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*Review Article*

# Emerging Technologies for Converting Mixed Plastic Waste into Biodegradable Polymers

**B. Thangabalan, T. Rejeev Kumar, Jonnalagadda Pravallika*, C. H. Srividhya, K. Lavanya, L. Basundhara Devi, S. Gowthami, S. K. Javeriya, T. Rejeev Kumar**

*SIMS College of Pharmacy*

Plastic pollution has become a critical global environmental issue due to the rapid growth in plastic production, extensive use of single-use plastics, and inefficient waste management systems. A large proportion of plastic waste exists as mixed plastics, comprising different polymer types and multilayer materials that are difficult to recycle using conventional mechanical methods. As a result, mixed plastic waste is often landfilled, incinerated, or released into the environment, leading to long-term contamination of soil and aquatic ecosystems, formation of microplastics, and potential risks to human health. This review focuses on the emerging concept of converting mixed plastic waste into biodegradable polymers as a sustainable and circular solution to plastic pollution. It discusses the limitations of traditional recycling practices and highlights biodegradable polymers as environmentally friendly alternatives to conventional plastics. Recent advances in conversion strategies, including chemical depolymerization, enzymatic and biocatalytic degradation, microbial upcycling, and hybrid chemical–biological technologies, are comprehensively reviewed. The underlying reaction mechanisms, process pathways, and material outcomes are explained in a simple and student-friendly manner while maintaining scientific accuracy. The review also examines the environmental and economic benefits of polymer conversion, along with key technological, industrial, and regulatory challenges such as feedstock variability, scalability, cost, and sustainability assessment. Finally, future perspectives are outlined to emphasize the potential of integrated and interdisciplinary approaches in transforming mixed plastics into biodegradable polymers. Overall, this review highlights mixed plastic upcycling as a promising pathway toward sustainable plastic waste management and circular economy development.

**Keywords**: Mixed plastic waste; Biodegradable polymers; Plastic upcycling; Chemical depolymerization; Enzymatic degradation; Microbial conversion; Hybrid recycling; Circular economy; Sustainable materials.

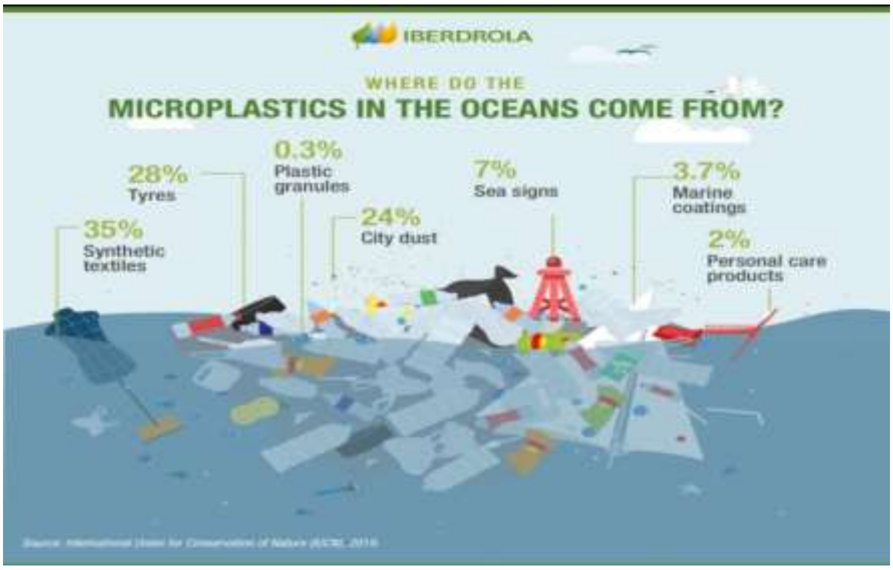
## INTRODUCTION

Plastics have become an integral part of modern life due to their versatility, durability, low cost, and wide range of applications in packaging, healthcare, construction, agriculture, and consumer goods. Since their large-scale production began in the mid-20th century, plastics have significantly improved living standards and industrial efficiency. However, the rapid and uncontrolled growth in plastic production and consumption has resulted in an unprecedented accumulation of plastic waste, leading to severe environmental, ecological, and socio-economic consequences. Today, plastic pollution is recognized as a global environmental crisis requiring urgent and sustainable solutions [15,1]. A major portion of plastic waste generated worldwide consists of **mixed plastics**, which include a combination of different polymer types such as polyethylene, polypropylene, polystyrene, polyethylene terephthalate, and multilayer composite materials. These plastics often enter the waste stream together and are contaminated with food residues, additives, and non-plastic materials. Due to their heterogeneous nature, mixed plastics are extremely difficult to recycle using conventional mechanical recycling methods. As a result, they are frequently landfilled, incinerated, or discarded into the environment, contributing to longterm pollution of soil, water bodies, and marine ecosystems [12,13]. Conventional plastic waste management practices have proven inadequate to handle the growing volume and complexity of mixed plastic waste. Mechanical recycling requires strict sorting and produces lower-quality materials, while chemical recycling methods are often energy-intensive and costly. Incineration and open dumping further exacerbate environmental problems by releasing greenhouse gases, toxic pollutants, and microplastics. These limitations highlight the urgent need for alternative strategies that can effectively manage mixed plastics while minimizing environmental harm [14,16]. In this context, **biodegradable polymers** have emerged as a promising sustainable alternative to conventional plastics. Biodegradable polymers are capable of breaking down into environmentally benign products under natural conditions, thereby reducing long-term pollution. Recent advances in chemical, enzymatic, microbial, and hybrid conversion technologies have opened new pathways to **convert mixed plastic waste into biodegradable polymers**, transforming waste into value-added, eco-friendly materials. This innovative approach not only addresses plastic pollution but also supports circular economy principles by recovering material value and reducing dependence on fossil-based resources [5,7]. Therefore, the conversion of mixed plastics into biodegradable polymers represents a transformative and forward-looking solution to the global plastic waste problem. Understanding the environmental impacts of mixed plastics, the limitations of existing recycling methods, and the emerging conversion strategies is essential for developing sustainable plastic management systems. This review aims to provide a comprehensive overview of these aspects, highlighting recent advances, challenges, and future prospects in the conversion of mixed plastic waste into biodegradable polymers [6,9].

