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# Addressing plastic pollution: Sustainable alternatives and advanced waste management

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## Abstract

Plastic pollution has escalated into a major environmental crisis, endangering wildlife, people, and economies around the globe. This prompted the need to investigate and assess cutting-edge waste management systems and environmentally friendly alternatives to combat this mounting problem. When considering alternatives to traditional plastics and waste recycling methods, it is important to evaluate each candidate's ecological footprint, financial feasibility, and potential for widespread use.

The findings emphasize the importance of comprehensive waste management by demonstrating, sustainable alternatives that can be seamlessly integrated into existing systems. This study examines the necessity of producer accountability in fostering enduring transformation, as well as innovative waste management strategies, such as circular economy models, enhanced recycling techniques, and plastic degradation methods, to mitigate environmental damage. The research examines environmental, socio-economic, psychological, and consumer behaviour issues vital to sustainable development. Important research shows that creative waste management techniques paired with sustainable plastic substitutes can significantly reduce the negative impacts of plastic pollution. While acknowledging the importance of policy and regulatory frameworks, this study highlights the revolutionary potential of new technical breakthroughs and Industry 5.0 in achieving a circular economy. When it comes to effectively addressing the worldwide plastic pollution challenge, the conclusions drawn highlight the importance of adopting an integrated approach that balances technological innovation, policy implementation, and participant participation from consumers.

**Keywords:** Plastic waste; Sustainable Development Goal; Circular Economy; Industry 5;0

## 1. Introduction

Plastics are very versatile materials that are widely used in the modern economy due to their exceptional utility and cost-effectiveness, resulting in their widespread presence globally. Global plastics production reached 407 million tonnes in 2015, surpassing paper (400 million tonnes) and aluminum (57 million tonnes). Plastic production is expected to reach 1,600 million metric tonnes per annum (Mtpa) by 2050 if growth rates remain steady [1]. Although plastics provide numerous advantages, their extensive production and inadequate waste handling have caused significant environmental apprehensions. Plastic pollution, which refers to the uncontrolled disposal of plastic garbage in both water and land, has emerged as a rapidly escalating worldwide catastrophe with detrimental impacts on the environment, wildlife, and human well-being. Plastic products and garbage present dangers due to their poisonous nature, ability to transmit diseases, and disruption of the food chain. If system improvements are not made, it is estimated that 12 billion metric tonnes of plastic waste will be deposited in landfills and natural environments by 2050

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[2]. Additionally, the entire lifecycle of plastic is responsible for 15% of the global carbon budget, as greenhouse gas emissions are produced [3].

The increasing worldwide problem of plastic pollution has sparked a pressing search for sustainable alternatives to traditional polymers derived from petroleum. Plastics, regardless of whether they come from natural or manmade sources, can take hundreds of years to break down, resulting in the formation of microplastics and worsening environmental issues. The urgency of this environmental issue highlights the need for strong laws on plastic waste and enhanced techniques for managing waste. The shift from traditional plastics to bioplastics is motivated by various considerations, such as the limited availability of fossil fuels, the harmful ecological consequences of plastic pollution, and the increasing need for environmentally benign materials. Plastic pollution endangers ecosystems, marine life, and human health. Although bioplastics reduce fossil fuel dependency and carbon emissions, contamination and inadequate infrastructure make recycling and composting organic waste problematic. This article discusses recycling concerns like as contamination and economic barriers, while also highlighting worldwide breakthroughs and best practices. It also discusses converting plastic trash into fuels, building materials, and biogas. This article examines the bio-circular-green (BCG) economy, Industry 5.0, and blockchain technologies in the context of circular economy sustainability, including global standards, EPR, and plastic levies. It also discusses public awareness and behavioral change strategies, as well as future research directions in technology, politics, and consumer behaviour to prevent plastic pollution.

