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RECENT FINDINGS ON PLASTIC WASTE POLLUTION AND BIOTRANSFORMATION

Tushar Agarwal and Jai Gopal Sharma*

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Abstract

Plastic waste is generated in large quantities globally, and its disposal poses significant environmental challenges as it is non-biodegradable and can persist in the environment for hundreds of years. It is estimated that over 8 million tons of plastic waste end up in our oceans every year. Biodegradation is an eco-friendly approach to managing plastic waste as it does not result in the formation of toxic by-products. Types of plastic waste, degradation methods, and different microorganisms impacting biodegradation are discussed in this review. Overall, microbial bioremediation has the potential to provide an eco-friendly solution to the problem of plastic waste, and recent advances in this field have shown promising results. However, further research is needed to optimize bioremediation processes and to develop new microorganisms that can efficiently degrade and transform plastic waste.

Keywords: Bioremediation; Environment awareness; Biotransformation; Biodegradation; Plastic waste

Delhi Technological University, Shahbad Daulatpur Village, Rohini, New Delhi, Delhi 110042

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Introduction

Plastic waste is generated in large quantities globally, and its disposal poses significant environmental challenges as it is non-biodegradable and can persist in the environment for hundreds of years [1,2]. It is estimated that over 8 million tons of plastic waste end up in our oceans every year [3]. Plastic waste can also release toxic chemicals and greenhouse gases when burned, contributing to air pollution and climate change [4,5]. As plastic waste continues to be a major environmental problem, innovative solutions are required to address the challenges posed by plastic waste. This includes the development of new technologies and methods for the efficient and sustainable management of plastic waste, as well as awareness-raising and education efforts to encourage individuals and businesses to reduce their plastic consumption and waste. Efforts to manage plastic waste include recycling, reuse, reduction, and disposal [6]. Recycling involves the conversion of plastic waste into new plastic products [7]. Reuse involves finding new uses for plastic products, such as using plastic bags for shopping multiple times. Reduction involves reducing the amount of plastic used in products, such as by using reusable water bottles instead of disposable plastic ones. Finally, disposal involves the safe and environmentally friendly disposal of plastic waste, such as through landfilling or incineration.

Plastics can also be degraded into simpler compounds that can be absorbed or assimilated by the environment [8,9]. This process can occur naturally through physical, chemical, or biological means. Physical degradation occurs due to the action of external factors such as sunlight, heat, and mechanical stress [10]. Exposure to UV light and heat can cause the degradation of plastic, leading to the breaking of chemical bonds, which results in the formation of smaller molecules. Mechanical stress, such as grinding or shredding, can also break down plastic waste into smaller fragments. Chemical degradation involves the use of chemicals to break down the polymer chains of plastic into simpler compounds [9]. Chemicals such as acids, bases, and oxidizing agents can be used to degrade plastic waste. For example, hydrolysis is a common chemical method used to break down the ester linkages in PET plastics. However, not all plastics are easily biodegradable, and some may require special conditions or pre-treatments to enhance biodegradation. For example, polyethylene (PE) and polypropylene (PP) are difficult to biodegrade, and it can take hundreds of years for them to degrade in the environment [8]. This has led to the development of new technologies, such as the use of engineered microorganisms or enzymes to degrade specific types of plastics.

Bioremediation is an eco-friendly approach to tackle this problem, and it involves using microorganisms such as bacteria, fungi, and algae to break down plastic waste into simpler, non-toxic compounds (Figure 1) [11]. These microorganisms secrete enzymes that can break down the polymer chains of plastic into smaller molecules. Microbial bioremediation of plastic waste can be classified into two categories: biodegradation and biotransformation [12]. Biodegradation involves the complete breakdown of plastic waste into carbon dioxide and water [13]. This process is carried out by microorganisms such as bacteria and fungi, which secrete enzymes that break down the polymer chains of plastic into smaller molecules that can be used as an energy source for the microorganisms. The biodegradation of plastic waste has been extensively studied, and several microorganisms have been identified that can efficiently degrade plastic waste [14,15]. Biotransformation, on the other hand, involves the conversion of plastic waste into non-toxic compounds by microorganisms. This process is particularly useful for plastics that are difficult to biodegrade, such as polyvinyl chloride (PVC) and polystyrene (PS). Biotransformation can be carried out by microorganisms such as white rot fungi, which secrete enzymes that can break down the chemical bonds of plastic waste, resulting in the formation of non-toxic compounds.

