological Degradation of Plastics Through Microorganism

Biological degradation of plastics involves enzymatic breakdown of polymer chains by microorganisms, leading to the conversion of plastics into simpler compounds. Several mechanisms have been proposed for plastic degradation, including hydrolysis, oxidation, and depolymerization (Krueger et al., 2015). Enzymes produced by microorganisms play a crucial role in initiating and catalyzing these degradation processes, breaking down the complex polymer structure of plastics into smaller fragments that can be metabolized (Kundungal et al., 2019). Various microorganisms with varying characteristics have been identified as capable of breaking down plastics in different environmental settings. Bacteria, fungi, and algae have been discovered to have the ability to break down plastic, with certain strains showing enzymatic activities that can target various types of plastics. Gaining knowledge about the variety and role of microbes that may break down plastic is crucial for effectively utilizing their abilities in managing plastic waste (Palm et al., 2019). Various factors impact the speed and degree of biological breakdown of plastics, such as ambient conditions, polymer characteristics, and microbial activity. Temperature, moisture, oxygen availability, and nutrient availability are essential environmental elements that have the potential to impact microbial growth and enzymatic activity (Yang et al., 2015).

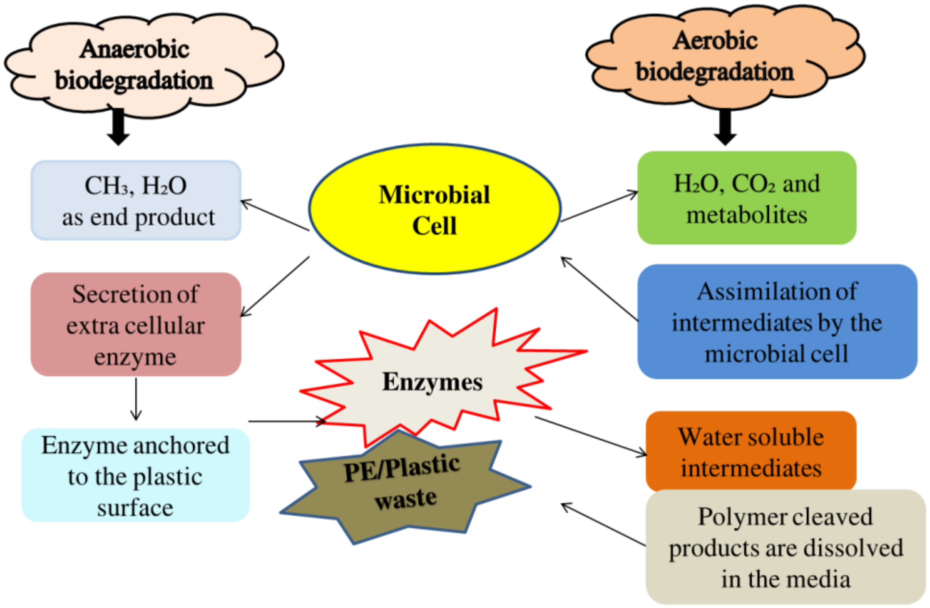

Figure 2. Microbial cell factories for plastic degradation, Adopted from (Venkatesh et al., 2021)

The biodegradation rates of polymers are influenced by various properties such as chemical composition, crystallinity, and surface shape. Certain polymers are more prone to degradation than others (Yang et al., 2014). Moreover, the structure and behaviour of microbial populations (Figure 2.) in various settings are essential in influencing the effectiveness of plastic decomposition procedures (Yang et al., 2014, Yang et al., 2015).

Besides artificial plastics, nature also generates a range of biodegradable polymers that can be broken down by microbes (Afshar et al., 2023). Naturally occurring polymers, including cellulose, chitin, and lignin, function as structural elements in plants and animals and can be easily degraded by microbial enzymes (Elgarahy et al., 2023). Biodegradable polymers, such as starch-based plastics and polylactic acid (PLA), are created from renewable resources and provide sustainable alternatives to traditional plastics. These polymers may be broken down by biological processes, which helps to reduce plastic pollution (Evode et al., 2021). Gaining knowledge about the processes and microorganisms responsible for breaking down plastics is essential for creating effective methods to utilize nature's skills in managing plastic waste. By investigating the capacity of biological systems to break down plastics, we can discover novel methods for reducing plastic pollution and shifting towards a more sustainable and eco-friendly approach to plastic utilization and disposal (Lee and Liew, 2021, Lomwongsopon and Varrone, 2022, Palm et al., 2019). Two types of marine bacterium namely *Alcanivorax borkumensis* and *Microbulbifer* were employed on low-density polyethylene (LDPE) surfaces to observe the biodegradation (Delacuvellerie et al.,2019). SEM images revealed the holes and cracks on several film surfaces containing the microorganisms (Figure 3.).