## 2. Type of plastic and bioplastic

### 2.1. Conventional plastic

Synthetic plastics are typically classified based on their degradation processes, which distinguish between those with carbon-carbon (C-C) backbones and those that include heteroatoms. This classification helps to understand their structural variety [4]. Polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC) are prominent examples of C-C backbone plastics. Each of these plastics possesses unique qualities and finds specific applications [5]. Polyethylene (PE), which includes both low-density (LDPE) and high-density (HDPE) forms, is found everywhere in disposable products and plays a major role in the buildup of garbage in landfills[6]. Polystyrene (PS), which is known for its cost-effectiveness and mechanical strength, is widely used in many forms such as general-purpose polystyrene (GPPS), oriented polystyrene (OPS), and high-impact polystyrene (HIPS)[7]. Polypropylene (PP), which is similar to polyethylene (PE) but has greater hardness and resilience, is used in many industries to meet different needs [4]. PVC, known for its stiffness, has a wide range of uses in various industries [8]. On the other hand, polymers such as polyethylene terephthalate (PET) and polyurethane (PU), which contain heteroatoms, have improved heat resistance but are difficult to break down because of their complex structures [9]. Although synthetic plastics are essential, they provide substantial environmental hazards since they degrade slowly in natural ecosystems. Interdisciplinary research and biotechnology advancements are urgently needed to tackle the worldwide problem of plastic pollution [10].

### 2.2. Bioplastic

Bioplastics, derived from renewable biomass sources, offer a promising solution to this pressing environmental issue. The transition from conventional plastics to bioplastics is driven by several factors, including the finite nature of fossil fuels, the detrimental environmental impacts of plastic pollution, and the growing demand for eco-friendly materials. As a result, bioplastics have a lower environmental impact than fossil fuel polymers since they are derived from renewable biomass, such as plants, animals, or bacteria [11]. Understanding the production processes, qualities, and environmental consequences of bioplastics is crucial as the demand for environmentally friendly materials continues to increase. Bioplastics are a wide range of materials made from sustainable biomass sources. They promote plastic recycling and provide (bio)degradable options. Due to their capacity to absorb $CO_2$ and disintegrate more rapidly than conventional plastics, these materials are well-suited to address the worldwide plastic waste dilemma. As a result, they can effectively reduce carbon emissions and plastic pollution, making them strong options for combatting this issue [12].

Bioplastics can be classified into two categories, biodegradable and non-biodegradable, based on their capacity to break down naturally [13]. Biodegradable bioplastics, which can decompose into natural chemicals under appropriate circumstances, provide an eco-friendly option to conventional plastics [14]. These plastics can be further categorized into subcategories, including bio-based biodegradable plastics, bio-compostable bioplastics, and non-biodegradable bioplastics. Each of these subcategories has distinct advantages [15]. In contrast, non-biodegradable bioplastics, despite being created from renewable resources, do not easily break down, requiring additional solutions for managing them at the end of their life cycle [16]. Multiple subcategories exist for non-biodegradable bioplastics. Non-biodegradable plastics made from bio-based polymers include PE, PET, and nylons. They are used in packaging and automotive parts that require durability. Bacteria and algae fermented with plant oils or sugars produce synthetic bioplastics. Synthetic bioplastics like polyhydroxyalkanoates (PHA) are biodegradable and customizable. Cultivated algae-based bioplastics can be created rapidly and sustainably, and could replace petroleum-based plastics in packaging and cosmetics. Cellulose-based bioplastics are made from wood pulp or agricultural waste. These bioplastics are strong and biodegradable. They are a sustainable alternative to plastics in packaging, textiles, and construction.