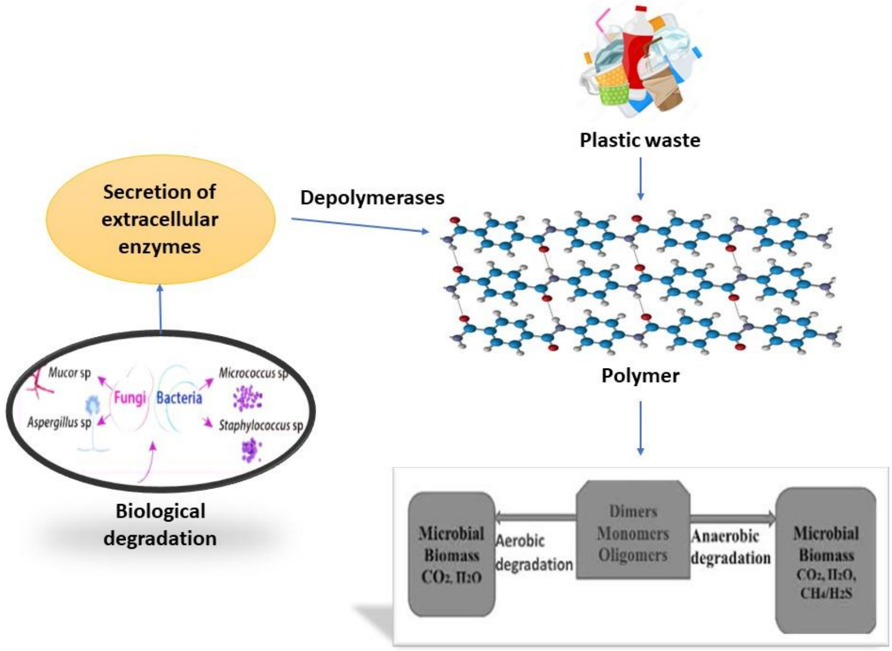

Figure 1: Process of biodegradation of plastic waste

Recent advances in microbial bioremediation for the disposal of plastic waste include the development of new microorganisms that can efficiently degrade and transform plastic waste, as well as the optimization of bioremediation processes to increase their efficiency. For example, genetic engineering has been used to develop microorganisms that can degrade specific types of plastics, such as polyethylene terephthalate (PET), which is commonly used in plastic bottles. In addition, bioremediation processes have been optimized by using pre-treatments such as mechanical shredding or chemical treatments to increase the surface area of plastic waste and make it more accessible to microorganisms. Overall, microbial bioremediation has the potential to provide an eco-friendly solution to the problem of plastic waste, and recent advances in this field have shown promising results. However, further research is needed to optimize bioremediation processes and to develop new microorganisms that can efficiently degrade and transform plastic waste.

Types of plastic waste

Plastic waste refers to any discarded or abandoned plastic material that has served its intended purpose and is no longer useful. It can accumulate in landfills, oceans, rivers, and other water bodies, causing harm to wildlife and ecosystems [16]. Plastics vary in their properties and degradation rates, and some are more environmentally friendly than others. Some plastics are easily recyclable, while others are difficult to recycle or not recyclable at all. It is essential to properly sort and dispose of plastic waste according to its type and to make efforts to reduce plastic waste in general. Plastics can be classified into various types based on their chemical structure and properties. The following are the most common types of plastic:

1. **Polyethylene (PE):** PE is a type of polymer made from the monomer ethylene. It is one of the most widely used plastics in the world and can be found in a variety of applications, including packaging, toys, pipes, and medical devices. PE is popular due to its low cost, versatility, and ease of manufacturing. It is also lightweight, moisture-resistant, and can be recycled, making it a popular choice for sustainable products. It can be produced in various forms, including high-density polyethylene (HDPE), low-density polyethylene (LDPE), and linear low-density polyethylene (LLDPE). HDPE is known for its strength, stiffness, and resistance to impact, while LDPE is known for its flexibility and transparency. LLDPE is a blend of the two and is used for

applications that require a combination of the properties of HDPE and LDPE [17,18].

