ANALYSING CHALLENGES AND OPPORTUNITIES FOR THE ADOPTION OF BIODEGRADABLE PLASTICS

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ABSTRACT

The increasing environmental concerns related to plastic pollution have greatly focused attention on biodegradable plastics as a promising alternative. However, large-scale applications are facing significant challenges due to technological, regulatory, and market-related problems. This paper identifies the major challenges and opportunities in large-scale applications of biodegradable plastics in terms of material performance, production viability, policy framework, and economic feasibility. It discusses the weaknesses of biodegradable plastics that include weakness in strength, durability, and degradation efficiency and recent advances in biotechnology and polymer science to improve the properties of these biodegradable plastics. This research also identifies significant opportunities for incorporating biodegradable plastics into many industries, including packaging, agriculture, and healthcare. The study puts forward the fact that the adoption of a circular economy will not be possible unless interdisciplinary collaboration, policy incentives, and technological innovation overcome the associated challenges. Conclusion The paper suggests future research directions and policy initiatives to ensure that biodegradable plastics can be used sustainably worldwide.

Keywords: Biodegradable Plastics, Sustainable Materials, Plastic Pollution, Environmental Impact.

1. INTRODUCTION

Plastic pollution has reached alarming proportions, significantly impacting the environment since conventional, non-biodegradable plastics are now being used abundantly. Plastics are basically derived from petrochemical sources and are very resistant to natural degradation processes. Therefore, these plastics remain for centuries in landfills, water bodies, and ecosystems. They have thus begun to accumulate in oceans, rivers, and land, posing massive hazards to both marine and terrestrial wildlife[1]. Animals, especially marine animals, have been found to consume plastic wastes, thinking that they are food, and eventually suffer from malnutrition, asphyxiation, or even death. Secondly, plastic pollution interferes with the natural cycle of soil and water and accelerates the movement of pollutants and invasive species in the environment. One of the most dangerous microplastics products is from the gradual degradation of larger plastic objects into smaller particles that are smaller than 5 millimetres in diameter, and are generally referred to as microplastics. Microplastics can be found almost anywhere on Earth; this includes isolated regions like deep sea and arctic areas [2]. They can be found in the air, as well as in drinking water and as contents in our food, which gives rise to the question of human health impacts. Microplastics also present a special risk to marine organisms as they can absorb toxic chemicals from their environmental surroundings, which are subsequently introduced into the food chain with associated higher concentrations at higher trophic

ISSN: 2278-4632
Vol-14, Issue-12, December: 2024

levels, thereby reaching humans. The scale of plastic production has worsened these problems. Global plastic production had crossed 368 million metric tons a year and would only increase over the coming decades. This is the widespread use of plastics without proper waste management systems, causing a global crisis. In most regions, collection and recycling facilities for waste are insufficient, hence leading to the improper disposal of plastic waste. Even in regions with already in place recycling systems, the amount of plastic waste that is actually recycled is so minimal that the remaining amounts mostly end up in landfills or get burnt, contributing to greenhouse gas emissions and air pollution [3].The challenges highlighted above have led to growing recognition of the need for sustainable alternatives in replacing conventional plastics. Such growing recognition has shaped the prominence of biodegradable plastics as a promising solution to this challenge. Biodegradable plastics, unlike traditional plastics, degrade naturally by microbial processes into non-toxic byproducts such as carbon dioxide, water, and biomass. These materials hold huge potential for cutting down the footprint of plastic wastes, especially under appropriate conditions for industrial composting[4].Biodegradable plastics are often sourced from renewable sources, including corn starch, sugarcane, and cellulose. They are, therefore, less bad for the environment compared to plastics based on petrochemicals. These include forms like PLA (poly lactic acid) and PHA (polyhydroxyalkanoates), which have become more popular in packaging, agriculture, and other fields due to a lower environmental impact. Proper production and disposal of biodegradable plastics will help decrease dependence on fossil fuels, minimize greenhouse gas emissions, and bring the world closer to a circular economy. There are, however several challenges which plague biodegradable plastics in widespread use. For instance, the biodegradation process often requires specific environmental conditions, like high temperatures and moisture levels. Many biodegradable plastics need industrial composting facilities to fully break down, and these facilities are not universally available [5]. Consequently, in the event of landfills or even in nature, biodegradable plastics will not degrade like it is desired. This therefore implies that, it causes damage to the environment, just like regular plastics do. In addition, the process of making biodegradable plastics might be much resource-intensive and costly than those made of ordinary plastics. Agricultural crops, such as corn and sugarcane, that are used for feedstock can compete with food production, cause land use conflicts, and result in increased water consumption. Biodegradable plastics also need proper management in their degradation process, as microplastics may be formed and these can still present environmental hazards, even if the plastic is engineered to degrade.

