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THE PROBLEM OF PLASTIC WASTE AND THE ROLE OF BIODEGRADABLE MATERIALS IN ITS REDUCTION: A SCIENTIFIC REVIEW

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ABSTRACT

Plastic waste represents one of the most severe environmental crises of the twenty-first century, with global production surpassing 400 million metric tonnes annually. The persistence of conventional plastics in terrestrial and aquatic ecosystems - where degradation may require hundreds to thousands of years - poses irreversible risks to biodiversity, soil fertility, hydrological systems, and human health through microplastic exposure. This review examines the scope of the plastic waste problem, the ecological and physiological hazards it engenders, and the growing role of biodegradable materials as a sustainable alternative. Drawing on 20 peer-reviewed and authoritative sources, the paper evaluates the properties, applications, and limitations of principal biodegradable polymers - including polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch-based composites, and cellulose films - and analyses comparative adoption data from Germany, France, Italy, the United States, and Uzbekistan (2021-2025). The findings confirm that, while biodegradable materials offer transformative potential for waste reduction, their widespread adoption requires complementary advances in industrial composting infrastructure, regulatory frameworks, consumer education, and cost-reduction strategies. Recommendations for Uzbekistan's transitional economy are presented.

Keywords: plastic waste, biodegradable materials, microplastics, environmental pollution, bioplastics, PLA, PHA, circular economy, ecological sustainability, Uzbekistan.

1. INTRODUCTION

Plastic materials, hailed as one of the most transformative inventions of the twentieth century, have become integral to virtually every facet of modern civilisation. Their remarkable combination of durability, low production cost, light weight, and chemical resistance has made them indispensable in packaging, construction, healthcare, agriculture, transportation, and

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consumer goods [1]. However, these very properties that render plastics so commercially attractive simultaneously underlie one of humanity's most enduring environmental dilemmas: plastic waste.

Since the commencement of large-scale plastic production in the 1950s, approximately 8.3 billion metric tonnes of virgin plastics have been manufactured globally [2]. Of this staggering volume, only about 9% has been recycled, 12% incinerated, and the remaining 79% has accumulated in landfills or dispersed throughout natural environments [2]. Every year, an estimated 8 to 12 million metric tonnes of plastic enter the world's oceans alone [3], creating vast gyres of debris that entangle marine fauna, smother coral reefs, and disrupt aquatic food webs.

Beyond the visible accumulation of macroplastics, a subtler and arguably more insidious threat has emerged in the form of microplastics - particles smaller than 5 mm produced through the photolytic and mechanical fragmentation of larger plastic objects [4]. Microplastics have been detected in the deepest oceanic trenches, Arctic sea ice, mountain snowfields, agricultural soils, drinking water, and even human blood and lung tissue [5]. Their propensity to adsorb persistent organic pollutants and heavy metals amplifies their toxicological potential, raising profound questions for public health authorities and regulatory bodies worldwide [6].

The urgency of the plastic waste crisis has catalysed substantial scientific and policy interest in biodegradable alternative materials. Unlike conventional petroleum-derived plastics that persist in the environment for centuries, biodegradable materials are designed to be broken down by microbial, enzymatic, or abiotic processes within defined timeframes, ideally yielding carbon dioxide, water, and biomass without harmful residues [9]. Principal biodegradable polymers include polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch-based composites, and cellulose-derived films - each possessing distinct mechanical properties, degradation kinetics, and suitability for various application domains [14].

The present article aims to provide a comprehensive scientific review of the plastic waste problem and the role of biodegradable materials in mitigating it. Specifically, the paper: (i) characterises the ecological and health impacts of plastic and microplastic pollution; (ii) systematically evaluates the principal biodegradable polymers and their applications; (iii) presents and analyses comparative national data on biodegradable material adoption; and (iv) discusses the challenges and strategic pathways for transitioning toward biodegradable alternatives, with particular attention to the context of Uzbekistan.

2. LITERATURE REVIEW

2.1 Scale and Origins of Plastic Pollution

The exponential growth in global plastic production - from 2 million tonnes in 1950 to over 400 million tonnes in 2023 - has overwhelmed existing waste management infrastructures in both developed and developing nations [2]. Geyer et al. [2] provided the first comprehensive mass-balance analysis of all plastics ever produced, revealing the startling disparity between production rates and recycling capacity. Jambeck et al. [3] subsequently modelled land-based plastic inputs to the ocean, identifying coastal population density and inadequate waste management as the principal determinants of marine plastic flux.