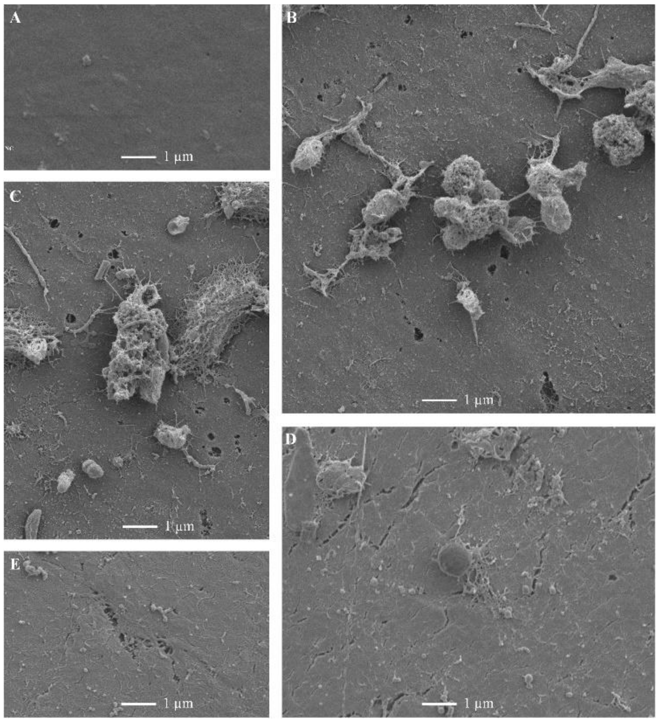

Figure 3.Scanning electron microscopy (SEM) images of the low-density polyethylene (LDPE) surface after two months of enrichment with *Alcanivorax borkumensis* and *Microbulbifer*. The negative control (A) and biofilm on LDPE (B, C, D and E). Adopted from Delacuvellerie et al., 2019.

Degradation of Plastics Through Enzymatic Action

Enzymatic degradation represents a promising approach for breaking down plastics into environmentally benign compounds (Pandey et al., 2023, Prieto, 2016). Some research revealed the role of enzymes in plastic degradation, highlighting examples of enzymes capable of degrading various types of plastics, discussing strategies for engineering enzymes to enhance plastic degradation, and addressing challenges and opportunities in enzymatic plastic degradation (**Figure 2**) (Silva, 2021). Enzymes are biological catalysts that accelerate chemical reactions, including the breakdown of complex molecules like plastics. In the context of plastic degradation, enzymes act on specific chemical bonds within polymer chains, initiating hydrolysis, oxidation, or depolymerization processes (Chen et al., 2020, Wei and Zimmermann, 2017). Enzymes produced by microorganisms, plants, and animals have been identified as effective catalysts for degrading different types of plastics, offering a sustainable and eco-friendly alternative to conventional plastic disposal methods (Skariyachan et al., 2022). A variety of enzymes have been discovered or engineered to degrade plastics effectively. One notable example is PETase, an enzyme produced by "*Ideonella sakaiensis*" bacteria, capable of hydrolyzing polyethylene terephthalate (PET) into its constituent monomers (Palm et al., 2019, Skariyachan et al., 2022). Similarly, enzymes such as lipases, esterases, and cutinases have been shown to degrade other types of plastics, including polyethylene (PE), polypropylene (PP), and polystyrene (PS). By targeting specific chemical bonds within polymer chains these enzymes facilitate the breakdown of plastics into smaller, more easily metabolizable compounds (Brandon et al., 2018).

The optimization of enzymes for plastic degradation represents a promising area of research. Through protein engineering techniques such as directed evolution and rational design, enzymes can be modified to enhance their catalytic activity, substrate specificity, and stability under harsh environmental conditions (Chen et al., 2020). By fine-tuning enzyme properties to match the chemical structure of target plastics, researchers can develop tailored enzymatic systems capable of efficiently degrading a wide range of plastic polymers (Mueller, 2006). However, advancements in enzyme discovery, engineering, and bioprocessing techniques offer opportunities to overcome these hurdles and unlock the full potential of enzymatic plastic degradation as a sustainable solution to plastic pollution (Sowmya et al., 2014). By harnessing the catalytic power of enzymes, researchers can develop innovative strategies for breaking down plastics into environmentally friendly byproducts, contributing to the mitigation of plastic pollution and the transition towards a circular economy (Yang et al., 2014). The exploration of enzymatic plastic degradation represents a promising avenue for addressing one of the most pressing environmental challenges of our time.

Microbial Synthesis of Bioplastics

Bioplastics have developed as promising alternatives to traditional plastics in order to address environmental concerns. They have the potential to reduce dependence on fossil fuels, lower carbon emissions, and alleviate plastic pollution (Yang et al., 2015). The research offers a comprehensive examination of bioplastics, encompassing their characteristics, classifications, manufacturing techniques, uses, ecological advantages, and obstacles.