Biodegradable plastics play a tremendous role in saving the world against plastic pollution across the globe and providing an effective alternative to current petroleum-based plastic products. However, unlike general plastics, whose presence in an environment can prevail for hundreds or thousands of years, bioplastics are moulded to break biologically through natural microbial activity for their final contribution to water and carbon dioxide formation with biomass leftovers[6]. This decomposition process leads to a remarkable reduction in plastic waste accumulation within landfills, oceans, and natural ecosystems; thus, environmental hazards due to plastic pollution would be minimized for a long term. Biodegradable plastics decompose under definite environmental conditions that make them potential solutions for managing waste sustainably and conserving resources. The importance of biodegradable plastics goes beyond waste reduction: they also play a role in reducing carbon emissions and decreasing fossil fuel dependence. Most biodegradable plastics come from renewable sources such as corn starch, sugarcane, and potato starch, making it an eco-friendlier alternative than traditional plastics made from petroleum-based raw materials [7]. The trend towards bio-based plastic production contributes to the reduction of greenhouse gases in plastic manufacturing and disposal with climate change mitigation. Also, the production of biodegradable plastics promotes the development of circular economy, in which materials are created for reusing, recycling, or natural decomposition, thus promoting sustainability in industrial and consumer use[8].The third major benefit of biodegradable plastics is their potential to change the industries dependent on disposable plastic products. These include food packaging, agriculture, and healthcare, among others. For instance, in agriculture, biodegradable mulch films eliminate the collection of plastic wastes after harvest. This saves labour costs and the environment. Biodegradable sutures and drug delivery systems for medical applications contribute to safe internal breakdown and help prevent the necessity of surgical removal, hence the amount of waste produced. Another industry is the packaging sector; biodegradable alternatives in single-use plastics will help to eliminate pollution that hinders human beings, especially with food and beverages packaging that comprises a great proportion of global plastic waste. Although biodegradable plastics have several advantages, their successful use is contingent upon improvements in waste management infrastructure and public awareness. Many biodegradable plastics need specific environmental conditions, such as high temperatures and moisture levels, to decompose properly. In the absence of industrial composting facilities, these materials may not decompose effectively, and their disposal will be problematic, just like conventional plastics. Therefore, proper labelling, disposal systems, and supportive policies are required for biodegradable plastics to actually deliver the desired environmental benefits[9].