## 3. Environmental impact and biodegradation of plastic

Although synthetic plastics are essential in various applications, they pose substantial environmental hazards due to their slow degradation in natural ecosystems. A variety of abiotic factors, including temperature, ultraviolet radiation, and physical and mechanical processes, are responsible for the progressive decomposition of plastics that are dispersed throughout the environment. The process of breakdown results in the development of smaller particles of plastic, such as microplastics, which are smaller than 5 millimeters in size, and nano-plastics, which are smaller than 1 micrometer in size[17]. Plastic waste has accumulated in terrestrial and aquatic compartments around the world as a result of low biodegradation, indiscriminate usage, poor disposal, or mismanagement. This has harmed natural biota, fishing, tourism, agricultural production, and human health and safety [18]. Microplastics can be transported by wind, streams, rivers, and currents, or through wastewater treatment plants. They can be present in aquatic habitats, even in extremely isolated locations such as lakes on remote islands, Antarctica, and the deep oceans [19]. In the natural environment, microplastic can be deliberately or involuntarily consumed by hundreds (or thousands) of species, producing physical abrasions and chemical toxicity from integrated additives, adsorbed pollutants, and infections[20]. In metropolitan areas, the accumulation of waste made of plastic, particularly near sewage systems, can make the risk of flooding worse and provide a breeding ground for mosquitoes, which are responsible for the transmission of zoonotic diseases such as dengue and Zika [21].

Food packaging constitutes a significant portion of India's plastic waste, hence transitioning to bio-based polymers could potentially have a substantial influence. Biotech Bags, Ravi Industries, Ecolife, J&K Agro Industries, and Truegreen in Ahmedabad are significant Indian manufacturers. J&K Agro Industries, in collaboration with Earth Soul, runs a bioplastic manufacturing facility with a yearly production capacity of 960 tonnes. Meanwhile, Truegreen in Ahmedabad can generate 5000 tonnes of bioplastic per year. Hi-Tech International has introduced a plant-derived bio-polymer as an alternative to disposable and reusable plastic products like cups, bottles, and straws. Approximately three to four months after its production, this bio-polymer begins to decompose, and it can completely dissolve within six months [22].

### 3.1. Advances in plastic degradation and upcycling

Microbial degradation is a potentially effective alternative, although it is impeded by the intricate chemical compositions and limited capabilities of microorganisms to break down these compounds[23].Recent progress in the study of microbial enzymes has enhanced our understanding of plastic breakdown, facilitating the development of innovative methods for cleaning up polluted environments, such as bioremediation [24]. Biofilm-based technologies and chemical changes, such as degradable polyethylene (DPE), provide other methods to increase the rate at which natural decomposition occurs [25]. Furthermore, the process of biological upcycling presents a sustainable method for transforming plastic waste into valuable bioproducts, signifying a notable shift in the field of waste management [26].

## 4. Managing bioplastic waste

Global accords to promote a sustainable and circular economy prioritize the substitution of petroleum-derived raw materials and energy in the plastics value chain. Although bio-based plastics are becoming more and more well-liked as a sustainable substitute, their market share is still less than 2%, or 7.4 million metric tonnes, out of 348 million in 2017. This is because fossil-based plastics are less expensive, require less land and money to produce, and have fewer recycling and disposal options [27]. Utilizing biorefinery as a biotechnological method to extract raw materials from biomass waste and byproduct streams appears to be a promising option for enhancing the production of bio-based plastics. This approach eliminates the requirement for land and has the potential to enhance production efficiency, resulting in reduced pricing [28]. However, to directly convert biomass for the synthesis process, a significant amount of work needs to be put towards the process of screening and developing microbial strains that have increased hydrolytic capacities.

Hopefully, bio-based polymers with favourable properties will soon be available, along with a greater possibility of sustainable end-of-life solutions [29]. Although bioplastics are touted as a sustainable substitute for conventional plastics, reducing fossil fuel use and environmental impact, they also present fresh challenges for waste management. The management of bioplastic waste entails a complex interaction between socioeconomic, psychological, and environmental elements. Even though they are biodegradable, bioplastics don't always decompose as quickly as one might anticipate, particularly when combined with organic municipal waste like food scraps and yard material. This complexity may present an even greater issue than traditional plastics in some situations since it can cause contamination, inefficiencies in sorting, and difficulties in composting and recycling.

### 4.1. Environmental and Socio-economic Factors

To develop a truly sustainable plastics economy, it is imperative to have effective waste management systems in place for bioplastic waste, regardless of its biodegradability, as the production of bioplastics continues to grow [30].Factors such as the conditions required for biodegradation, the presence of additives or contaminants in bioplastic products, and the availability of suitable composting facilities influence the environmental impact of bioplastic waste[31].