Bioplastics are polymers derived from renewable biomass sources, such as plants, algae, or microorganisms, as opposed to traditional plastics derived from petrochemicals. These materials can be either biobased, meaning they are made wholly or partially from renewable resources, or biodegradable, capable of being broken down by biological processes (Peng et al., 2019). Bioplastics exhibit a wide range of properties, including mechanical strength, flexibility, and biocompatibility, making them suitable for various applications across industries (Singh and Sharma, 2008). Bioplastics encompass a diverse range of materials, each with unique properties and applications (Atiwesh et al., 2021). Common types of bioplastics include: (1) Polylactic Acid (PLA): Derived from fermented plant sugars, PLA is biodegradable and compostable, making it suitable for applications such as packaging, disposable utensils, and biomedical devices, (2) Polyhydroxyalkanoates (PHA): Produced by microbial fermentation of renewable feed stocks, PHA bioplastics exhibit properties similar to conventional plastics and can be used in packaging, agriculture, and biomedical applications, (3) Polybutylene Succinate (PBS): Derived from renewable resources such as corn starch or sugar cane, PBS bioplastics offer good mechanical properties and biodegradability, making them suitable for packaging and textile applications, (4) Starch-Based Plastics: Comprising blends of starch with biodegradable polymers such as PLA or PHA, starch-based plastics are renewable, biodegradable, and widely used in packaging, disposable products, and agricultural applications (Rahmatiah Al Faruqy and Liew, 2016, Ahn et al., 2011, Marjadi et al., 2010).

Bioplastics can be produced using a variety of methods, including fermentation, chemical synthesis, and enzymatic polymerization (Ahn et al., 2011). Fermentation processes involve the conversion of sugars or other biomass-derived feedstocks into biopolymer precursors by microorganisms, followed by purification and polymerization steps. Bioplastics find applications in diverse industries, including packaging, agriculture, automotive, textiles, and healthcare, offering environmentally friendly alternatives to conventional plastics (Marjadi et al., 2010). Bioplastics also known as green plastics offer several environmental benefits compared to conventional plastics, including reduced reliance on finite fossil resources, lower carbon emissions, and potential biodegradability, which can help mitigate plastic pollution in marine and terrestrial environments (Pandey et al., 2023). However, bioplastics also face challenges such as hurdles to sustainable microbial bioplastic production (Varghese et al., 2022), competition with food production for biomass feedstocks, limited scalability of production processes, and uncertainty regarding end-of-life disposal options. Additionally, the environmental impact of bioplastics depends on factors such as feedstock sourcing, production methods, and waste management practices, highlighting the need for life cycle assessments to evaluate their overall sustainability (Elgarahy et al., 2023). Despite these challenges, bioplastics represent a promising avenue for transitioning towards a more sustainable and circular economy. By harnessing renewable resources and leveraging innovative production technologies, bioplastics have the potential to mitigate the environmental impacts associated with conventional plastics and contribute to a more environmentally friendly and resource-efficient future (Ahsan et al., 2023). The microbial generation of biodegradable polymers provides a sustainable and environmentally favourable option as compared to traditional techniques of plastic manufacturing. Topics covered include microorganisms with the ability to produce biodegradable polymers, fermentation techniques for polymer synthesis, genetic modification of microbial strains to enhance polymer production and quality, and the practical uses of microbial biopolymer manufacturing (Afshar et al., 2023).

Various microorganisms, including bacteria, archaea, fungi, and algae (Table 1) have the ability to produce biodegradable polymers as intracellular storage materials (Skariyachan et al., 2022). Polyhydroxyalkanoates have gained major magnitude due to their structural diversity and close analogy to plastics. Different sources (natural isolates, recombinant bacteria, plants) Their biodegradability makes them extremely desirable substitutes for synthetic plastics. One of the most extensively studied microbial polymers is polyhydroxyalkanoates (PHA), which are synthesized by numerous bacterial species under nutrient-limiting conditions (Reddy et al., 2003). Other microbial polymers include polysaccharides such as cellulose and xanthan gum, as well as protein-based polymers like cyanophycin and polyhydroxybutyrate (PHB) (Lomwongsopon and Varrone, 2022). Microbial synthesis of biodegradable polymers commonly occurs through fermentation processes, during which bacteria transform renewable carbon sources into polymer precursors. The regulation of polymer synthesis and production is heavily influenced by fermentation conditions, such as nutrient availability, pH, temperature, and oxygen levels (Silva, 2021). Fed-batch and continuous fermentation strategies are commonly employed

Table 1. List of microbes for the production of polyhydroxyalkanoates (PHA), polyhydroxybutyrate (PHB) and their derivatives