2. TECHNOLOGICAL CHALLENGES AND INNOVATIONS

Despite the environmental advantages of biodegradable plastics, they are often handicapped by the materials' weakness, non-durability, and usability compared to traditional petroleum-derived plastics. A majority of biodegradable polymers, such as PLA and PHA, usually have inferior mechanical strength and thermal resistance that cannot be used in applications requiring high performance, for example, automobile components, construction materials, and heavy-duty packaging. In addition, brittleness and reduced flexibility further limit their use in industries where robust and durable plastic materials are required. Other significant disadvantages are their performance in different environmental conditions[10]. Biodegradable plastics may, in such environments, degrade prematurely, thereby compromising stability upon storage and transportation. On the other hand, in conditions without optimal microbial activity, oxygen, and moisture, the materials may take much longer to degrade while degrading, making it much less effective as an alternative of sustainability. In addition, their use is limited by cost factors since most of the biodegradable plastics are still more expensive to produce than regular plastics on account of high costs associated with raw material and processing. To overcome these challenges, researchers and manufacturers have developed improved formulations of biodegradable plastics that increase the strengths, flexibility, and thermal stability of materials. The types of mechanical properties modified in biodegradable plastics include the incorporation of plasticizers, reinforcing fibres, and polymer blends. For example, the introduction of polycaprolactone or starch-based polymers into PLA improves flexibility and impact resistance for applicability in packaging materials[11]. Moreover, the nano-enhanced biodegradable plastics with the reinforcement of nanocellulose or graphene provide excellent strength, barrier property, and biodegradability without losing any sustainability. One of the emerging trends is in the production of biodegradable polymers where degradation rates could be tuned as per environmental condition. Scientists have been engineering plastic materials that break down at specified rates under set environmental conditions ensuring optimal performance under use while getting broken down once disposed of effectively. For instance, water-soluble biodegradable plastics have the potential of reducing waste issues in medical and agricultural applications. Biodegradable coatings for food packages are also being researched to improve shelf life but guarantee eco-friendly disposal. Improvement of degradation efficiency for biodegradable plastics is crucial, and with biotechnology and microbial engineering, people are exploring ways such as genetically engineered microorganisms and enzymes that can significantly break down plastics under natural conditions. For example, certain bacterial species like Ideonellasakaiensis have been capable of breaking down polyethylene terephthalate or PET; with such development, bioengineered remediation for plastic waste is now being explored [12].Recently, enzyme engineering advances have yielded highly efficient plastics degrading enzymes like PETase and cutinase, among others, and degrades it much faster, even into their monomeric constituents. Some of the present concepts under scrutiny also include 'enzyme-coated plastics' to further embed in them biodegradable materials comprising microbial or enzymatic agents within these plastics such that they self-destruct upon getting discarded. The synthetic biology approach in the future might be applied for the production of biodegradable plastics, not only efficiently decomposing but also contributing to the circular economy. The engineering of microbes for converting biodegradable plastic waste into valuable bio-based chemicals or new bioplastics is envisioned by researchers as a self-sustaining system with minimal waste and maximum resource efficiency. Though strength, durability, and usability of biodegradable plastics remain limited, continuous development in material formulations and biotechnological advances rectify the shortcomings. Reinforced polymers, nano-additives, and enzyme-based degradation technologies may further drive the feasibility of biodegradable plastics for a large number of applications. Eventually, through research and industrial collaboration, biodegradable plastics might become a mainstream alternative for consumers and industry to address the environmental issue without loss of convenience [13].

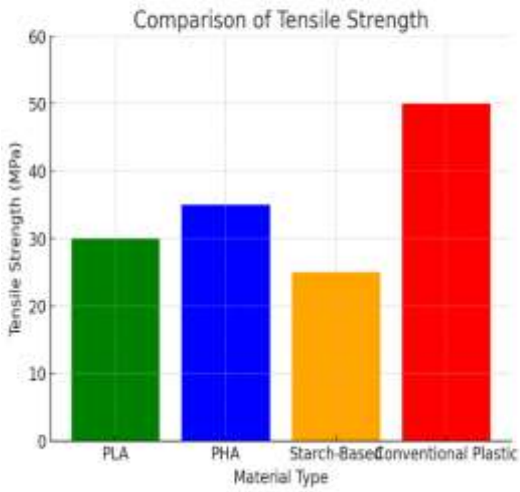

Fig: Comparison of Tensile Strength (Biodegradable vs. Conventional Plastics)

3. REGULATORY AND POLICY FRAMEWORK

With growing concerns of plastic pollution around the world, governments have recently established policies and regulations to develop and use biodegradable plastics. The key idea is that such policies minimize reliance on traditional plastics while setting standards for environment-friendly and performing biodegradable alternatives. The European Union promotes the acceptance of biodegradable and compostable plastics and clearly guides disposal and environmental consequences through the European Green Deal and the Circular Economy Action Plan. The EU Single-Use Plastics Directive demands restrictions on the use of plastic products in select categories and hence nudges various industries toward adoption of biodegradable products. China has followed a