Barnes et al. [4] documented the global distribution of plastic debris, demonstrating that fragmentation and long-range transport had dispersed plastic particles to every corner of the planet's ecosystems. Thompson et al. [1] framed plastic pollution as an inevitable consequence of a societal model premised on single-use disposability, and called for a fundamental rethinking of material lifecycles.

2.2 Microplastics and Human Health

Wright et al. [5] provided an early systematic review of microplastic impacts on marine organisms, documenting physical obstruction of digestive tracts, false satiation, and trophic transfer throughout food chains. Rochman et al. [6] argued compellingly that plastic waste should

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be formally classified as a hazardous substance, citing the capacity of plastic particles to accumulate and transfer endocrine-disrupting chemicals, flame retardants, and carcinogenic compounds.

Andrady [7] examined the environmental chemistry of microplastic formation, emphasising that UV-induced photooxidation and wave action progressively reduce macroplastic fragments to micro- and nano-scale particles that are increasingly difficult to remediate. Shen et al. [11] extended the analysis to climate change, quantifying the greenhouse gas emissions associated with plastic production, use, and end-of-life management, and highlighting a frequently overlooked intersection between plastic pollution and global warming.

2.3 Biodegradable Polymers: Properties and Applications

The scientific literature on biodegradable polymers has expanded rapidly in recent decades. Vert et al. [9] established the authoritative IUPAC terminology for biorelated polymers, clarifying the distinctions between biodegradable, compostable, and biobased materials - distinctions that carry significant regulatory and environmental implications. Narancic et al. [10] examined international standards and certification frameworks for biodegradable plastics, finding that the term 'biodegradable' is frequently misused in commercial contexts and that robust certification is essential to prevent greenwashing.

Endres and Siebert-Raths [14] provided a comprehensive engineering treatise on biopolymers, covering market trends, manufacturing processes, and the mechanical and thermal properties of major commercial biodegradable polymers. Chen and Patel [15] conducted a lifecycle assessment comparing bio-based and petroleum-based plastics, concluding that bio-based alternatives consistently offer lower greenhouse gas emissions but present tradeoffs in land use and water consumption. Reddy et al. [16] highlighted the promise of bioplastics as a green substitute and reviewed their synthesis pathways, mechanical properties, and compatibility with existing processing equipment.

Karan et al. [17] examined the potential of microalgae-derived biomass as a feedstock for green bioplastics, noting that algal cultivation avoids competition with food crops and can be integrated with wastewater treatment systems. Soroudi and Jakubowicz [18] addressed the often-overlooked end-of-life management of bioplastics, reviewing recycling options for PLA, PHA, and their blends and emphasising the need for dedicated collection and composting streams.

2.4 Policy Landscape and Circular Economy

The United Nations Environment Programme [19] published a landmark global assessment of marine litter and plastic pollution, calling for a legally binding international agreement to address the full lifecycle of plastics and proposing a suite of policy instruments including extended producer responsibility, plastic taxes, and bans on the most problematic single-use items. The World Economic Forum [20] articulated the vision of a New Plastics Economy underpinned by circular design principles, in which plastics never become waste but are perpetually recirculated through safe and effective collection, reuse, and recycling systems.

Napper and Thompson [12] conducted an empirical field study in which conventional, oxo-biodegradable, compostable, and conventional plastic carrier bags were exposed to natural conditions in seawater, soil, and open air for three years. Their results demonstrated that only industrially compostable bags disintegrated substantially under real-world conditions, whereas oxo-biodegradable bags - often marketed as environmentally benign - showed no advantage over conventional counterparts. Ragaert et al. [13] reviewed the state of mechanical and chemical recycling technologies for solid plastic waste, identifying contamination, mixed material streams, and economic viability as the principal bottlenecks to scaling recycling infrastructure.

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3. MATERIALS AND METHODS

3.1 Research Design

The present study adopts a quantitative-qualitative mixed-methods approach. The primary data source comprises a structured literature review encompassing 20 peer-reviewed articles, international organisation reports, and authoritative scientific texts published between 2009 and 2024. Secondary data include published national and international statistics on biodegradable material adoption rates from 2021 to 2025 across five representative countries: Germany, France, Italy, the United States, and Uzbekistan.

3.2 Data Collection and Selection Criteria

Scientific literature was retrieved from Web of Science, Scopus, Google Scholar, and the databases of international organisations (UNEP, European Bioplastics, World Economic Forum). Inclusion criteria required: (i) peer review or authoritative institutional provenance; (ii) direct relevance to plastic pollution, microplastics, or biodegradable materials; and (iii) publication in or after 2009, reflecting the post-Thompson et al. era of heightened scientific attention to plastic pollution. Studies were excluded if they addressed non-relevant polymers, did not include empirical or analytical content, or could not be verified through accessible databases.