## 1. Global Plastic Pollution: An Emerging Environmental Crisis

### 1.1 Growth of Plastics Production and Consumption

The growth of plastic production has been exponential since its large-scale commercialization in the mid-20th century. Initially developed as a substitute for scarce natural materials such as rubber, ivory, and metals, plastics quickly gained popularity due to their low cost, light weight, durability, and ease of manufacturing. With advances in petrochemical industries, plastics such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET) became widely available. As a result, global plastic production increased from just a few million tonnes in the 1950s to over hundreds of millions of tonnes annually today [1,5,6]. One of the main drivers of increased plastic production is the rapid growth of single-use plastic products. Packaging materials, including plastic bags, bottles, wrappers, and containers, account for the largest share of plastic consumption worldwide. These products are designed for short-term use but persist in the environment for decades or even centuries. Urbanization, population growth, changing lifestyles, and increased demand for convenience products have further accelerated plastic consumption, especially in developing and emerging economies [2,3,4].



Plastics have also become indispensable in sectors such as healthcare, construction, electronics, agriculture, and transportation. In healthcare, plastics are used in syringes, intravenous bags, gloves, and medical devices due to their sterility and flexibility. In agriculture, plastic films and pipes are used for mulching and irrigation. While these applications bring significant benefits to society, they also contribute substantially to the overall volume of plastic waste generated after use [4,7]. Furthermore, the low cost of virgin plastic compared to recycled plastic discourages recycling and promotes continuous production. The dependence on fossil fuels for plastic manufacturing links plastic growth to oil and gas industries. Without strict regulations and sustainable alternatives, plastic production is expected to continue rising, intensifying environmental pollution and resource depletion [11].

### 1.2 Accumulation of Plastic Waste in the Environment

The accumulation of plastic waste in the environment is a direct consequence of increased production combined with poor disposal practices. Once discarded, plastics do not biodegrade easily; instead, they fragment into smaller pieces while remaining in ecosystems for long periods. Large quantities of plastic waste accumulate in landfills, open dumping sites, roadside areas, rivers, and oceans, creating visible and invisible pollution across the planet [8,3].

Aquatic environments are among the most affected by plastic accumulation. Rivers act as major transport pathways, carrying plastic waste from inland areas to seas and oceans. Floating plastics form massive garbage patches, while heavier plastics sink and accumulate on ocean floors. Marine organisms often ingest plastic debris, mistaking it for food, which can cause choking, internal injuries, and death. Coral reefs and coastal habitats are also damaged due to plastic entanglement and smothering [6,9]. On land, plastic waste accumulates in soil and agricultural fields, where it disrupts soil structure and reduces fertility. Plastic residues hinder water infiltration and aeration, negatively affecting plant growth. Microplastics formed from degraded plastic items mix with soil particles and can be absorbed by crops, raising concerns about food safety and long-term ecological impacts [4,3]. Additionally, plastic accumulation in urban environments clogs drainage systems, leading to water stagnation and increased risk of flooding. This stagnant water becomes a breeding ground for disease-carrying mosquitoes, indirectly affecting public health. The widespread accumulation of plastic waste highlights the urgent need for improved waste management and preventive strategies [9].

### 1.3 Limitations of Current Plastic Waste Management Practices

Despite growing awareness, current plastic waste management practices remain inadequate to address the scale of the problem. Mechanical recycling, the most common method, requires proper segregation and clean plastic waste streams. However, mixed plastics, multilayer packaging, and contaminated materials are difficult to recycle, leading to low recycling efficiency. As a result, a significant portion of plastic waste is either landfilled or discarded into the environment [10]. In many developing countries, waste management infrastructure is poorly developed or inconsistently implemented. Open dumping and uncontrolled landfilling are still widely practiced, allowing plastics to leak into surrounding ecosystems. Even in developed nations, recycling systems are often overwhelmed by the sheer volume of plastic waste generated, and exported plastic waste may end up being mismanaged in other regions [3]. Incineration is sometimes used to reduce plastic waste volume, but it poses serious environmental and health concerns. Burning plastics releases toxic gases such as dioxins, furans, and greenhouse gases, contributing to air pollution and climate change. While energy recovery from plastic incineration is possible, it does not address the root cause of excessive plastic production and consumption [5]. Another major limitation is the lack of strong policy enforcement and public participation. Insufficient regulations on single-use plastics, limited producer responsibility, and low consumer awareness hinder effective waste reduction. Without systemic changes that prioritize waste prevention, material redesign, and sustainable alternatives, existing waste management practices will remain insufficient to control global plastic pollution [8].

## 2. Mixed Plastic Waste: A Major Recycling Challenge

### 2.1 Definition and Sources of Mixed Plastic Waste

Mixed plastic waste refers to plastic waste streams that contain a combination of different types of polymers rather than a single, uniform plastic material. Unlike mono-material plastic waste (such as only PET bottles or only HDPE containers), mixed plastic waste consists of various plastics blended together, often along with non-plastic materials such as paper, metal, food residues, inks, and adhesives. This mixture makes identification, separation, and recycling extremely difficult using conventional methods [16]. The primary sources of mixed plastic waste are municipal solid waste and post-consumer packaging materials. Household waste commonly contains a mixture of plastic bags, food wrappers, bottles, containers, sachets, and multilayer packaging. These materials are often disposed of together without proper segregation, resulting in highly contaminated and heterogeneous waste streams that are challenging to recycle effectively [1]. Industrial and commercial sectors also generate significant amounts of mixed plastic waste. Packaging waste from supermarkets, e-commerce deliveries, pharmaceutical blister packs, agricultural films, and electronic product casings frequently contain multiple polymer types combined into a single product. For example, multilayer food packaging may include layers of polyethylene, polypropylene, nylon, and aluminum to provide strength, barrier protection, and shelf stability [2]. Additionally, informal recycling systems, especially in developing countries, contribute to the generation of mixed plastic waste. Waste pickers often collect only high-value plastics such as PET and HDPE, leaving behind low-value mixed plastics. These leftover materials accumulate in landfills or open dumping sites, becoming a major environmental burden and highlighting the need for advanced recycling solutions [3].