ISSN: 2278-4632
Vol-14, Issue-12, December: 2024

phase-wide ban on the use of non-degradable plastic bags, creating incentives for producing bioplastic. Composting plastics are supported in the United States, state by state. California is particularly strong in labelling laws and waste management policies that encourage the use of compostable plastics. In many developing countries, India being one, single-use plastics have been banned, and alternative biodegradable solutions are still being explored. One of the problems with the global policy on this issue is that there are no uniform laws, which would cause confusion within the industry. While some focus on composability, others put much emphasis on biodegradability in marine or recyclability. Global regulation harmony will play an important role in the adoption and environmental impact of biodegradable plastics.

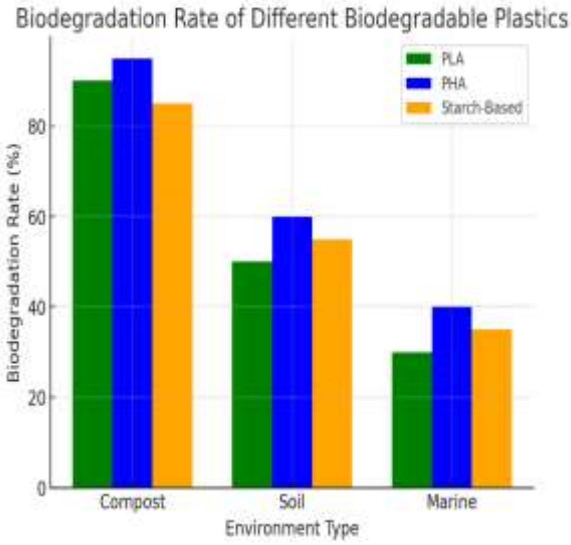

Fig: Biodegradation Rate of Different Biodegradable Plastics

Certification Standards and Compliance (ASTM, ISO, EN Standards)

Numerous international organizations have set certification requirements to guarantee biodegradable polymers fulfil performance and environmental criteria:

- ASTM International (American Society for Testing and Materials): ASTM D6400 is the standard which ensures that plastics can be certified compostable under industrial conditions. This standard defines standards for the biodegradation rate, disintegration, and nontoxicity. ASTM D6868 covers biodegradable coatings on paper and other products.
- ISO (International Organization for Standardization): The testing procedures for figuring out plastics' ultimate aerobic biodegradability under regulated composting conditions are outlined in ISO 14855. Biodegradability in soil, marine, and anaerobic settings is defined by other ISO standards.
- EN (European Norm) Standards: The main European standard for biodegradable plastics is EN 13432, which mandates that polymers must decompose in six months under industrial composting settings without leaving any hazardous residues.

Hence, compliance with all these certification standards is essential, as biodegradable plastics acquire consumer trust only when they find the products manufactured by companies upholding the correct national and international standards to abstain from deceitful environmental labels.

