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Plant-based bio plastics from agricultural waste: Opportunities and challenges

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Abstract
Plastic pollution is one of the biggest environmental issues of the 21st century since conventional petroleum-based plastics cause long-term environmental and health issues. Bioplastics, especially renewable ones, are becoming global alternatives. Among feedstocks, agricultural waste is promising due to its abundance, low cost, and valorization potential. Rice husk, wheat straw, sugarcane bagasse, corn stover, vegetable and fruit peels, oilseed cakes, and forestry byproducts can be utilized to manufacture plant-based bioplastics. This paper discusses this process's merits and downsides. Production technologies include pretreatment, microbial fermentation, enzymatic processes, and chemical synthesis. New nanotechnology and composite materials with improved properties are also highlighted. Bioplastics generated from agricultural waste are compared to traditional polymers in mechanical, thermal, biodegradability, and life cycle studies. Technical scalability, cost competitiveness, infrastructure shortages, customer acceptance, environmental benefits, circular economy integration, rural income creation, and industrial usage are addressed. Policy insights and case studies from Europe, the US, India, and China give global and regional perspectives. Biotechnology, renewable energy, superior bioplastic mixes, and enabling legal frameworks are the article's final suggestions. Bioplastics derived from agricultural waste can help sustain development when technology and policy are integrated.

Keywords: Bioplastics, agricultural waste, circular economy, biodegradability, sustainable materials, renewable resources, plastic pollution, biomass valorization

Introduction

Medicinal plants have greatly gained importance in the management and treatment of human Plastic pollution is a major environmental issue nowadays. Conventional plastics, largely derived from petroleum, cause soil erosion, water pollution, and marine species extinction due to their non-biodegradability and long-term persistence. The growing need for plastics in packaging, agriculture, construction, and consumer products worsens the situation. This causes fossil fuel dependence and environmental degradation (Rai & Choure, 2023) [1]. Thus, long-term solutions that meet industrial and social needs and reduce plastics' environmental impact are needed. Bioplastics, a viable alternative to plastics, are gaining popularity. Bioplastics are made from renewable biological sources and can be biodegradable or compostable, depending on their chemical composition. Biodegradable plastics, like polylactic acid and polyhydroxyalkanoates, can be broken down in nature by microbes, while bio-based plastics, like bio-based polyethylene, are made from biomass but don't break down in nature (Myeni *et al.*, 2024) [2]. This category underlines the importance of thoroughly examining bioplastics' environmental performance and their diversity and complexity.

Bioplastics can be made from agricultural waste. Agricultural leftovers are wasted or burned worldwide, polluting the air and emitting greenhouse gases. Rice husks, wheat straw, sugarcane bagasse, corn stover, and fruit peels. Making high-value bioplastics from low-value byproducts helps manage trash and promotes a circular economy (Shafqat *et al.*, 2021) [3]. Bioplastics made from agricultural waste save resources, offer jobs for farmers and rural populations, and protect food crops. This research examines agricultural waste's potential as a sustainable bioplastic input, considering its pros and cons. Bioplastics derived from agricultural waste and their production processes will be reviewed in this article. There will be discussions of social, economic, environmental, and broad use barriers. This paper provides a detailed overview of bioplastics derived from agricultural waste, which can encourage sustainable development and a greener future.