### 2.2 Composition and Heterogeneity of Mixed Plastics

The composition of mixed plastic waste is highly complex due to the presence of multiple polymer types with different chemical and physical properties. Common plastics found in mixed waste include polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), polyvinyl chloride (PVC), and polyurethane (PU). Each of these polymers has a distinct melting point, density, chemical structure, and degradation behavior, which complicates recycling processes [4]. In addition to polymer diversity, mixed plastics often contain additives such as plasticizers, stabilizers, flame retardants, colorants, and fillers. These additives are incorporated during manufacturing to improve performance but can interfere with recycling by altering thermal stability and mechanical properties. When different additives are present together, they may react unpredictably during processing, resulting in poor-quality recycled products [5]. Mixed plastic waste is also heterogeneous in terms of physical form and contamination. It may include rigid containers, flexible films, foams, fibers, and multilayer laminates. Food residues, oils, moisture, labels, and adhesives further contaminate the waste, increasing the difficulty of cleaning and processing. This heterogeneity reduces the efficiency of sorting technologies and increases recycling costs [6]. Furthermore, multilayer and composite plastics represent one of the most challenging components of mixed plastic waste. These materials are intentionally designed by combining different polymers to achieve superior performance, such as improved barrier properties and durability. However, separating these layers after use is technically complex and often economically unviable, making such plastics nearly impossible to recycle using conventional techniques [7].

### 2.3 Why Conventional Recycling Fails for Mixed Plastics

Conventional recycling methods, particularly mechanical recycling, are not well-suited for mixed plastic waste. Mechanical recycling requires plastics to be sorted by type, cleaned, shredded, and remelted. When different polymers are melted together, they are usually immiscible, meaning they do not blend uniformly. This incompatibility leads to weak, brittle, and low-quality recycled materials that have limited commercial value [8]. Another major limitation is the difficulty of efficient sorting. Traditional sorting techniques such as manual separation, density-based flotation, and optical sorting work best for clean and uniform waste streams. Mixed plastics, especially flexible and multilayer materials, are hard to identify accurately. Even small amounts of incompatible plastics like PVC can contaminate an entire batch of recyclable material, rendering it unsuitable for reuse [9]. Thermal processing of mixed plastics also presents challenges. Different plastics have different melting temperatures and thermal degradation limits. During recycling, some polymers may degrade or release toxic compounds before others melt, resulting in poor material quality and environmental risks. For example, PVC can release hydrogen chloride gas when heated, damaging recycling equipment and posing health hazards [10]. Economic factors further contribute to the failure of conventional recycling for mixed plastics. The cost of sorting, cleaning, and processing mixed plastic waste often exceeds the value of the recycled output. As virgin plastic remains relatively cheap, industries have little incentive to invest in complex recycling systems. Consequently, mixed plastics are frequently diverted to landfills, incineration, or the environment, emphasizing the urgent need for innovative chemical, biological, and hybrid recycling approaches [11].

## 3. Environmental and Economical Impacts of Mixed Plastics

Mixed plastic waste not only poses recycling challenges but also causes severe environmental and economic damage. When plastics are not properly managed, they accumulate in natural ecosystems and gradually degrade into smaller particles, affecting soil, water, living organisms, and human health. The long persistence of plastics in the environment leads to hidden costs, including ecosystem degradation, loss of biodiversity, healthcare expenses, and reduced economic productivity [2].

### 3.1 Impact on Soil Quality and Microbial Ecosystem

Mixed plastic waste has a significant negative impact on soil quality, particularly when plastics accumulate in agricultural land, landfills, and open dumping sites. Plastic debris alters the physical structure of soil by reducing porosity, water infiltration, and aeration. This leads to poor soil health, increased surface runoff, and reduced water retention, ultimately affecting crop growth and agricultural productivity [5]. As plastics degrade over time, they form microplastics that mix with soil particles. These microplastics interfere with soil aggregation and root penetration, making it difficult for plants to absorb water and nutrients. Studies have shown that the presence of plastic fragments in soil can reduce seed germination rates and stunt plant growth, especially in long-term contaminated areas [6]. Soil microbial communities are highly sensitive to environmental changes, and plastic pollution disrupts their natural balance. Microplastics provide artificial surfaces for microbial colonization, altering microbial diversity and activity. This can affect essential soil processes such as nutrient cycling, organic matter decomposition, and nitrogen fixation, leading to reduced soil fertility [13,16]. Additionally, plastics often contain toxic additives and can adsorb heavy metals and pesticides from the environment. These contaminants can leach into the soil, creating toxic conditions for beneficial microorganisms and earthworms. Over time, this degradation of soil ecosystems results in economic losses for agriculture and threatens food security [9].

### 3.2 Effects on Aquatic and Marine Environments

Aquatic and marine environments are among the most severely affected by mixed plastic pollution. Rivers act as major transport pathways, carrying plastic waste from urban and rural areas into lakes, seas, and oceans. Once in the water, plastics can float, sink, or remain suspended, spreading across vast geographical areas [16]. Marine organisms are directly harmed by plastic pollution through ingestion and entanglement. Fish, turtles, seabirds, and marine mammals often mistake plastic fragments for food. Ingested plastics can block digestive tracts, reduce feeding capacity, and cause internal injuries, leading to starvation and death. Entanglement in fishing nets and plastic packaging restricts movement and increases mortality [12]. Plastic pollution also damages marine habitats such as coral reefs, mangroves, and seagrass beds. Plastics can smother corals, block sunlight, and introduce harmful pathogens. Floating plastics act as carriers for invasive species and microorganisms, disrupting native ecosystems and altering biodiversity patterns [14]. From an economic perspective, marine plastic pollution affects fisheries, tourism, and coastal livelihoods. Declining fish populations, contaminated seafood, and polluted beaches result in financial losses for communities that depend on clean and healthy marine ecosystems. The cost of cleanup and ecosystem restoration further adds to the economic burden [10].