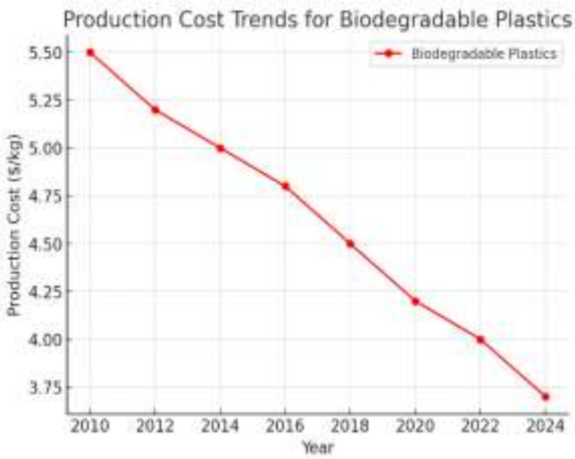

Fig: Production Cost Trends for Biodegradable Plastics

Role of Government Incentives and Subsidies in Promoting Adoption

Governments can motivate the use of biodegradable plastics with fiscal incentives, subsidies, and grants for research. Most countries offer tax cuts, subscriptions, or even subsidies on bio-based feedstock and funding for innovation on biodegradable plastic technology. Most recently, Horizon Europe in the European Union funded projects oriented toward research into sustainable alternatives for plastics. The United States grants funds under the Biorefinery Assistance Program to develop bio-based and biodegradable products. China implements financial incentives in the form of tax breaks or other incentives to companies investing in biodegradable packaging as part of its wide-ranging environmental agenda. Besides these direct financial incentives, governments provide incentives through the green procurement policies. Many institutions today prefer using biodegradable and compostable materials in purchases, thereby raising demand in the market. But the incentives can be effective only when they go with well-designed waste management systems. Without the infrastructure for composting or biodegradation, the biodegradable plastics can again end up in landfills and reduce their environment-friendly value. Future policies would be focusing both on the production incentives and effective disposal pathways that maximize the sustainable benefits. International regulations, standards for certification, and incentives at the governmental levels are essential drivers of the biodegradable plastics industry. While policies encourage the use of sustainable alternatives, there is the challenge of the lack of harmonized regulations. Certification standards have ensured the credibility of products, but implementation and enforcement are lacking. Government incentives are in support of adoption, but need to be matched by infrastructure in waste management. Implementation would be a comprehensive approach that integrates policy, industry cooperation, and technological advancements.

4. MARKET CHALLENGES AND ECONOMIC VIABILITY

The shift from traditional plastics to biodegradable plastics has challenged the economic and market environments involved. One of the key limitations is the cost inefficiency differential between biodegradable plastics and their petroleum-based counterparts. Biodegradable plastics are often more costly due to high raw material costs, complex processes in manufacturing, and low volumes of large-scale manufacturing production. Moreover, the logistics of supply chains for biodegradable plastics pose challenges relating to material access, production economies of scale, and distribution infrastructures. Consumer perception also comes into play because of the rapid acceptance of biodegradable plastics. As a result of heightened environmental awareness, many consumers continue to be fearful due to prices and doubts surrounding the durability and performance of biodegradable plastics. Misunderstandings associated with biodegradability as well as biodegradable materials disposal are the other reasons hampering the markets. Governments as well as bodies of regulations now offer incentives and subsidies as well as mandates toward the use of biodegradable plastics. However, technical developments and effective manufacturing techniques are still required to meet the crucial issue of economic viability.

Table: Cost Comparison of Biodegradable Plastics vs. Conventional Plastics

Plastic Type	Average Cost (per kg) in USD	Production Complexity	Market Availability
Conventional Plastics	$1.00 - $1.50	Low	High
Polylactic Acid (PLA)	$2.50 - $3.50	Moderate	Moderate
Polyhydroxyalkanoates (PHA)	$4.00 - $5.50	High	Low
Starch-Based Plastics	$2.00 - $3.00	Moderate	Moderate

ISSN: 2278-4632
Vol-14, Issue-12, December: 2024

Polybutylene Succinate (PBS)	$3.50 - $4.50	High	Low

The table indicates that biodegradable plastics are more expensive to produce than traditional plastics. The production processes of materials such as PHA and PBS are highly complex, and the manufacturing infrastructure is not developed enough. In order to be competitive with conventional plastics, the cost of biodegradable alternatives must be lowered through improved technology and economies of scale.