SI No.	Production strain	Source	Type	Reference
1.	*Bacillus firmus*	Cocoa bean shell	PHB	(Sánchez et al., 2023)
2.	*Bacillus wiedmannii*	Agricultural wastes	PHB	(Danial et al., 2021)
3.	*Rasltonia eutropha*	Bagasse	PHB	(Luengo et al., 2003)
4.	*Burkholderia sacchari*	Sugarcane	PHB	(Martin Koller et al., 2012)
5.	*Halomonas boliviensis*	Wheat bran and potato waste	PHA	(Kanekar et al., 2014)
6.	*Azotobacter bejenicck*i	Coir pith	PHB	(Castillo, T. et al., 2020)
7.	*Bacillus megaterium*	Oil pump empty fruit bunch	PHB	(Amiri Kojuri et al., 2021)
8.	*Saccharophagus degradans*	Waste from tequila bagasse	PHA	(Alva Munoz and Riley, 2008)

9.	*Pseudomonas sp.*	Grass	PHA	(Sharma and Dhingra, 2021)
10.	*Pseudomonas lemoignei*	Sugarcane effluent	PHB and PHB-co-HV	(Kumaravel, 2010)
11.	*Alcaligens eutrophus*	Auxotrophic mutant strain	PHB	(Prabakaran, 2006)
12.	*Bacillus cereus* PS 10	Rice straw	PHB	(Sharma and Bajaj, 2015)
13.	*Klebsiella sp.*	Molasses	PHA	(Jamil, 2020)
14.	*Pseudomonas putida* KT2442	Mutant strain	P3HHp	(Wang et al., 2009)
15.	*Methylobacterium extorquens*	Methanol	PHB	(Bourque et al., 1992)

**P3HHp: polyhydroxyheptanoate, PHA: polyhydroxyalkanoates, PHB: polyhydroxybutyrate, (PHB-co-HV: polyhydroxy butyrate-co-hydroxyvalerate*

to optimize polymer production, while downstream processing techniques such as cell harvesting and polymer purification are used to isolate and recover microbial biopolymers (Lee and Liew, 2021). Besides PHA biosynthesis in natural isolates, Genetic Engineering approaches allow for the manipulation of microbial metabolism to improve the production, composition, and characteristics of polymers. Bacteria such as *E. coli* are incapable of synthesizing or degrading PHA which grows fast, even at high-temperature and is easy to lyse will enable it to accumulate a large amount of polymer that can be engineered with PHB biosynthetic genes *phb*A (for 3-ketothiolase), *phb*B (NADPH-dependent acetoacetyl-CoA reductase), and *phb*C (PHB synthase) from acetyl-CoA are clustered and are presumably organized in one operon *phb*CAB (Reddy et al., 2003). Noteworthy, metabolic engineering and synthetic biology employ strategies to add or increase biosynthetic pathways for polymer production, optimize the allocation of cellular resources, and boost microbial tolerance to environmental challenges (Evode et al., 2021). Researchers can customize microbial biopolymer production for specific industrial uses, such as packaging, textiles, medicinal devices, and biodegradable plastics, by altering microbial strains through recombinant DNA technology (Atiwesh et al., 2021).

Microbial biopolymers are now commercially important as environmentally friendly substitutes for petroleum-based plastics in multiple industries. PHA bioplastics have garnered interest because of their biodegradability, biocompatibility, and thermoplastic characteristics, which make them well-suited for uses such packaging films, disposable utensils, and medical implants (Palm et al., 2019). Other microbial biopolymers, including cellulose and xanthan gum, find applications in food additives, cosmetics, pharmaceuticals, and wastewater treatment (Tanasupawat et al., 2016).

The microbial synthesis of biodegradable polymers offers a renewable and environmentally friendly approach to plastic production, with the potential to reduce reliance on fossil resources, minimize carbon emissions, and mitigate plastic pollution (Singh and Sharma, 2016a). By harnessing the metabolic capabilities of microorganisms and advancing bioprocess engineering technologies, microbial biopolymer production holds promise for addressing the sustainability challenges associated with conventional plastics and driving the transition towards a circular bioeconomy (Singh and Sharma, 2016a, Rahmatiah Al Faruqy and Liew, 2016).

Phytoremediation of Microplastics

In recent times, the attention of microplastics (MPs) or Nanoplastics (NPs) uptake by various plants has been drawn by many scientists. This perspective lays out recent advances to propel both research and action. It is proposed that phytoremediation could be a potential possible way for the in situ remediation of MPs/NPs-contaminated environment (Figure 5). In this process, phytoaccumulation, phytostabilization, and phytofiltration can be applied to reduce the concentration of nanoplastics and submicron plastics in terrestrial, aquatic, and atmospheric environments, as well as to prevent the transport of microplastics from sources to sinks (Gong, X.,et al.,2023). In addition, phytoremediation improvements (endophytic-bacteria, hyperaccumulator species, symbiotic species, omics investigations, and CRISPR-Cas9) have been proposed to enhance micro/nano plastic degradation in agroecosystems (Bansal, M.et al., 2024).