Fast urbanization and a misunderstanding of bioplastics as a sustainable substitute have led to a rise in the generation of bioplastic waste, which presents unique environmental and socioeconomic challenges for India. Due to inadequate waste management practices, bioplastics, particularly those that are not fully biodegradable in the local environment, pollute waterways and landfills in India, mainly in rural areas where the system is weak [32]. Improved waste management infrastructure and increased public awareness are necessary to overcome the negative effects of urban-rural socioeconomic differences on recycling rates and garbage collection efficiency[33].

### 4.2. Psychological Factors and Consumer Behaviour

The psychological factor associated with biodegradability plays a pivotal role in shaping attitudes and behaviors toward waste management [34]. Consumers may perceive bioplastics as inherently less harmful to the environment, fostering a sense of complacency or justification in their usage. However, the reality of bioplastic disposal presents complexities that extend beyond mere biodegradability. Moreover, the juxtaposition of bioplastics with other organic municipal waste underscores the interconnectedness of waste management systems. Awareness about the impacts of plastic pollution (socioeconomic, health impacts, and bio-ecological impacts) is highly associated with pro-environmental behaviour [35].

In India, managing bioplastic waste effectively depends heavily on consumer behaviour. Indian consumers' knowledge and understanding of bioplastics are still developing. Despite the increased demand for sustainable products, many customers do not understand the distinctions between bioplastics and traditional plastics, which might result in inappropriate disposal practices [36]. Furthermore, consumer behaviour in India is influenced by the sociocultural context. For example, the desire for single-use plastics in some areas and the absence of incentives for recycling or correct disposal led to the build-up of garbage made of bioplastics [18]. Governmental measures and educational campaigns are required to change consumer behaviour towards more environmentally friendly habits.

## 5. Circular economy and advanced plastic waste management strategies

A circular economy emphasizes "reduce, reuse, and recycle" instead of the linear "take–make–dispose" economic models. This approach maximizes resource utilization, recovers and regenerates products and materials at the end of their life, and promotes environmental sustainability. Designing plastic items for recycling from the start, using mono-materials, and eliminating additives that make recycling harder is key to a circular economy[37].

### 5.1. Rules and policies for the reduction of plastic waste

There have been several directives issued on a global scale, as well as national, local, and regional initiatives, to reduce the environmental impact and leakage caused by plastics. Fines, environmental fees, and legislative limitations on single-use plastics such as plastic bags and microbeads are some of the initiatives that have been taken [38]. Several international agreements have been established to mitigate the social, environmental, and economic risks associated with plastic pollution [39]. The fundamental objective of the Basel Convention and the revision that was made to it in 2019 is to regulate and restrict the movement of waste made of plastic across international borders. The fundamental purpose of the United Nations Convention on the Law of the Sea (UNCLOS) is to regulate and reduce the contamination of the marine ecosystem that is caused by waste consisting of plastic. Under the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), it is forbidden for ships to throw plastic that has been discarded into the ocean. Plastics and microplastics in the marine environment, including those that originate from inland regions, are the subject of research conducted by the Joint Group of Experts on the Scientific Aspects of Marine Environmental

Protection (GESAMP) and the United Nations Global Partnership on Marine Litter (GPLM). Their primary objective is to investigate the origins, fate, and impacts of these types of environmental contaminants.

Enhancing recycling rates for plastic waste management is a less contentious approach compared to restricting its usage or production, as recycling enjoys greater popularity [40]. Recycling reduces oil use, carbon dioxide emissions, and garbage disposal, hence various laws prioritize it. The European Union's (EU) plastic policy for a circular economy prioritizes single-use plastic recycling by improving waste management processes [41]. The Plastic Waste Management Rules, 2016 (PWM-2016), implemented by the Indian Government (GoI), aims to mitigate the ecological consequences of plastic waste by implementing various significant steps. These measures consist of requiring the reduction of plastic waste production, ensuring separate storage and disposal, and adopting Extended Producer Responsibility (EPR) on producers, importers, and brand owners to handle plastic packaging waste. The regulations also raised the minimum thickness of plastic carry bags, expanded its scope to include rural areas where Gramme Panchayats are responsible for enforcement, and implemented a gradual removal of non-recyclable multi-layered plastics. In July 2022, a ban was implemented on specific single-use plastics.