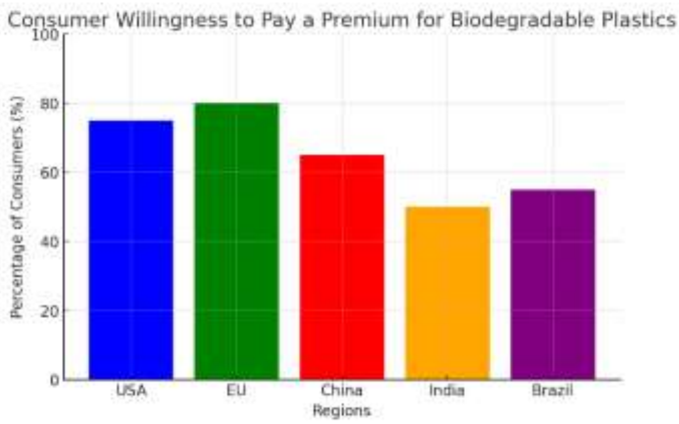

Fig : Consumer Willingness to Pay a Premium for Biodegradable Plastics

The following bar chart details the percentage of consumers in different regions, who are willing to pay a premium for biodegradable plastics. The regions with the highest percentage have turned out to be the EU and USA, with 75-80% willingness, where there is excellent environmental awareness and regulatory support, while Indian and Brazilian percentages were down at 50-55%. This may be attributed to their price sensitivity and lack of wider adoption. This analysis is on the opportunities and challenges for economic viability within the market and emphasizes the cost reduction, supply chain infrastructure improvement, and education of consumers as a way of increasing the usage of biodegradable plastics.

5. OPPORTUNITIES FOR WIDESPREAD ADOPTION

One opportunity for sustainable development lies in the integration of biodegradable plastics into circular economies and waste management strategies. Biodegradable plastics contrast with conventional plastics, which create long-term environmental pollution. Biodegradable plastics are developed in such a way that they can fit into a closed-loop system in the decomposition cycle or be converted into new materials. Efficient waste management techniques, including composting facilities, enzymatic recycling, and improved biodegradation infrastructure, will make them more efficient and less dependent on landfills. The government and private sectors must join hands to construct effective collection, sorting, and processing systems to ensure that these materials reach the right end-of-life solutions instead of piling up as waste. Biodegradable plastics have vast potential applications in various sectors, such as packaging, agriculture, and healthcare. In the packaging industry, they can replace one-time plastics thus reducing plastic wastes in food and beverage containers, shopping bags, and disposable utensils. Agriculture mulch films may decrease the contamination of soils while enhancing growth. Bioplastics are set to be developed in the area of healthcare biodegradable sutures, drug delivery systems, and medical packing, which eliminate hazardous waste. Diversification into industries such as automobiles, electronics, and textiles is a potential step for increasing the demand for alternatives made from sustainable plastics. Much research and development need to be undertaken to combat current challenges plaguing biodegradable plastics; such challenges include costs, low performance, and less efficient rates of degradation. Improvement in strength and flexibility due to nanotechnology or microbial engineering for biopolymer synthesis increases the chances for extensive use of biodegradable plastics. Government incentives, private sector investments, and public awareness initiatives can promote the transition towards sustainable alternatives faster, thereby setting up a market for biodegradable plastics in the future.

6. ENVIRONMENTAL AND SUSTAINABILITY CONSIDERATIONS

The use of biodegradable plastics has a tremendous impact on the environment, especially concerning their impact on ecosystems and soil and marine environments. While conventional plastics remain in the environment for hundreds of years, biodegradable plastics are indeed planned to break down under specific conditions. They can limit long-term contamination and thus make a promising alternative for various uses of plastics such as mulch films and seed coatings for soil ecosystems. However, their degradation depends highly on the environmental factors: temperature, humidity, and microbial activity. Marine environments, with plastic pollution rapidly becoming a global crisis, promise relief through biodegradable plastics, but still remain uncertain for effectiveness. Some of the biodegradable plastics are known to break down into micro-particles that may cause harm in aquatic environments. The most significant sustainability concern is the potential for microplastic formation and incomplete degradation. Biodegradable plastics are promoted as the greenest option. However, the process of their degradation is not uniform or complete. Some biodegradable plastics need industrial composting conditions with high temperatures and specific microbial communities to decompose fully. They can degrade partially in natural environments without proper disposal measures, creating microplastics that still pose risks to marine life and soil health. This shows the need for clear marking, adequate waste management, and advanced degradation technologies in ensuring that biodegradable plastics live up to their intended environmental advantages. Biodegradable plastics have long-term benefits in that they help reduce carbon footprint and plastic pollution. Production through renewable resources like plant-based polymers, starch, and algae also lowers greenhouse gas emissions since it is not based on petroleum. In addition, better waste disposal approaches, such as composting, enzymatic degradation, and microbial treatments, can make them sustainable because they break down completely. This has the potential of reducing the level of plastic wastes in landfills and oceans since the use of biodegradable plastics is relatively widespread if it is well-managed. But for these benefits, it would have to be done holistically - advancement in the technology of biodegradable material, regulatory support, and consumers' awareness toward responsible use and disposal.