### 3.3 Formation and Risks of Microplastics and NanoPlastics

Microplastics and nanoplastics are formed through the fragmentation of larger plastic items due to sunlight exposure, mechanical abrasion, and environmental weathering. Microplastics are typically less than 5 mm in size, while nanoplastics are even smaller, often invisible to the naked eye. Mixed plastics are a major source of these particles due to their varied composition and degradation patterns [8,9]. These tiny plastic particles are widely distributed in soil, water, air, and living organisms. Because of their small size, microplastics and nanoplastics are easily ingested by plankton, insects, fish, and other organisms at the base of the food chain. This leads to bioaccumulation and biomagnification as plastics move up the food web [7,3]. Microplastics also act as carriers for toxic chemicals, heavy metals, and pathogenic microorganisms. Their large surface area allows them to adsorb pollutants from the surrounding environment, increasing their toxicity. When ingested, these particles can release harmful substances into biological tissues, posing risks to organisms and ecosystems [1,6]. Nanoplastics are of particular concern due to their ability to cross biological barriers. They can penetrate cell membranes and interact with cellular components, potentially causing inflammation, oxidative stress, and genetic damage. Although research is still evolving, the growing presence of micro- and nanoplastics represents a serious long-term environmental and health risk [8,9].

### 3.4 Human Health Concerns Associated with Plastic Pollution

Human health is increasingly threatened by plastic pollution through multiple exposure pathways, including food, water, air, and skin contact. Microplastics have been detected in drinking water, seafood, table salt, fruits, vegetables, and even the air we breathe. Continuous exposure raises concerns about their long-term effects on human health [4,5]. Plastics contain various chemical additives such as plasticizers, stabilizers, and flame retardants, some of which are known to be toxic. These chemicals can leach out of plastics and enter the human body, where they may disrupt hormonal balance and endocrine function. Long-term exposure has been linked to reproductive disorders, developmental issues, and metabolic diseases [1,2,3]. Inhalation of airborne microplastics is another emerging health concern, particularly in urban and industrial areas. These particles can accumulate in the lungs, causing respiratory irritation, inflammation, and potentially increasing the risk of chronic lung diseases. Workers involved in plastic manufacturing and waste management are at higher risk of exposure [7,3]. From an economic standpoint, plastic-related health issues increase healthcare costs and reduce workforce productivity. The combined burden of environmental cleanup, healthcare expenditure, and loss of ecosystem services highlights the urgent need for effective plastic pollution control strategies. Protecting human health requires reducing plastic production, improving waste management, and promoting safer, sustainable alternatives [7,9].

## 4. **Biodegradable Polymers: A Sustainable Alternative**

Biodegradable polymers have emerged as a promising solution to overcome the environmental problems caused by conventional petroleum-based plastics. These materials are designed to degrade naturally into harmless products such as carbon dioxide, water, methane, and biomass through the action of microorganisms, enzymes, and environmental conditions. With increasing concerns over plastic pollution, biodegradable polymers are gaining attention in packaging, agriculture, biomedical, and pharmaceutical applications [2,8].

### 4.1 Definition and Classification of Biodegradable Polymers

Biodegradable polymers are polymeric materials that can be broken down by biological processes into simple, non-toxic substances within a reasonable period of time. Unlike conventional plastics, which persist in the environment for hundreds of years, biodegradable polymers undergo degradation through microbial activity, enzymatic action, moisture, temperature, and oxygen. Their degradation rate depends on polymer structure, molecular weight, crystallinity, and environmental conditions [2]. Based on their origin, biodegradable polymers can be broadly classified into **natural**, **synthetic**, and **semi-synthetic** polymers. Natural biodegradable polymers are derived from renewable biological sources such as plants, animals, and microorganisms. Examples include starch, cellulose, chitosan, alginate, and proteins. These polymers are inherently biodegradable and environmentally friendly [8]. Another important classification is based on **mechanism of degradation**. Some biodegradable polymers degrade through hydrolysis of chemical bonds (such as ester or amide bonds), while others degrade primarily through enzymatic action. Polymers like polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) degrade mainly by hydrolysis followed by microbial assimilation [3]. Biodegradable polymers can also be classified based on **application**, such as biodegradable packaging materials, agricultural films, biomedical implants, sutures, and drug delivery systems. This wide classification highlights their versatility and growing importance in replacing conventional plastics across multiple sectors [9].

### 4.2 Natural vs Synthetic Biodegradable Polymers

Natural biodegradable polymers are obtained directly from biological sources and include polysaccharides (starch, cellulose), proteins (gelatin, collagen), and microbial polymers. These materials are renewable, biodegradable, and generally biocompatible. Due to their natural origin, they are widely used in food packaging, wound dressings, and pharmaceutical formulations [5]. However, natural polymers often suffer from limitations such as poor mechanical strength, high moisture sensitivity, and limited thermal stability. For example, starch-based plastics may absorb water easily and lose their structural integrity. To overcome these drawbacks, natural polymers are often blended with other polymers or chemically modified to improve their performance [8]. Synthetic biodegradable polymers are chemically synthesized but designed to be biodegradable. Examples include polylactic acid (PLA), polycaprolactone (PCL), polyglycolic acid (PGA), polybutylene succinate (PBS), and poly (lactic-co-glycolic acid) (PLGA). These polymers offer better mechanical strength, controlled degradation rates, and improved processability compared to natural polymers [5]. While synthetic biodegradable polymers provide superior performance, they may be more expensive and sometimes rely on industrial composting conditions for complete degradation. In practice, a combination of natural and synthetic biodegradable polymers is often used to balance sustainability, performance, and cost [7].

### 4.3 Advantages of Biodegradable Polymers over Conventional Plastics

One of the most significant advantages of biodegradable polymers is their ability to reduce long-term environmental pollution. Unlike conventional plastics that accumulate in landfills, oceans, and soil, biodegradable polymers break down into environmentally benign products. This reduces plastic persistence and minimizes ecological damage [4]. Biodegradable polymers are often produced from renewable resources such as corn starch, sugarcane, and microbial fermentation products. This reduces dependence on fossil fuels and lowers the carbon footprint associated with plastic production. As a result, they support sustainability and circular economy principles [6,2]. Another important advantage is their reduced impact on wildlife and ecosystems. Biodegradable plastics are less likely to cause long-term harm through ingestion or entanglement. Even if they enter natural environments, their ability to degrade lowers the risk of accumulation and microplastic formation compared to conventional plastics [4,6]. From a socio-economic perspective, biodegradable polymers encourage innovation, green industries, and sustainable waste management practices. They are particularly valuable in applications such as medical devices, drug delivery systems, and agricultural films, where controlled degradation is beneficial. Overall, biodegradable polymers represent a key step toward addressing global plastic pollution and promoting environmental sustainability [1,2].