2. **Polypropylene (PP):** PP is a thermoplastic polymer made from the monomer propylene. It is a versatile material with a wide range of applications due to its excellent chemical and heat resistance, high stiffness, and low density. PP is commonly used in packaging, textiles, automotive parts, yogurt cups, bottle caps, straws and consumer goods. It is also used in the medical industry for applications such as surgical instruments and medical devices. Its resistance to chemicals and sterilization makes it a popular choice for these applications. PP is often produced in a variety of forms, including homopolymer, copolymer, and random copolymer. Homopolymer is the most common form and is used in applications that require high strength and stiffness. Copolymer and random copolymer have improved impact resistance and are often used in applications that require more flexibility. PP is a highly recyclable material and is often used in products that promote sustainability. It is also lightweight, which makes it an attractive option for manufacturers looking to reduce the weight of their products [19].
3. **Polyvinyl Chloride (PVC):** PVC is a synthetic thermoplastic polymer made from the monomer vinyl chloride. It is one of the most widely used plastics in the world due to its versatility, durability, and low cost. PVC is commonly used in a variety of applications, including construction, electronics, automotive, pipes, vinyl flooring, window frames, and healthcare. In the construction industry, PVC is used for pipes, flooring, roofing, and siding due to its durability, weather resistance, and ease of installation. In the healthcare industry, PVC is used for medical tubing, blood bags, and other medical devices due to its biocompatibility and sterilization resistance [20]. PVC can be produced in different forms, including rigid and flexible PVC. Rigid PVC is used in applications that require strength, durability, and rigidity, while flexible PVC is used in applications that require flexibility, such as electrical cables and hoses. However, PVC has also been associated with environmental concerns due to the release of dioxins during its manufacturing process and when it is burned. Efforts are being made to improve the sustainability of PVC production and reduce its impact on the environment. Additionally, PVC can be recycled, although it requires specialized processing to remove additives and impurities.
4. **Polystyrene (PS):** PS is a synthetic thermoplastic polymer made from monomer styrene. It is a widely used plastic due to its versatility, low cost, and good insulation properties. PS is commonly used in a variety of applications, including packaging, disposable insulation, foam cups, disposable cutlery, and consumer electronics. Its excellent insulation properties make it a popular choice for insulation boards and packaging materials. In the food industry, PS is used for disposable food containers and packaging due to its low cost and durability. PS can be produced in different forms, including crystal and expandable. Crystal PS is a clear and rigid plastic used for products such as disposable cutlery and CD cases. Expandable PS is a foam plastic used for packaging materials and insulation. However, PS is also associated with environmental concerns due to its slow rate of decomposition and the difficulty of recycling. When disposed of improperly, PS can contribute to litter and pollution. Efforts are being made to reduce the environmental impact of PS through recycling programs and the development of biodegradable alternatives [21].

5. **Polyethylene Terephthalate (PET):** PET is a type of thermoplastic polymer that is commonly used in the manufacture of plastic bottles, food containers, and other products. It is a clear, strong, and lightweight material that is resistant to moisture and many chemicals. PET is made by polymerizing ethylene glycol and terephthalic acid or by using dimethyl terephthalate and ethylene glycol as starting materials. PET has several advantages as a packaging material, including its low cost, versatility, and recyclability. It is widely used in the food and beverage industry because it is safe for food contact and does not react with the contents of the container. PET can also be easily recycled, which makes it an environmentally friendly choice. However, PET also has some disadvantages. It is not heat-resistant and can deform at high temperatures, and it is also susceptible to UV degradation. PET can also take a long time to decompose in the environment, which can lead to pollution if not properly disposed of or recycled [22,23].
6. **Polycarbonate (PC):** PC is a type of thermoplastic polymer that is known for its strength, durability, and clarity. It is commonly used in the manufacture of a wide range of products, including electronic components, automotive parts, medical equipment, and sports equipment. PC is made by reacting bisphenol A (BPA) and phosgene, which produces a polymer that is tough, lightweight, and resistant to impact. It has a high melting point and is able to withstand high temperatures, making it suitable for use in applications where high heat resistance is required [24].