To achieves this pursuit, the possible mechanisms, influencing factors, and existing problems are need to be address, and further research needs are proposed. Meanwhile, advocating for a more promising future still requires significant efforts in screening hyperaccumulators, coupling multiple measures, and recycling stabilized plastics from plants. Phytoremediation can be an excellent strategy to alleviate global micro/nanoplastic pollution because of the cost-effectiveness and environmental sustainability of green technologies (Yuan, W.et al.,2024).

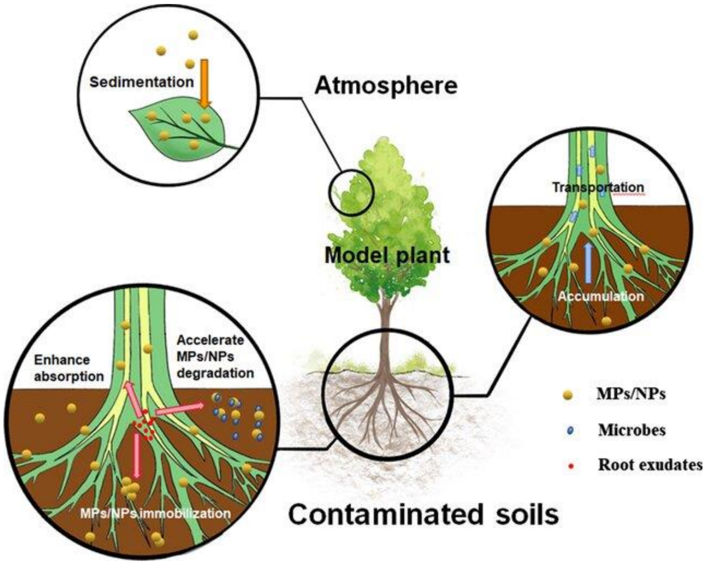

Figure 4. Mechanisms of microbial phytoremediation of MPs/NPs in contaminated environment, adapted from Gong, X., et al.,2023.

In an investigation of phytoremediation capacity of *Eichhornia crassipes* and *Typha capensis* for the removal of total dissolved solids (TDS) in plastic recycling industry wastewater shown that the decrease of 42.1% in TDS in wastewater + soil control experiments (Mudavanhu, N.et al., 2014). Phytoremediation shows promise as a sustainable alternative to remove Bisphenol-A (BPA) from contaminated soil and water systems in a cost-effective, ecologically-friendly, and socially-acceptable way (Peuke, A.D. and Rennenberg, H., 2005). However, BPA is a synthetic ingredient of the polycarbonate plastics and epoxy resins used in food containers, cans, and water bottles. To investigate the potential of two varieties of *switchgrass* (*Panicum virgatum*) for BPA removal, were tested in hydroponic media. Results showed significant BPA removal (40% and 46%, respectively) over approximately 3 months (Phouthavong-murphy, J.C.et al., 2020). Here, new insights into the development of plant-based process for emerging pollutants decontamination, as well as the alleviation of MPs/NPs-induced toxicity to the ecosystem.

Bio-based management of Plastics

As the global plastic pollution crisis continues to escalate, there is an urgent need for sustainable solutions to manage plastic waste. Bio-based recycling, which utilizes biological catalysts to break down plastics into valuable products or monomers, offers a promising approach to address this challenge (Ahamed et al., 2021). Recently, various bio-based recycling methods, including chemical recycling using biological catalysts, biological processes for upcycling plastic waste, and the integration of bio-based recycling with traditional recycling methods are well discussed among research society (Ghorbannezhad et al., 2020).

Recycling of Plastics

Bio-based recycling encompasses a range of innovative approaches that leverage biological processes to convert plastic waste into valuable materials or feedstocks. Unlike mechanical recycling, which involves melting and reshaping plastics, bio-based recycling focuses on breaking down polymer chains into smaller molecules using biological catalysts (Chen et al., 2020). These approaches offer several advantages, including the ability to process mixed or contaminated plastic waste streams and the potential to produce high-value products with minimal environmental impact (Peng et al., 2019). Biological catalysts, such as enzymes or microorganisms, offer a sustainable and eco-friendly alternative to traditional chemical catalysts (Kundungal et al., 2019). Enzymatic depolymerization, for example, utilizes enzymes capable of cleaving specific chemical bonds within polymer chains, resulting in the production of monomers or oligomers (Figure 5) that can be used to synthesize new plastics or other chemical products (Brandon et al., 2018).