## 5. Conversion of Mixed Plastics into Biodegradable

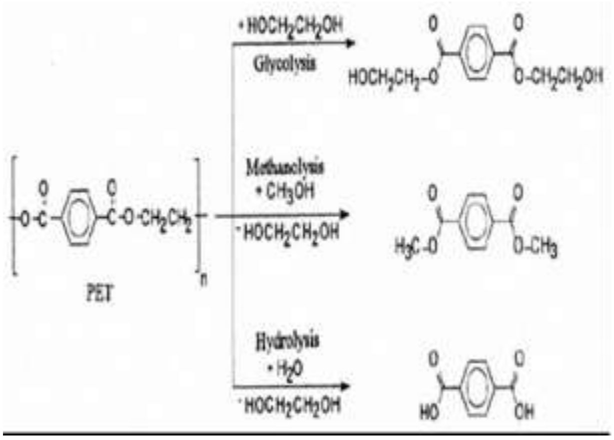
## Polymers: Methods, Mechanisms, and Rationale

The conversion of mixed plastic waste into biodegradable polymers represents a next generation solution to plastic pollution. Conventional recycling methods fail to treat mixed plastics due to their heterogeneous composition, contamination, and polymer incompatibility. Therefore, advanced **chemical, biological, and hybrid conversion methods** are employed to break down mixed plastics and rebuild them into environmentally safe biodegradable polymers. These methods aim to **recover carbon value**, **reduce pollution**, and **support circular economy principles [13]**.

### 1. Chemical Depolymerization–Based Conversion

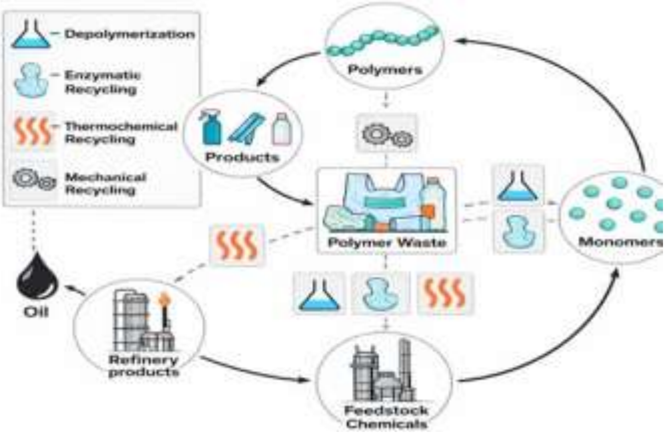
### What is the method?

Chemical depolymerization is a process that breaks long polymer chains of mixed plastics into smaller chemical units such as monomers, oligomers, oils, waxes, or organic acids using heat, solvents, or catalysts.



### How does it convert mixed plastics?

Mixed plastics are first shredded and cleaned to remove metals and non-plastic impurities. The waste is then subjected to processes such as **pyrolysis, catalytic cracking, or solvolysis**.



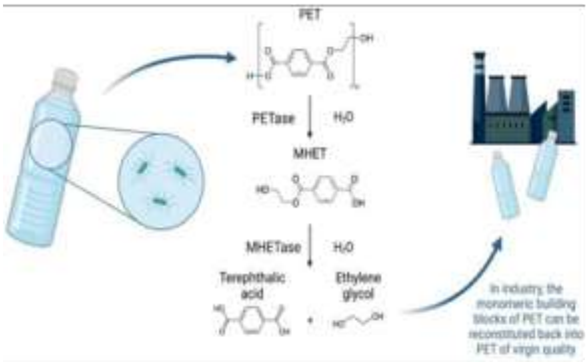
- **Pyrolysis** thermally decomposes plastics in the absence of oxygen, producing hydrocarbon oils and gases.
- **Solvolysis** selectively breaks ester-based plastics (like PET) into monomers using solvents.

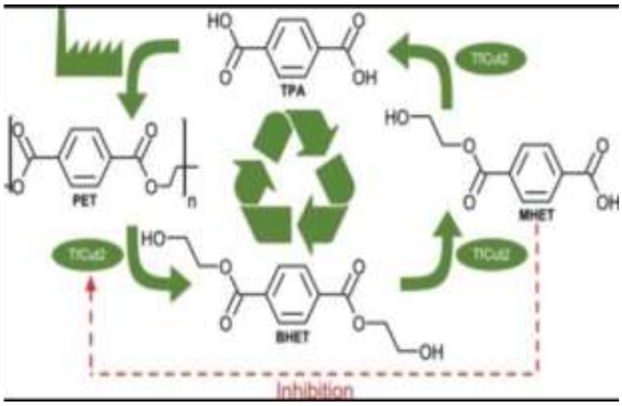
These intermediates are later polymerized or biologically transformed into biodegradable polymers such as PLA, PBS, or bio-polyesters [16].

**Why do we take this method?**

Chemical depolymerization is chosen because it can process **highly mixed, multilayer, and contaminated plastics** that cannot be mechanically recycled. It does not require strict sorting and recovers useful chemical feedstocks from waste. Why is it important? This method transforms plastic waste into reusable chemical building blocks, reduces landfill accumulation, and provides raw materials for biodegradable polymer production, making it a key step in plastic upcycling [11,15].

### 2. Enzymatic Conversion of Plastics





**What is the method?**

Enzymatic conversion uses **biological enzymes** to selectively degrade plastic polymers into their monomers under mild environmental conditions. How does it convert plastics? Specific enzymes such as **PETase, cutinase, and esterase** attack ester bonds in plastics like PET. These enzymes hydrolyze polymer chains into monomers such as terephthalic acid and ethylene glycol. These monomers are then reused to synthesize biodegradable polymers [12].

**Why do we take this method?**

This method is preferred because it is **highly selective, low-energy, and environmentally friendly**. It avoids harsh chemicals and produces high-purity monomers suitable for polymer synthesis [13].