   One of the most notable properties of PC is its clarity. It is often used in place of glass in applications where impact resistance is needed, such as in safety glasses, windows, and skylights. PC is also used in the manufacture of electronic components because of its excellent electrical insulation properties. However, there are concerns about the potential health risks associated with PC, particularly regarding the use of BPA in its production. BPA is a chemical that has been linked to a range of health problems, including reproductive disorders, diabetes, and cancer. As a result, some manufacturers have begun to shift away from using PC in their products and are instead exploring alternatives such as PET or PP.
7. **Acrylonitrile Butadiene Styrene (ABS):** ABS is a thermoplastic polymer that is commonly used in the manufacture of a wide range of products, including automotive parts, toys, appliances, and piping systems. It is a copolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. ABS has several desirable properties, including its strength, impact resistance, and toughness. It is also resistant to heat and chemicals, making it suitable for use in harsh environments. ABS has a relatively low melting point, which means that it can be easily molded into complex shapes using injection molding or extrusion techniques. ABS is also known for its aesthetic qualities. It can be easily colored and has a shiny, glossy appearance that makes it a popular choice for consumer products such as toys and electronic devices.

   One of the disadvantages of ABS is that it can release toxic fumes when burned, which can be harmful to health. This makes it important to use proper ventilation and safety precautions when working with or disposing of ABS products. Additionally, ABS is not biodegradable, which can lead to environmental concerns if it is not properly disposed of or recycled [25].

Degradation methods of plastic waste

There are several methods available for the degradation of plastic waste, including physical, chemical, and biological methods [26,27].

1. **Physical methods**

Physical methods of plastic degradation involve breaking down plastic waste into smaller pieces through mechanical or physical means. These methods do not involve any chemical reactions and are typically less energy-intensive than chemical methods. Physical methods of plastic degradation have some advantages over chemical methods, such as being less energy-intensive and producing fewer emissions. However, they may not be suitable for all types of plastic waste, and some methods may produce by-products that are difficult to dispose of. Additionally, physical methods may not completely break down plastic waste and may only produce smaller particles that can still pose environmental risks. Here are a few examples of physical methods of plastic degradation:

Shredding or Grinding: This involves shredding or grinding plastic waste into smaller pieces, which can then be used as feedstock for other processes, such as recycling or fuel production.

Pyrolysis: This involves heating plastic waste in the absence of oxygen to break down the long chains of polymers into smaller hydrocarbons, which can be used as feedstock for fuel production.

Hydrogenation: This involves adding hydrogen to plastic waste under high pressure and temperature, which breaks down the long chains of polymers into smaller molecules that can be used as feedstock for fuel production.

Mechanical recycling: This involves sorting and cleaning plastic waste and then mechanically processing it into pellets or flakes, which can be used as feedstock for the production of new plastic products.

2. **Chemical methods**

Chemical methods of plastic degradation involve breaking down plastic waste through chemical reactions. These methods typically require more energy and resources than physical methods but can be more effective in breaking down plastic waste into its constituent molecules. Chemical methods of plastic degradation can be effective in breaking down plastic waste into its constituent molecules, which can then be used as feedstock for the production of new plastic products. However, these methods typically require more energy and resources than physical methods and can produce hazardous by-products if not properly managed. Additionally, some chemical methods may not be suitable for all types of plastic waste. Here are a few examples of chemical methods of plastic degradation:

Depolymerization: This involves breaking down the long chains of polymers that make up plastic waste into their constituent monomers using chemical reactions. The monomers can then be purified and used as feedstock for the production of new plastic products.

Solvolysis: This involves breaking down plastic waste using a solvent, such as an acid or a base, to dissolve the polymers into their constituent molecules. The resulting solution can then be purified and used as feedstock for the production of new plastic products.

Gasification: This involves heating plastic waste in the presence of oxygen or steam to break down the polymers into their constituent gases, such as methane and carbon dioxide. These gases can then be used as fuel or feedstock for the production of new plastic products.

Hydrolysis: This involves breaking down plastic waste using water and an acid or a base to break the long chains of polymers into their constituent monomers. The resulting monomers can then be purified and used as feedstock for the production of new plastic products.

3. **Biological methods**

Biological methods of plastic degradation involve using microorganisms, such as bacteria or fungi, to break down plastic waste. Biological methods of plastic degradation are considered more environmentally friendly than physical and chemical methods, as they use natural processes to break down plastic waste. However, these methods may require specific environmental conditions to be effective and may not be suitable for all types of plastic waste. Additionally, some methods may produce hazardous by-products if not properly managed. Here are a few examples of biological methods of plastic degradation:

Biodegradation: This involves using microorganisms to break down plastic waste into simpler compounds, such as carbon dioxide and water. Some microorganisms, such as certain bacteria and fungi, are capable of breaking down certain types of plastic, such as polyhydroxyalkanoates (PHAs) or polylactic acid (PLA).