### 5.2. Plastic waste recycling and valorization

Innovative recycling methods, such as chemical recycling, convert polymers into monomers or usable chemicals, allowing for more efficient and high-quality recycling compared to mechanical recycling [33]. Valorization of plastic waste into value-added products, such as fuels, chemicals, and new plastics, represents a transformative approach to waste management, contributing to the circular economy. Technologies such as pyrolysis, gasification, and chemical recycling enable the breakdown of plastics into basic chemical components [11].

Chemical treatment methods, which break down polymers into monomers or other usable chemicals, are essential for valorizing plastic waste in a circular economy. They provide a workable substitute for severely contaminated or heterogeneous plastic waste streams[42]. By processing mixed and contaminated plastics, chemical recycling outperforms mechanical recycling and increases the amount of recyclable materials [43]. To produce petrochemicals or recover energy, depolymerization breaks down plastics into smaller molecules. This process is particularly helpful for excavated plastic garbage, which usually contains impurities that make mechanical recycling challenging [44]. Refuse Derived Fuel (RDF) from excavated plastic debris supports energy recovery and the circular economy by transforming garbage into energy [45]. Despite its benefits, chemical recycling faces financial and environmental hurdles and relies on the pre-treatment of pollutants and wastes[46].

Microorganisms or their metabolites can degrade and assimilate materials, making biodegradation a clean and gentle choice for plastic disintegration [47]. Microorganisms in soil, compost, and marine settings have developed the ability to digest plastic and use it as an energy source due to extended exposure to plastic contaminants [48]. Degradative enzymes in some microorganisms break down polymers neutrally with little energy. The finding of microbes offers a potential alternative to plastic recycling, potentially simplifying the process [49]. In that process, microorganisms stick to plastic, proliferate, and colonize via biofilm development, enzymatic cleavage into shorter molecules, and degrade into low-molecular-weight oligomers, dimers, and byproducts like $CO_2$, water, and methane [50]. Surface hydrophobicity, crystalline architectures, and high melting temperatures prevent microbe adherence and access to receptive polymer areas, limiting plastics' enzymatic breakdown [51].

Anaerobic digestion (AD) is a prominent method for the decomposition of plastic and other organic waste, as well as the production of renewable resources. However, it involves intricate biochemical interactions between anaerobic bacteria and is susceptible to instability under unfavorable conditions [52]. There is a rising apprehension about plastics releasing detrimental monomers and chemicals into the environment, as well as plasticizers and stabilizers leaking and causing contamination [53]. Microplastics (MPs) and nano-plastics (NPs) derived from plastics have the potential to cause harm to organisms and disturb their physiological systems[54]. Additionally, these particles can also transport heavy metals, exacerbating their detrimental effects [55]. Although there are difficulties, the potential advantages of bioplastics in AD are substantial. AD methods transform bioplastics into biogas, thereby contributing to the creation of renewable energy and reducing emissions of greenhouse gases.

### 5.3. Bio-Circular-Green Economy (BCG)

To generate high-value goods and services that are environmentally benign and require less resource inputs while simultaneously protecting natural and biological resources, the BCG economy intends to apply the principles of bioeconomy, circular economy, with green chemistry [56]. This model promotes sustainable practices, extended producer responsibility, and the development of bioplastics that are easier to recycle or compost.

In a move towards BCG, an amendment to PWM-2016, introduced in 2022 by the GoI, targets to reduce plastic pollution by outlawing certain single-use plastics, setting recycling standards, imposing penalties for noncompliance, and setting targets for Extended Producer Responsibility (EPR). In an attempt to target microplastics and set stricter criteria for biodegradable plastics, the PWM-2016 was again amended in 2024 as PWM- -2024, which defines biodegradable plastics, as plastics that break down completely and do not leave behind microplastics, which are harmful pollutants in water. This definition aims to promote the circular economy and move more closely to achieve a BCG economy. The legislation expands the definition of "importer," "manufacturer," and "producer" to encompass a wider range of activities linked to plastic. This amendment mandates, that the manufacturers of compostable and biodegradable plastics obtain certification from the Central Pollution Control Board (CPCB) of GoI, before marketing or selling their products [57].