In addition to depolymerization, biological processes can be employed to upcycle plastic waste into valuable products or materials. Microorganisms capable of metabolizing plastic monomers or oligomers can be used to produce bio-based polymers, fuels, chemicals, or biodegradable materials through fermentation or bioprocessing techniques (Wei and Zimmermann, 2017). By harnessing the metabolic diversity of microorganisms, researchers can develop tailored bioprocesses for converting plastic waste into useful commodities, thereby reducing the reliance on fossil resources and minimizing environmental pollution (Schmidt et al., 2017).

By integrating bio-based recycling technologies into existing waste management infrastructure, stakeholders can enhance the overall efficiency and sustainability of plastic waste management systems (Bombelli et al., 2017). For example, bio-based recycling facilities could be co-located with traditional recycling facilities or waste-to-energy plants to maximize resource recovery and minimize environmental impacts (Singh and Sharma, 2016b). Despite the potential benefits of bio-based recycling, several challenges remain, including the scalability of enzymatic processes, the development of cost-effective bioprocessing technologies, and the need for regulatory frameworks to support the implementation of bio-based recycling solutions. However, with continued research and innovation, bio-based recycling holds promise as a sustainable and environmentally friendly approach to managing plastic waste and moving towards a circular economy (Gajendiran et al., 2016).

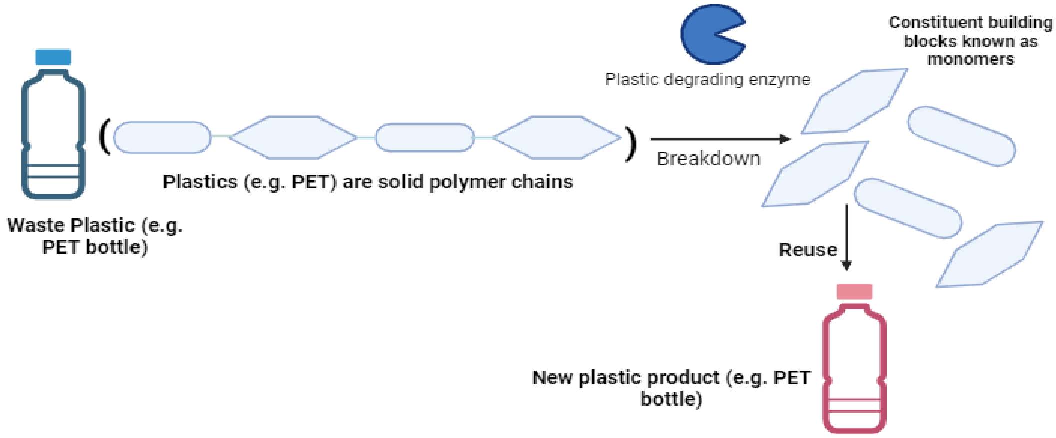

Figure 5. Recycling of plastic wastes after breaking down into monomers with enzymes.

Bio-inspired Design for Sustainable Materials

Nature has evolved elegant solutions to complex challenges over millions of years, inspiring scientists and engineers to develop sustainable materials and technologies. This section explores the principles of bio-inspired design for sustainable materials, examples of biomimetic approaches to plastic waste management, advances in bio-based materials inspired by natural systems, and potential applications of bio-inspired materials in reducing plastic pollution (Yang et al., 2015). Bio-inspired design draws inspiration from biological systems to develop innovative materials and technologies that mimic nature's efficiency and resilience (Figure 6). By understanding the underlying principles of biological systems, such as self-assembly, hierarchical structure, and adaptive response to environmental stimuli, researchers can design materials with enhanced properties and functionalities. Biomimetic approaches to materials design emphasize sustainability, resource efficiency, and environmental compatibility, aligning with the goals of circular economy and green chemistry (Krueger et al., 2015). Biomimetic strategies offer novel solutions to plastic waste management challenges, drawing inspiration from nature's ability to recycle and repurpose organic materials. Examples include the development of self-healing polymers inspired by the wound-healing mechanisms of living organisms, biodegradable plastics synthesized from renewable biomaterials, and surface coatings that mimic the anti-fouling properties of marine organisms to prevent biofouling on plastic surfaces (Gewert et al., 2015). By emulating nature's strategies for material recycling and regeneration, biomimetic approaches hold promise for advancing sustainable plastic waste management practices.