Composting: This involves using microorganisms, such as bacteria and fungi, to break down organic waste, including certain types of plastic, into nutrient-rich compost. Composting requires specific environmental conditions, such as moisture, temperature, and oxygen levels, to be effective.

Anaerobic digestion: This involves breaking down organic waste, including certain types of plastic, using microorganisms in the absence of oxygen. This process produces biogas, which can be used as fuel, and a nutrient-rich digestate that can be used as fertilizer.

Enzymatic degradation: This involves using enzymes, such as lipases and proteases, to break down certain types of plastic, such as PET and polyurethane (PU), into smaller molecules.

Plastic-degrading microorganisms

Biodegradation of plastic waste by microorganisms involves the breakdown of the plastic polymer into smaller compounds by the action of enzymes produced by microorganisms. There are various microorganisms capable of degrading plastic waste, including bacteria, fungi, and algae. The following are some examples of microorganisms that can degrade plastic:

Pseudomonas putida**:** This bacterium has been found to have the ability to degrade certain types of plastic. Specifically, it has been shown to be capable of degrading PET, which is commonly used in the production of plastic bottles and packaging. The degradation process involves the production of certain enzymes, such as PET hydrolase, by *Pseudomonas putida*. PET hydrolase is able to break down the long chains of polymers that make up PET into smaller, more manageable molecules. These smaller molecules can then be used as feedstock for the production of new plastic products or for other purposes, such as fuel production. Overall, *Pseudomonas putida*'s application in plastic breakdown has the potential to be a successful and sustainable way to cut down on plastic waste [28,29].

Bacillus subtilis**:** *Bacillus subtilis* is a type of bacteria that has been found to have the ability to degrade certain types of plastic. Specifically, it has been shown to be capable of degrading polyethylene, which is commonly used in the production of plastic bags and packaging. The degradation process involves the production of certain enzymes, such as lipases and esterases. These enzymes are able to break down the long chains of polymers that make up polyethylene into smaller, more manageable molecules. These smaller molecules can then be used as feedstock for the production of new plastic products or for other purposes, such as fuel production. Overall, the use of Bacillus subtilis in plastic degradation has the potential to be an effective and environmentally-friendly method for reducing plastic waste [30].

Aspergillus niger**:** *Aspergillus niger* is a type of fungus that has been found to have the ability to degrade LDPE types of plastic. Specifically, it has been shown to be capable of degrading polyurethane, which is commonly used in the production of foams, coatings, and adhesives. The degradation process involves the production of certain enzymes, such as polyurethanease and esterase. These enzymes are able to break down the long chains of polymers that make up polyurethane into smaller, more manageable molecules. These smaller molecules can then be used as feedstock for the production of new plastic products or for other purposes, such as fuel production [31,32].

***Rhizopus arrhizus*:** *Rhizopus arrhizus* has been found to be effective in degrading PU plastics. Specifically, it has been shown to be capable of degrading PS, which is commonly used in the production of disposable cups, containers, and packaging materials. The degradation process involves the production of certain enzymes, such as styrene monooxygenase and laccase, by *Rhizopus arrhizus*. These enzymes are able to break down the long chains of polymers that make up PS into smaller, more manageable molecules. These smaller molecules can then be used as feedstock for the production of new plastic products or for other purposes, such as fuel production [33].

***Penicillium simplicissimum*:** *Penicillium simplicissimum* has been found to be effective in degrading PVC plastics. Specifically, it has been shown to be capable of degrading PET, which is commonly used in the production of plastic bottles and packaging materials. The degradation process involves the production of certain enzymes, such as PETase and MHETase. These enzymes are able to break down the long chains of polymers that make up PET into smaller, more manageable molecules. These smaller molecules can then be used as feedstock for the production of new plastic products or for other purposes, such as fuel production. Overall, the use of *Penicillium simplicissimum* in plastic degradation has the potential to be an effective and environmentally-friendly method for reducing plastic waste, particularly in the case of PET plastics [34,35].