Over the past few years, corporations and organizations have been making efforts to develop criteria for quantifying circularity in products and activities. However, attaining a consistent global standard is still proving to be difficult. The ISO 59000;2024 series is making substantial progress in developing a standard that specifically addresses product durability, resource utilisation, and lifecycle management. It is crucial to include these circularity indicators to decrease plastic waste production and promote a sustainable, bio-circular green economy[58].

## 6. Industry 5.0 and technological innovations

A new stage in industrial development, known as Industry 5.0 (Ind 5.0), combines human capabilities with cutting-edge technology to improve manufacturing procedures. It emphasizes the needs of people and utilizes innovations such as blockchain (BC), Internet of Things (IoT), robotics, and artificial intelligence (AI) to enhance manufacturing processes [59]. India is tackling the growing plastic waste problem by implementing Industry 5.0 principles and utilizing technological advances like digitization and blockchain. These advancements are leading to substantial improvements in waste management techniques. Numerous technologies have been used to reduce plastic pollution and improve plastic recycling. Blockchain (BC) seems promising for plastic recycling and circular economy (CE) enabling transparent, safe, and decentralized tracking of plastics throughout their lifecycle through watermarking. Digital watermarks save plastic item information such as material, production date, manufacturer, and recycling instructions [60]. This technology enhances supply chain management, guarantees data accuracy, and aids in sustainability initiatives [61].

*Recycle*, a digital technology company based in Hyderabad has developed a comprehensive and automated digital solution that improves transparency and efficiency throughout the waste management process for achieving the objective of EPR. This platform is cloud-based and covers the entire waste management value chain, connecting waste generators, collectors, and recyclers, enabling smooth transactions and encouraging recycling. This implementation has resulted in a significant increase in the amount of waste processed, with daily volumes rising from 20 to 30 kg initially to over 10,000 to 15,000 kg in recent times[62]. An Android application has been developed to facilitate the effective collection of plastic waste through pick-up or drop-off services. This innovation not only improves the effectiveness of collecting and classifying waste plastic but also promotes recycling by providing incentives, such as e-coupons, to encourage people to recycle [63]. The decentralized architecture and minimal transaction expenses of blockchain, together with its associated advantages of easy access, continuous availability, and incorruptible frameworks, can be effortlessly integrated with artificial intelligence tools. The goal of integrating AI into this multi-sensor architecture is to minimize ambiguity and facilitate reliable discrimination by teaching the system to precisely detect and differentiate them [64]. *Swachhcoin* is one program that uses BC technology and AI tools powered by multiple sensors to efficiently handle and transform household and industrial waste into valuable resources to improve plastic recycling and advance the circular economy. This method uses a combination of techniques to generate a sequential and recurring sequence that relies on information sharing between different ecosystem participants. The system analyses the inputs and generates useful recommendations using descriptive algorithms, ultimately allowing it to become self-sustaining, cost-efficient, and financially rewarding[65].

## 7. Conclusion

To address the global issue of plastic pollution, it is imperative to engage in interdisciplinary research and make significant improvements in biotechnology. To design efficient waste management systems that support a circular economy, it is crucial to have a comprehensive understanding of the production processes, characteristics, and environmental impacts of bioplastics. This knowledge allows us to incorporate technical advancements and effectively manage bioplastic waste. These initiatives promote environmental sustainability, generate new economic prospects, and are in line with global sustainability objectives. To mitigate the harmful effects of plastic pollution and to promote a more sustainable future, it is vital to implement waste management systems that are effective and that take into account the various components that are included in the waste stream.

## Compliance with ethical standards

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No conflict of interest to be disclosed.

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