Bio-based materials derived from renewable biomass sources offer sustainable alternatives to conventional plastics, reducing reliance on fossil resources and mitigating environmental impacts (Yang et al., 2014). Biomimetic design principles guide the development of bio-based materials with tailored properties and functionalities, such as high strength-to-weight ratios, biodegradability, and biocompatibility. Examples include cellulose-based nanocomposites inspired by plant cell walls, chitin-derived materials inspired by crustacean exoskeletons, and silk-like proteins (Figure 6). engineered from recombinant spider silk proteins (Sowmya et al., 2014, Jeon and Kim, 2013, Gyung Yoon et al., 2012). These bio-based materials exhibit promising performance characteristics and can be utilized in various applications, including packaging, textiles, construction, and biomedical devices (Jeon and Kim, 2013).

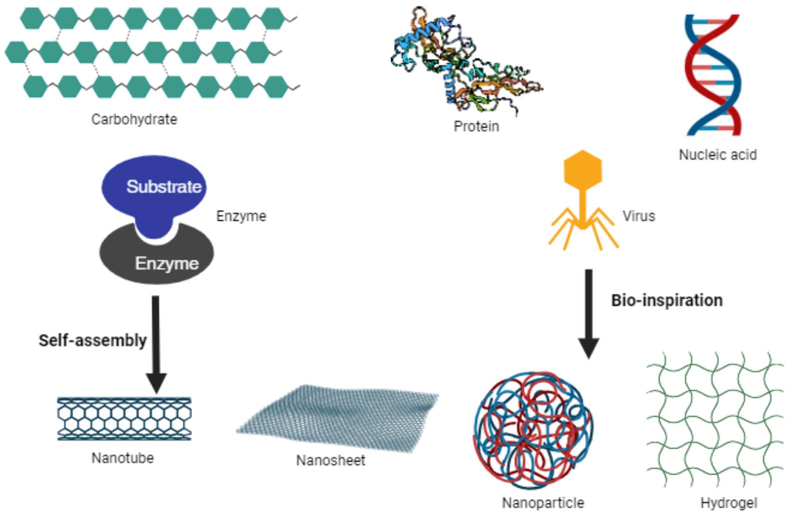

Figure 6. Bio-inspired designs for biodegradating materials development to reduce plastic pollution.

Bio-inspired materials hold the potential for reducing plastic pollution by offering sustainable alternatives to conventional plastics and enabling innovative waste management solutions (Figure 6). Examples include biodegradable packaging materials derived from plant-based polymers, bio-based textiles with antimicrobial properties inspired by natural fibers, and bio-based adhesives for repairing and recycling plastic products (Gyung Yoon et al., 2012). By harnessing nature's design principles, researchers can develop materials that mimic the functionality and sustainability of natural systems, contributing to the transition towards a circular bioeconomy and a cleaner, healthier environment. Nevertheless, bio-inspired design offers a promising approach to developing sustainable materials and technologies for addressing the challenges of plastic pollution and advancing towards a more environmentally friendly future.

Future Directions and Challenges

The pursuit of reducing plastic pollution and attaining sustainable management of plastic trash is a continuing effort that necessitates constant innovation, teamwork, and dedication. The importance is in understanding the emerging trends in biological systems for managing plastic waste, exploring potential for interdisciplinary research and collaboration, considering the policy implications and regulatory frameworks that promote bio-based solutions, and addressing the remaining obstacles and identifying areas for future innovation (Silva, 2021).

Advancements in biotechnology, materials science, and environmental engineering are driving innovation in biological systems for plastic waste management. At this horizon, the role of industrial biotechnology is obvious in converting plastic wastes to value-added products (Rahman et al., 2023). Additionally, emerging trends include the development of novel enzymes and promising microbial strains capable of degrading a wider range of plastic polymers, the integration of bioremediation techniques into circular economy models (Figure 7) and the exploration of synthetic biology approaches for designing custom-tailored bioplastics with improved properties and functionalities (Gyung Yoon et al., 2012, Kawai, 2010). Furthermore, bio-inspired design principles continue to inspire the improvement of sustainable materials and technologies that mimic nature's efficiency and resilience.