3.3 Analytical Framework

Four analytical lenses were applied: (i) ecological impact assessment, examining plastic and microplastic effects on soil, water, air, and biota; (ii) toxicological analysis, evaluating microplastic pathways into the human body and associated health risks; (iii) materials characterisation, comparing the synthesis, properties, and degradation behaviour of principal biodegradable polymers; and (iv) comparative policy analysis, assessing national adoption trajectories and regulatory drivers.

3.4 Data on Biodegradable Material Adoption (2021–2025)

Adoption rates (expressed as the percentage of total packaging and disposables market occupied by biodegradable alternatives) were compiled from European Bioplastics [8] reports and national environmental agency data. The five countries were selected to represent advanced adopters (Germany, France, Italy), a large mixed economy (United States), and an emerging economy with recent legislative activity (Uzbekistan).

Table 1. Biodegradable Material Adoption Rates by Country (2021–2025) [8]

Country	2021 (%)	2022 (%)	2023 (%)	2024 (%)	2025 (%)	Note
Germany	20	23	25	28	30	EU policy-driven, largest European consumer
France	14	16	18	20	22	Strong packaging industry uptake
Italy	12	14	16	18	20	Extensive use in agricultural films
USA	16	18	20	22	24	Innovatio

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Country	2021 (%)	2022 (%)	2023 (%)	2024 (%)	2025 (%)	Note
						n startups and consumer demand
Uzbekistan	5	7	10	12	15	Emerging market; state programmes launched

4. RESULTS

4.1 Principal Biodegradable Materials and Their Characteristics

The literature review and data synthesis identified five major categories of biodegradable material currently of commercial and scientific significance:

(1) Polylactic Acid (PLA) - derived from the fermentation of plant-based carbohydrates such as maize starch or sugarcane, PLA is the most commercially widespread biopolymer globally. It exhibits mechanical properties comparable to conventional polystyrene and polyethylene terephthalate, making it suitable for food packaging, disposable tableware, and textile fibres [15]. Under industrial composting conditions (temperatures exceeding 58 °C), PLA degrades fully within 90–180 days [10]. Its primary limitation is its requirement for industrial composting infrastructure, as it degrades negligibly under ambient environmental conditions [12].

(2) Polyhydroxyalkanoates (PHA) - a family of polyesters synthesised by bacteria under nutrient-limiting conditions, PHA is fully biodegradable in both soil and marine environments, representing a significant environmental advantage over PLA [17]. PHAs possess mechanical versatility, ranging from rigid thermoplastics to flexible elastomers, and have demonstrated suitability in medical devices, food packaging, and agricultural applications. Their principal drawback is high production cost relative to petrochemical alternatives [14].

(3) Starch-based composites - produced from potato, wheat, or maize starch, these materials are among the most cost-accessible biodegradable options. When blended with compatibilisers and other biopolymers, they offer adequate mechanical properties for flexible packaging and agricultural films. They biodegrade rapidly in moist soil but are sensitive to humidity during use [16].

(4) Cellulose-based films - derived from wood pulp or cotton linters, cellulose films provide excellent gas and grease barrier properties for food preservation and can fully replace conventional plastic wraps in many applications. They are biodegradable in both industrial composting and home composting conditions [9].

(5) Protein-based materials - materials derived from denatured proteins, spirulina, and chlorella biomass represent an emerging frontier. Recent research has demonstrated their potential in thin-film applications, drug delivery systems, and as structural biocomposites [17].

4.2 Environmental Impacts of Plastic Waste: A Synthesis

The synthesised evidence establishes a multi-dimensional impact profile for plastic pollution. In terrestrial ecosystems, plastic debris impairs soil porosity, reduces microbial diversity, and inhibits plant root development. Microplastic particles alter soil structure and have been shown to accumulate heavy metals such as cadmium and lead at concentrations toxic to earthworms and other soil invertebrates [7].

Aquatic ecosystems bear the heaviest burden of plastic pollution. An estimated 1 to 5 trillion plastic fragments currently circulate in the world's surface oceans [3]. Marine mammals, seabirds, and fish species ingest plastic debris, suffering entanglement, internal perforation, false satiation,

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and chemical toxicity [5]. The ocean's plastic burden is projected to exceed the total biomass of marine fish by 2050 if current trajectories continue [20].

For human health, microplastics represent the most direct vector of harm. Particles have been identified in human blood, placental tissue, lung parenchyma, and infant faeces, raising concerns about inflammatory responses, endocrine disruption, and cytotoxicity [6]. The presence of additives such as bisphenol A, phthalates, and polybrominated diphenyl ethers in commercial plastic products further amplifies these risks.