7. FUTURE PROSPECTS

The future of the biodegradable plastics will essentially depend on countering key aspects such as expense, scalability, regulation, and technological advancement over time. Following are a number of strategies available to make its mass use ensure and sustain with time. Mainly, overcoming the problem to become cost-efficient and scalable for large-scale industries is a dire need. Biodegradable plastics are much costlier than traditionally petroleum-based plastics due to high manufacturing costs, a raw material that is not readily available and only under specific conditions can degrade. Bioprocessing and material engineering in polymer synthesis is much needed for competitive biodegradable plastics. Scaling up of production through biorefineries, waste agriculture utilization, advanced biopolymer engineering will significantly cut costs to improve the access to plastics, while investment into efficient supply logistics and global hubs for manufacturing seems critical to fully enter the markets. Enhancing regulatory policies further will also be necessary to improve better market adoption. Tax benefits, subsidies, and even stiffer regulations on the use of traditional plastics can be incentivized by governments and international organizations. Mandatory composability standards, certification for biodegradability under improved standards, including ASTM, ISO, and EN standards, along with transparent waste management standards will push industries as well as consumers toward these green alternatives. In the latter aspect, adoption will be higher, and consequently, the damage caused to the environment will also be lower, for countries incorporating biodegradable plastics into national policies on sustainability. Lastly, it is in interdisciplinary research where the technological obstacles are going to be overcome. This requires collaboration between material scientists, biotechnologists, chemists, and environmental policymakers to develop the next generation of biodegradable plastics with better strength, optimized degradation rates, and a lower ecological footprint. The discovery of new enzymes and bacteria through synthetic biology and microbial engineering can lead to efficient plastic degradation under diverse environmental conditions. Another direction of integration would be AI and data analytics with material science. This would facilitate faster development of customized biopolymers for specific industrial uses with enhanced performance. The future of biodegradable plastics would thus be governed by a holistic approach that takes into account breakthroughs in technology, regulatory encouragement, and economic incentives. Addressing the current limitations and considering the assistance from innovation, biodegradable plastics can be mainstreamed as an environmentally friendly, sustainable alternative and minimize the consumption of fossil fuel-based plastics so that environmental pollution for the foreseeable generations can be prevented.

8. CONCLUSION

These analyses involve a complex discussion of how the adoption challenges and opportunities from biodegradable plastics are discussed. Although an alternative to synthetic plastics, challenges in the introduction of these new materials include such technological, legal, and cost barriers that remain to be settled. The important limitations include mechanical strength, long-term durability and efficiency of breakdown, as well as the enhancements in biotechnologies and in polymer science made to improve functions. In addition, government policies and certification standards on regulatory frameworks together with financial incentives accelerate market adoption. Lastly, opportunities for using biodegradable plastics in different industries such as packaging, agriculture, and health care are weighed against the importance of strategic research and development investment that would have to be undertaken. It suggests the need for collaboration between science, policy makers, and industries in order to make innovation towards a sustainable way of waste management. Future work must be centered on cost efficiency, biodegradation efficiency improvement, and effective regulation at global levels. When these challenges are overcome and such opportunities are well harnessed, biodegradable plastics could have a substantial impact on diminishing plastic pollution, as well as encouraging a sustainable and circular economy.

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