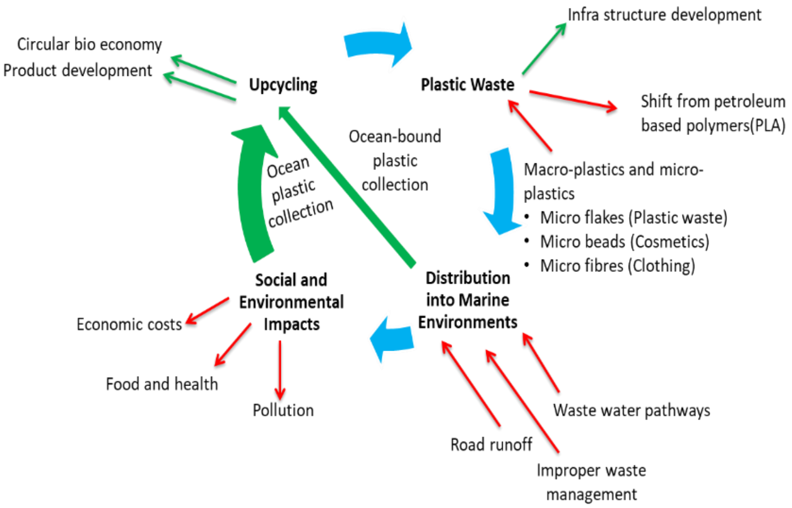

Figure 7. Plastics in ecosystems: their implications and mitigation pathways

To effectively address the intricate issues surrounding plastic pollution, it is necessary to use interdisciplinary approaches that connect the fields of research, engineering, politics, and society. Collaboration among researchers, industries, government, non-government agencies, and civil organizations can promote the exchange of knowledge, transfer of technology, and joint development of creative solutions. Interdisciplinary research initiatives that concentrate on plastic waste management can utilize a wide range of knowledge and resources to create comprehensive plans that tackle the social, economic, and environmental aspects of the plastic pollution challenge (Kawai, 2010, Singh and Sharma, 2008, Mueller, 2006).

Regulatory regulations pertaining to the biodegradability, compostability, and eco-labeling of products can play a crucial role in creating a market demand for bio-based products and guaranteeing customer trust in their environmental assertions (Shah et al., 2008). These measures encompass enhancing the scalability and cost-efficiency of bio-based recycling technologies, optimizing waste collection and sorting infrastructure to facilitate plastic recycling and recovery, and raising awareness and promoting behaviour change among consumers and businesses to decrease plastic consumption and waste generation (Elgarahy et al., 2023).

Although there have been advancements in using biological systems to handle plastic trash, there are still some unresolved difficulties that need to be tackled. While enzymatic degradation shows great potential for addressing plastic pollution, several challenges must be overcome to realize its full benefits. Enzyme stability, substrate specificity, and scalability are key considerations in the development of enzymatic plastic degradation technologies. Additionally, the integration of enzymatic processes into existing waste management systems and regulatory frameworks presents logistical and regulatory challenges (Peng et al., 2019). Moreover, we need to focus on the challenges or obstacles for practical implementation or real-world applications. By learning from nature's solutions, researchers can unlock new possibilities for sustainable material innovation and contribute to the global effort to reduce plastic waste and protect our planet's ecosystems.

Conclusion

Ultimately, the effective management of plastic trash in the future hinges on adopting a comprehensive approach that integrates biological, technical, policy, and behavioral interventions. Through the utilization of biological systems, promoting collaboration across different fields, and implementing policies that provide support, we can make progress towards a more sustainable and circular economy. In this economy, plastics will be used responsibly, recycled efficiently, and managed in a way that safeguards the environment and human health. The worldwide plastic pollution epidemic presents a substantial menace to ecosystems, human well-being, and the long-term viability of the planet.

By drawing inspiration from biological systems and leveraging biotechnological advancements, we can develop sustainable materials and technologies that minimize environmental impact and promote resource efficiency. Biological methods provide distinct benefits for managing plastic waste, such as the ability to break down naturally, using renewable resources, and being compatible with natural environments. Through using the metabolic capacities of microbes, enzymes, and biomaterials, we can create environmentally-friendly substitutes for traditional plastics and decrease our need on fossil fuels. By combining biological approaches with standard waste management strategies, we can improve the effectiveness and long-term viability of plastic waste management systems (Peng et al., 2019, Ronkay et al., 2021).

While significant progress has been made in the field of biological systems for plastic waste management, many challenges remain to be addressed. Continued research and development efforts are needed to improve the scalability, cost-effectiveness, and environmental performance of bio-based recycling technologies (Shah et al., 2008, Singh and Sharma, 2008). Interdisciplinary collaboration and knowledge sharing are essential for advancing scientific understanding, fostering innovation, and translating research findings into real-world solutions. As we look towards the future, it is clear that concerted action is needed to address the plastic pollution crisis and build a more sustainable future (Omondi and Asari, 2021). Collaboration among governments, industry stakeholders, academia, and civil society must work together to promote policies and initiatives that incentivize the adoption of bio-based solutions, reduce plastic consumption and waste generation, and enhance plastic waste management infrastructure (Yang et al., 2014, Yang et al., 2015). By adopting a circular economy approach and using the capabilities of biological systems, we can establish a global scenario in which plastics are utilized in a responsible manner, recycled efficiently, and managed in a way that ensures the protection of the environment for future generations. To conclude, let us pledge to take resolute measures to tackle plastic pollution and construct a more sustainable and robust future for everyone. Through collaboration and the adoption of biomimetic approaches, we may surmount the obstacles presented by plastic waste and establish a future in which plastic contamination becomes obsolete.

Competing interests

We declare that the authors have no competing interests in this paper.

Contribution of author

All authors contribute equally to prepare the manuscript.

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