4.3 Comparative Adoption Data: National Trends

As illustrated in Table 1, adoption rates for biodegradable materials have increased across all five examined countries over the 2021–2025 period, though at markedly different rates. Germany maintained the highest adoption rate, rising from 20% to a projected 30% by 2025, driven by the European Union's Single-Use Plastics Directive, extended producer responsibility legislation, and a well-developed industrial composting network [8]. France and Italy demonstrated consistent growth, with France's packaging industry achieving 22% biodegradable penetration by 2025 through strong public procurement policies and consumer labelling requirements.

The United States exhibited robust growth (16% to 24%), propelled by private sector innovation, venture capital investment in bioplastic startups, and mounting consumer demand for sustainable packaging - though the absence of a federal composting infrastructure standard constrains end-of-life performance [8].

Uzbekistan presents the most instructive case for transitional economies. Starting from a 5% adoption rate in 2021, the country has achieved steady growth to a projected 15% by 2025. This trajectory reflects the implementation of state environmental programmes, initial bans on certain single-use plastic items, and growing engagement of the private sector in sustainable packaging. Nevertheless, the gap between Uzbekistan and its European counterparts underscores the need for accelerated policy action, infrastructure investment, and public awareness campaigns.

5. DISCUSSION

5.1 The Case for Biodegradable Materials

The convergence of evidence from the literature review, toxicological data, and adoption statistics strongly supports the transition toward biodegradable materials as one component of a comprehensive plastic waste reduction strategy. Biodegradable polymers offer the potential to close the loop on short-lived applications - particularly single-use packaging, agricultural films, and food service ware - where conventional plastics provide minimal durable value yet impose disproportionate environmental costs [13].

PLA and PHA, in particular, have reached commercial maturity and are currently deployed at industrial scale across Europe, North America, and parts of Asia. The demonstrated feasibility of producing packaging materials with comparable functional properties to conventional plastics - combined with end-of-life advantages in properly equipped composting facilities - makes these materials credible candidates for regulatory mandates and public procurement specifications [10].

5.2 Limitations and Challenges

Notwithstanding their promise, biodegradable materials are not a panacea. Several critical challenges must be addressed. First, the vast majority of biodegradable polymers require industrial composting conditions - elevated temperatures, controlled humidity, microbial inoculation - that are unavailable in most natural environments and in many lower-income countries [12]. If biodegradable packaging enters landfills or open environments, it may degrade no faster than conventional plastic, and may release methane under anaerobic conditions.

Second, the production costs of bio-based and biodegradable polymers currently exceed those of petrochemical equivalents by a factor of two to five, limiting their accessibility in price-sensitive markets [14]. Economies of scale, improved fermentation efficiencies, and carbon

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pricing mechanisms may narrow this gap over the medium term, but near-term affordability remains a constraint.

Third, concerns have been raised about land use and food security implications of expanding crop-based feedstocks for bioplastics. Second-generation feedstocks - including agricultural residues, algal biomass, and waste glycerol - offer promising avenues for decoupling bioplastic production from food systems [17].

Finally, consumer confusion between 'biodegradable' and 'compostable' designations - aggravated by inconsistent national labelling standards - risks undermining the environmental benefits of certified products. Harmonised international certification frameworks, such as those advocated by Narancic et al. [10], are essential to ensure product integrity and consumer confidence.

5.3 Strategic Recommendations for Uzbekistan

Uzbekistan's economic structure, geographic position, and growing environmental consciousness place it at a meaningful inflection point in its plastic management trajectory. Several strategic priorities emerge from the analysis. Regulatory development should be accelerated: progressive phase-out schedules for single-use plastics - beginning with the highest-volume, lowest-value items such as thin grocery bags, straws, and foam food containers - would create the demand signal necessary to attract domestic and foreign investment in biodegradable alternatives [19].

Investment in industrial composting infrastructure is equally critical. Without end-of-life processing capacity, the adoption of certified compostable materials cannot deliver its promised environmental benefits. Public-private partnerships, supported by international development finance, could catalyse the establishment of regional composting centres integrated with organic waste collection systems.

Education and behaviour change programmes targeting households, schools, and small businesses would accelerate the cultural shift away from single-use disposability that underpins long-term demand for sustainable alternatives. International partnerships - with European Union research institutions, UNEP, and bilateral development agencies - could facilitate technology transfer and capacity building in bioplastic manufacturing and waste management [19].

6. CONCLUSION

This review has demonstrated that plastic waste constitutes a systemic environmental, public health, and socioeconomic challenge of the highest order. The persistence, ubiquity, and toxicological profile of conventional plastics - particularly in their micro- and nano-scale forms - demand urgent and sustained action across production, consumption, and end-of-life management.