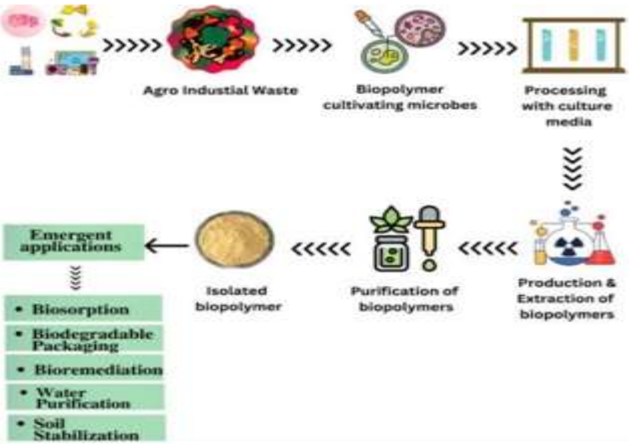
**Why is it limited but valuable?**

Although enzymatic methods work mainly on specific plastics and require pre-treatment, they are extremely valuable for sustainable recycling due to their precision and minimal environmental impact [8].

### 3. Microbial Upcycling into Biodegradable Polymers

**What is the method?**

Microbial upcycling uses microorganisms to convert plastic-derived compounds into **biodegradable polymers**, especially **polyhydroxyalkanoates (PHAs)**. How does it convert plastics?



Mixed plastics are first depolymerized chemically or enzymatically into smaller molecules such as organic acids, alcohols, or hydrocarbons. These compounds are fed to bacteria under controlled fermentation conditions. The microbes metabolize these compounds and store biodegradable polymers inside their cells, which are later extracted [3,4].

**Why do we take this method?**

This method is chosen because it converts plastic waste into fully biodegradable, biocompatible, and high-value polymers. It integrates waste management with biotechnology [8].

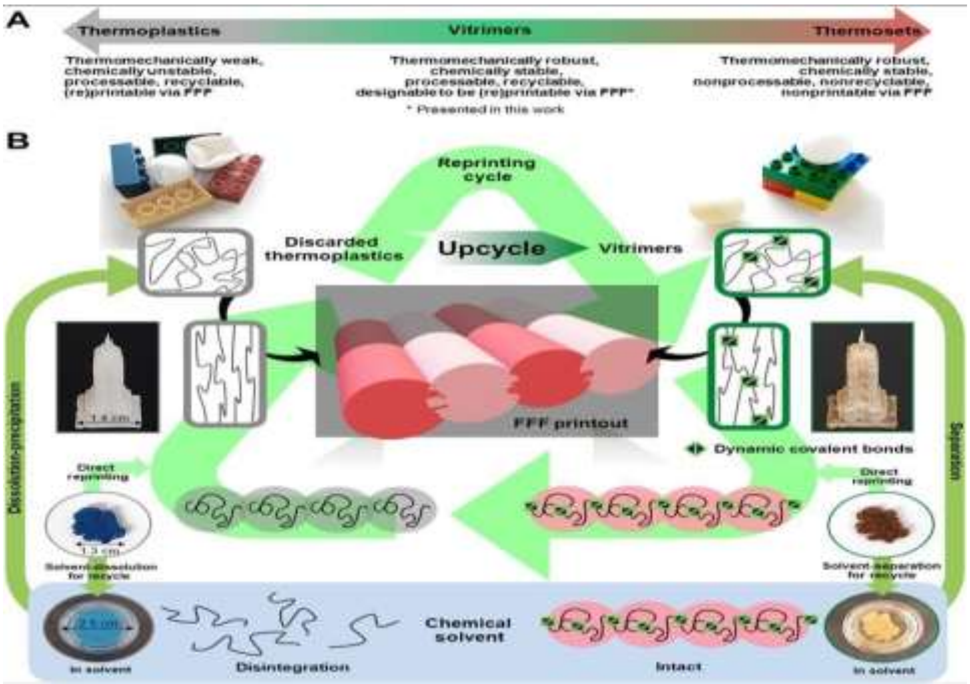
**Why is it promising?**

PHAs degrade naturally in soil and water, making microbial upcycling one of the most sustainable solutions for plastic waste utilization, especially for medical and packaging applications [5].

## 4. Hybrid Chemical–Biological Conversion What is the method?

Hybrid conversion combines **chemical depolymerization** with **biological or microbial synthesis** to maximize efficiency and sustainability. How does it convert mixed plastics? In this method, chemical processes first break mixed plastics into simpler intermediates. These intermediates are then biologically converted by microbes or enzymes into biodegradable polymers such as PHAs or bio-polyesters [10].

**Why do we take this method?**



No single method can efficiently process mixed plastics alone. Chemical methods handle complexity, while biological methods ensure selectivity and eco-friendliness. Hybrid systems combine the strengths of both [5,6].

**Why is it considered the best approach?**

Hybrid conversion shows high efficiency, reduced emissions, better product quality, and industrial scalability. It is currently the **most realistic pathway** for large-scale conversion of mixed plastics into biodegradable polymers [1,8].

## 5. Thermochemical Conversion Integrated with Biopolymer Production What is the method?

Thermochemical conversion uses extreme heat to convert plastics into gases or oils, which are further used to synthesize biodegradable polymers. How does it convert plastics? Processes like **gasification** convert plastics into synthesis gas (CO and $H_2$). These gases are chemically or biologically converted into monomers, which are polymerized into biodegradable plastics [6,9].

**Why do we take this method?**

This method is used for **highly complex, multilayer, and unrecyclable plastic waste** where other methods fail.

**Why is it important?**

Although energy-intensive, it ensures complete carbon utilization and prevents plastic leakage into the environment.

Why These Methods Are Selected (Overall Justification)

- They treat **mixed and contaminated plastics**
- They reduce **landfill and incineration**
- They convert waste into **biodegradable polymers**
- They support **circular economy and sustainability**
- They reduce **long-term environmental and health risks**

## 6. Need for Converting Mixed Plastics into Biodegradable Polymers

The rapid increase in mixed plastic waste and the failure of conventional recycling systems have made it essential to rethink how plastics are managed after use. Converting mixed plastics into biodegradable polymers is not just a technological choice, but a **strategic necessity** to protect the environment, conserve resources, and ensure sustainable development. This section explains **why** such conversion is needed, from circular economy perspectives to environmental and economic benefits [16, 12].