***Saccharomyces cerevisiae*:** This yeast has been shown to degrade polycaprolactone (PCL) plastics. While *S. cerevisiae* is not known to have any direct involvement in plastic degradation, it is possible that it could be used indirectly in the production of bio-based plastics. Bio-based plastics are made from renewable sources such as plant materials or microorganisms like algae, and *S. cerevisiae* has been used in the fermentation of various types of plant materials for bio-based plastic production. Although there is no proof that *Saccharomyces cerevisiae* can break down plastics directly, a recent study indicates that it might be viable to use this yeast as a component of a biohybrid system for breaking down plastic [36].

***Chlorella vulgaris*:** *Chlorella vulgaris* is a type of freshwater microalgae that has been studied for its potential in bioremediation, including the degradation of two common types of plastic, i.e., PE and PVC. The degradation process involves the production of certain enzymes by the algae, which are able to break down the long chains of polymers that make up the plastic into smaller, more manageable molecules. In addition to degrading plastic, *Chlorella vulgaris* has also been shown to have potential in other areas of bioremediation, such as wastewater treatment and carbon capture. However, more research is needed to fully understand the potential of this microalga in plastic degradation and other applications [37].

Conclusion

Due to biodegradation, thermo-oxidative degradation, photodegradation, thermal, and hydrolysis processes in the ecosystem, the concentration of in the aquatic environment has grown dramatically, which is very detrimental for both marine and freshwater organisms as well as humans owing to their impact on the food chain. To completely remove these polymers from the environment, effective biodegradable strategies are required. Polymers are generally difficult to eliminate or break down due to their hydrophobic and inert properties. Microbes have also shown promise as a means of degrading these polymers, complementing physical and chemical approaches. The use of microorganisms in plastic degradation has shown promising results in laboratory settings. However, there are still challenges that need to be addressed before this method can be scaled up for large-scale industrial applications. These challenges include optimizing the conditions for the growth and activity of microorganisms, developing cost-effective methods for producing and using the necessary enzymes, and ensuring that the by-products of the degradation process are safe and environmentally friendly. However, it is important to note that the efficiency of plastic degradation by microorganisms can be affected by various factors such as temperature, pH, nutrients, and the structure and properties of plastic waste. Therefore, further research is required to optimize the conditions for the efficient and sustainable biodegradation of plastic waste by microorganisms (Figure 2).

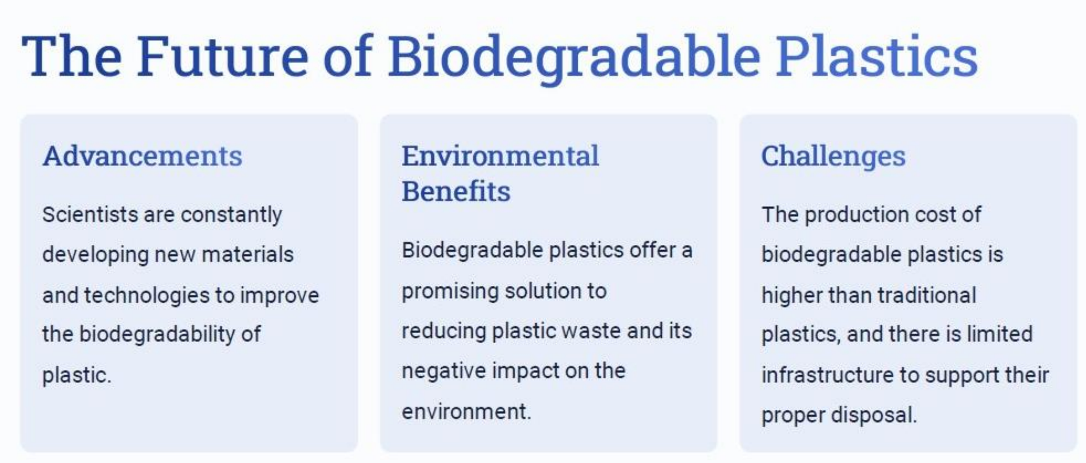

Figure 2: Future of biodegradable plastics

More evaluation utilizing original polymers polluted wastewater is required to assess the possible usage of microorganisms for polymer removal. Further work is needed on issues related to plastic cleanup, plastic toxicity, and microbe use. It is important to effectively advocate for the transfer of plastic polymers from wastewater to a suitable area for deposition/incineration to prevent them from entering the aquatic environment, which includes rivers and seas. Evaluating the cumulative impact on ecosystems requires coordinated long-term cleaning efforts.

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