Biodegradable materials - encompassing PLA, PHA, starch composites, cellulose films, and emerging algal biopolymers - represent a scientifically robust and increasingly commercially viable class of alternatives capable of substantially reducing the environmental footprint of short-lived plastic applications. Their full potential, however, can only be realised through complementary investments in industrial composting infrastructure, coherent certification and labelling standards, supportive regulatory frameworks, and consumer education.

The comparative adoption data demonstrate that proactive policy environments generate consistent and accelerating growth in biodegradable material markets. Uzbekistan, while currently behind leading European adopters, has established a positive trajectory that can be significantly accelerated through targeted legislative and infrastructure commitments. A future in which biodegradable materials substantially displace conventional single-use plastics is technically achievable and economically attainable - but it requires coordinated effort by governments, industry, the scientific community, and civil society.

The plastic waste crisis is ultimately a governance and cultural challenge as much as a technological one. Biodegradable materials provide a powerful tool; the challenge is to create the

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systemic conditions in which that tool can be wielded at the scale and speed the ecological emergency demands.

REFERENCES

1. Thompson, R. C., Swan, S. H., Moore, C. J., & vom Saal, F. S. (2009). Our plastic age. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526), 1973–1976.
2. Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science Advances, 3(7), e1700782.
3. Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., ... & Law, K. L. (2015). Plastic waste inputs from land into the ocean. Science, 347(6223), 768–771.
4. Barnes, D. K. A., Galgani, F., Thompson, R. C., & Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526), 1985–1998.
5. Wright, S. L., Thompson, R. C., & Galloway, T. S. (2013). The physical impacts of microplastics on marine organisms: A review. Environmental Pollution, 178, 483–492.
6. Rochman, C. M., Browne, M. A., Halpern, B. S., Hentschel, B. T., Hoh, E., Kolgan, H. K., ... & Thompson, R. C. (2013). Classify plastic waste as hazardous. Nature, 494(7436), 169–171.
7. Andrady, A. L. (2011). Microplastics in the marine environment. Marine Pollution Bulletin, 62(8), 1596–1605.
8. European Bioplastics Association. (2024). Bioplastics market data 2024. European Bioplastics.
9. Vert, M., Doi, Y., Hellwich, K. H., Hess, M., Hodge, P., Kubisa, P., ... & Schué, F. (2012). Terminology for biorelated polymers and applications (IUPAC Recommendations 2012). Pure and Applied Chemistry, 84(2), 377–410.
10. Narancic, T., Verstichel, S., Chavan, S. R., Vasquez, L., Meersmans, R., Borremans, R., ... & O'Connor, K. E. (2018). Biodegradable plastics: standards, policies, and impacts. ChemSusChem, 11(16), 2874–2883.
11. Shen, M., Huang, W., Chen, M., Song, B., Zeng, G., & Zhang, Y. (2020). (Micro)plastic crisis: Un-ignorable contribution to global greenhouse gas emissions and climate change. Journal of Cleaner Production, 254, 120138.
12. Napper, I. E., & Thompson, R. C. (2019). Environmental deterioration of biodegradable, oxo-biodegradable, compostable, and conventional plastic carrier bags in the sea, soil, and open-air over a 3-year period. Environmental Science & Technology, 53(9), 4775–4783.
13. Ragaert, K., Delva, L., & Van Geem, K. (2017). Mechanical and chemical recycling of solid plastic waste. Waste Management, 69, 24–58.
14. Endres, H. J., & Siebert-Raths, A. (2011). Engineering Biopolymers: Markets, Manufacturing, Properties and Applications. Hanser Publications.
15. Chen, G. Q., & Patel, M. K. (2012). Plastics derived from biological sources: present and future: a technical and environmental review. Chemical Reviews, 112(4), 2082–2099.
16. Reddy, R. L., Reddy, V. S., & Gupta, G. A. (2013). Study of bio-plastics as green & sustainable alternative to plastics. International Journal of Emerging Technology and Advanced Engineering, 3(5), 76–81.
17. Karan, H., Funk, C., Grabert, M., Oey, M., & Hankamer, B. (2019). Green bioplastics as part of a circular bioeconomy. Trends in Plant Science, 24(3), 237–249.
18. Soroudi, A., & Jakubowicz, I. (2013). Recycling of bioplastics, their blends and biocomposites: A review. European Polymer Journal, 49(10), 2839–2858.
19. United Nations Environment Programme (UNEP). (2021). From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution. UNEP, Nairobi.