### 6.1 Circular Economy and Sustainable Material Concepts

The circular economy is a sustainable model that aims to keep materials in continuous use, minimize waste generation, and regenerate natural systems. Unlike the traditional linear economy (take–make–dispose), the circular economy focuses on reducing resource extraction and maximizing material recovery. Converting mixed plastics into biodegradable polymers directly supports this model by transforming waste into useful, eco-friendly materials [14]. Mixed plastic waste represents a significant loss of material value in the current linear system. When plastics are landfilled or incinerated, the embedded carbon, energy, and resources are permanently lost. By converting mixed plastics into biodegradable polymers, these valuable resources are recovered and reintroduced into the material cycle, reducing dependence on virgin fossil-based raw materials [7,3]. Sustainable material concepts emphasize the use of renewable, biodegradable, and lowtoxicity materials that do not persist in the environment. Biodegradable polymers fit perfectly into this framework because they are designed to safely degrade after use. When derived from plastic waste, they further enhance sustainability by addressing both waste management and material production simultaneously [10,9]. In addition, circular economy approaches promote innovation and system-level thinking. The conversion of mixed plastics into biodegradable polymers encourages the integration of chemistry, biotechnology, and engineering. This not only reduces environmental burden but also drives the development of sustainable industries and green technologies essential for long-term environmental protection [7,9].

### 6.2 Upcycling vs Recycling of Plastic Waste

Recycling and upcycling are often used interchangeably, but they represent fundamentally different approaches to plastic waste management. **Recycling**, particularly mechanical recycling, typically involves reprocessing plastics into materials of similar or lower quality. In many cases, recycled plastics suffer from degraded mechanical properties, limiting their applications and leading to eventual disposal [13,11]. Mixed plastic waste is especially problematic for conventional recycling because different polymers are incompatible when melted together. This results in low-quality recycled products, often referred to as **downcycling**. Such products have limited lifespan and value, and recycling does not fully solve the problem of plastic accumulation in the environment [1,10]. **Upcycling**, on the other hand, involves converting waste materials into products of **higher value and functionality**. Converting mixed plastics into biodegradable polymers is a clear example of upcycling. Instead of producing inferior plastics, the waste is transformed into advanced materials that offer environmental benefits and improved end-of-life options [3,6]. Upcycling also aligns better with sustainability goals because it creates long-term solutions rather than temporary fixes. While recycling delays plastic disposal, upcycling fundamentally changes the material’s environmental behavior. Biodegradable polymers produced through upcycling safely return to nature after use, reducing pollution and closing the material loop more effectively than conventional recycling [16].

### 6.3 Environmental and Economic Benefits of Polymer Conversion

One of the strongest reasons for converting mixed plastics into biodegradable polymers is the significant **environmental benefit**. This approach reduces plastic accumulation in landfills, oceans, and soils, thereby minimizing harm to ecosystems and wildlife. Biodegradable polymers degrade naturally under appropriate conditions, lowering the risk of long-term pollution and microplastic formation [3,5]. From a climate perspective, polymer conversion helps reduce greenhouse gas emissions. Landfilling and incineration of plastics release carbon dioxide and other harmful gases. In contrast, converting plastics into biodegradable polymers recovers carbon in a controlled and productive manner. This reduces the overall carbon footprint associated with plastic waste management and material production [13]. The economic benefits are equally important. Mixed plastics are often considered low-value or negative-value waste due to high disposal costs. Converting them into biodegradable polymers creates **value-added products**, opening new markets in packaging, agriculture, healthcare, and pharmaceuticals. This transformation turns waste management from a cost burden into an economic opportunity [5]. Furthermore, polymer conversion supports job creation, industrial innovation, and sustainable economic growth. Investment in advanced recycling and biopolymer production encourages the development of green industries and reduces dependence on imported fossil resources. In the long term, the combined environmental and economic advantages make the conversion of mixed plastics into biodegradable polymers a critical strategy for sustainable development [1,6].

## 7. Technological and Industrial Challenges

Although converting mixed plastics into biodegradable polymers is a highly promising solution, its large-scale implementation faces several **technological, economic, and regulatory challenges**. These challenges arise due to the complex nature of mixed plastic waste, limitations in current technologies, high production costs, and the need to ensure true environmental sustainability. Understanding these barriers is essential for improving existing processes and enabling industrial adoption [8,2].

### 7.1 Feedstock Variability and Process Compatibility

One of the most significant challenges in converting mixed plastics is **feedstock variability**. Mixed plastic waste does not have a uniform composition; it varies widely depending on the source, region, consumer behavior, and waste collection systems. A single waste stream may contain polyethylene, polypropylene, PET, polystyrene, PVC, multilayer composites, and non-plastic contaminants such as food residues, metals, and paper [11]. This variability makes it difficult to design conversion processes that work consistently. Chemical and biological processes are often optimized for specific polymer types or feedstock compositions. When the input composition changes, process efficiency, product quality, and yield can fluctuate significantly. This lack of consistency poses a major challenge for industrial operations that require stable and predictable performance [9,3]. Process compatibility is another major issue. Not all plastics respond equally to a single depolymerization or conversion method. For example, condensation polymers like PET are suitable for solvolysis or enzymatic degradation, while addition polymers such as PE and PP require high-energy thermochemical methods. Integrating these different requirements into one process is technically complex [9,7]. To address these challenges, flexible and adaptive processing systems are needed. This includes advanced sorting technologies, real-time feedstock characterization, and modular process designs that can handle variations in waste composition. Without such innovations, feedstock variability will continue to limit the efficiency and reliability of mixed plastic conversion technologies [4,7].

### 7.2 Scalability and Cost Issues

Scalability is a critical barrier in translating laboratory-scale success into industrial reality. Many emerging technologies for converting mixed plastics into biodegradable polymers have shown excellent results at the bench or pilot scale, but scaling them up introduces new technical and economic difficulties. Reaction conditions that are easy to control in small systems become difficult to manage in large reactors [8,6]. High capital investment is one of the major cost-related challenges. Advanced chemical reactors, bioreactors, catalysts, enzymes, and downstream purification equipment require substantial upfront investment. For industries, this financial risk is often higher than continuing with conventional plastic production or disposal methods [7]. Operating costs also pose challenges. Chemical depolymerization processes may require high temperatures and pressures, leading to increased energy consumption. Biological processes, while milder, often involve long processing times, strict control of conditions, and expensive nutrients or enzymes. These factors increase production costs and reduce economic competitiveness [5]. In addition, biodegradable polymers produced from mixed plastics often struggle to compete with low-cost virgin plastics derived from fossil fuels. Until economies of scale are achieved and fossil-based plastics are appropriately regulated or taxed, cost competitiveness will remain a major hurdle for industrial adoption [ 6].

### 7.3 Regulatory and Sustainability Considerations

Regulatory frameworks play a crucial role in the adoption of mixed plastic conversion technologies. Currently, regulations related to plastic waste management, recycling, and biodegradable materials vary widely across regions and countries. This lack of harmonization creates uncertainty for industries looking to invest in advanced recycling and biopolymer production [8]. Another challenge is the definition and certification of “biodegradable” and “sustainable” materials. Some biodegradable polymers require specific industrial composting conditions and may not degrade effectively in natural environments. Without clear standards and labeling, there is a risk of greenwashing and public misunderstanding, which can undermine trust in biodegradable alternatives [9]. Sustainability assessment is also essential. While converting plastics into biodegradable polymers appears environmentally beneficial, the entire process must be evaluated using **life cycle assessment (LCA)**. Energy use, greenhouse gas emissions, water consumption, and waste generation across the full lifecycle must be considered to ensure that the process delivers real environmental benefits [10]. Finally, regulatory support is needed to encourage adoption. Policies such as extended producer responsibility, incentives for using recycled or bio-based materials, restrictions on single-use plastics, and investment in sustainable technologies are critical. Without strong regulatory and sustainability frameworks, technological advancements alone will not be sufficient to drive large-scale change [11].

## 8. Future Perspectives and Challenges

The conversion of mixed plastic waste into biodegradable polymers is still an emerging field, but it holds strong promise for addressing global plastic pollution in a sustainable manner. Future developments will depend on advances in science, technology, policy, and industrial collaboration. While significant progress has been made at laboratory and pilot scales, several challenges must be addressed before these approaches can be widely implemented. This section discusses the **future outlook** of mixed plastic conversion technologies along with the **key challenges** that need to be overcome [12]. One important future perspective is the **advancement of integrated conversion technologies**. Hybrid chemical–biological approaches are expected to play a central role, as they combine the robustness of chemical depolymerization with the selectivity and sustainability of biological processes. Future research will focus on designing integrated systems that can efficiently handle variable mixed plastic feedstocks while maintaining consistent product quality. Improvements in catalyst design, enzyme engineering, and microbial strain development are likely to enhance conversion efficiency and reduce processing time [13]. Another promising direction is the **development of tailored biodegradable polymers** derived from waste plastics. Future studies aim to control polymer properties such as molecular weight, mechanical strength, and degradation rate to meet specific application needs in packaging, agriculture, and biomedical fields. Advances in metabolic engineering and polymer chemistry will enable the production of customized biopolymers, increasing their commercial value and acceptance as alternatives to conventional plastics [14]. Despite these opportunities, several **technological challenges** remain. Feedstock variability, process optimization, and scale-up difficulties continue to limit industrial adoption. Many current processes are energy-intensive or costly, making them less competitive with virgin plastic production. Future efforts must focus on reducing energy consumption, improving process economics, and achieving scalability without compromising environmental benefits [15]. In addition to technical challenges, **regulatory, economic, and societal factors** will strongly influence future progress. Clear standards for biodegradability, life cycle assessment, and sustainability certification are essential to ensure genuine environmental benefits and avoid greenwashing. Strong policy support, financial incentives, and public awareness are needed to encourage industries to invest in advanced recycling and biopolymer production. Overall, while challenges remain, continued interdisciplinary research and supportive governance can enable the large-scale conversion of mixed plastics into biodegradable polymers, contributing significantly to a sustainable and circular plastic economy [16].

## CONCLUSION

Plastic pollution, particularly from mixed plastic waste, has emerged as one of the most serious environmental challenges of the modern era. The rapid growth in plastic production and consumption, combined with poor waste management practices, has led to the widespread accumulation of plastics in soil, water, and marine environments. Mixed plastics pose an even greater problem because their heterogeneous composition makes conventional mechanical recycling inefficient, economically unattractive, and environmentally insufficient. As a result, large quantities of mixed plastic waste continue to be landfilled, incinerated, or released into the environment, causing long-term ecological and health risks. This review has highlighted that biodegradable polymers offer a sustainable alternative to conventional plastics and present a valuable opportunity for addressing mixed plastic waste. Advanced conversion strategies such as chemical depolymerization, enzymatic and biocatalytic methods, microbial upcycling, and hybrid chemical–biological technologies provide promising pathways to transform low-value mixed plastics into high-value, environmentally friendly biodegradable polymers. These approaches move beyond simple recycling by enabling true **upcycling**, where waste is converted into materials with improved environmental performance and end-of-life behavior. The conversion of mixed plastics into biodegradable polymers strongly supports circular economy and sustainable material concepts by recovering carbon value, reducing dependence on fossil resources, and minimizing plastic leakage into ecosystems. Environmental benefits include reduced pollution, lower greenhouse gas emissions, and decreased formation of microplastics, while economic benefits include value creation, innovation, and the development of green industries. However, significant technological, industrial, and regulatory challenges remain, including feedstock variability, scalability, high costs, and the need for clear sustainability standards. In conclusion, converting mixed plastic waste into biodegradable polymers represents a transformative and forward-looking solution to global plastic pollution. Although further research, technological optimization, and policy support are required, integrated and interdisciplinary approaches have the potential to shift plastic waste management from a linear disposal model to a sustainable circular system. With continued scientific advancement and coordinated global efforts, these strategies can play a crucial role in achieving long-term environmental protection and sustainable development.

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