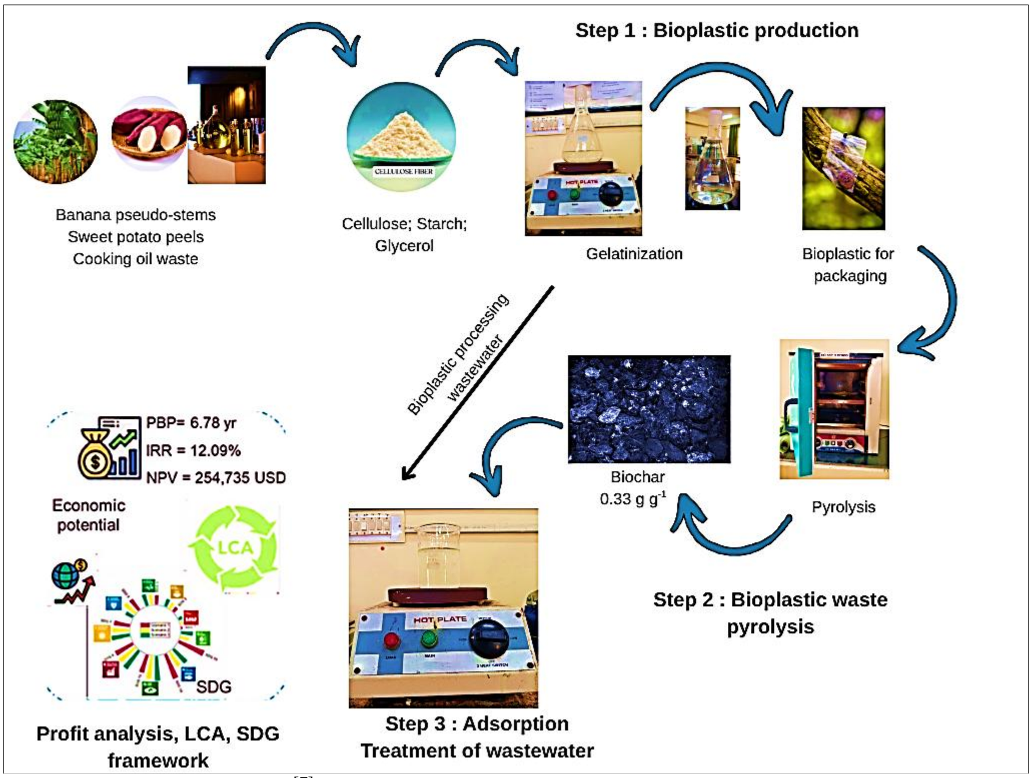
2. Sources of Agricultural Waste for Bioplastics

Table 1: Types of Agricultural Waste and Their Composition for Bioplastic Production (Shafqat *et al*., 2021) [3]

Agricultural Waste	Major Components	Potential Bioplastics	Applications
Rice husk	Cellulose, lignin, silica	PLA, bio-composites	Packaging, films, reinforced materials
Wheat straw	Cellulose, hemicellulose, lignin	PLA, PHA, bio-composites	Food packaging, agricultural mulch, biodegradable films
Corn stover	Cellulose, hemicellulose, lignin	PLA, PHA, starch-based plastics	Films, biodegradable packaging, composites
Sugarcane bagasse	Cellulose, hemicellulose	PLA, PHA, cellulose composites	Bio-composites, packaging, agricultural films
Fruit peels (banana, mango, citrus)	Starch, pectin, fiber	Starch-based plastics, PLA blends	Films, biodegradable packaging, coatings
Oilseed cakes (soybean, sunflower, groundnut)	Proteins, polysaccharides	Bioplastic blends, starch-based plastics	Films, coatings, biodegradable containers
Forestry residues (sawdust, wood chips, bark)	Cellulose, hemicellulose, lignin	PLA, PHA, lignin-based composites	Packaging, automotive, construction, bio-composites

A large untapped resource for eco-friendly bioplastic manufacture is agricultural waste. Millions of tons of agricultural byproducts and residues are produced worldwide, most of which end up in landfills, incinerators, or the trash, releasing greenhouse gases and soil erosion. Converting biomass into bioplastics can help with waste management and reduce fossil fuel use. Many types of agricultural waste have shown promise in this area (Mohanta *et al*., 2025) [4]. Cellulose, hemicellulose, and lignin are abundant in rice husk, wheat straw, and maize stover. Bio-based polymers like polyhydroxyalkanoates (PHA) and polylactic acid require these building blocks. Rice husk is suitable for composites due to its silica and cellulose, while wheat straw and maize stover fermentable sugars can be used to generate bioplastics. Fruit and vegetable peels, especially in food processing locations, are another major agricultural waste source (Chandra *et al*., 2024) [5]. The starch, pectin, and natural fibers in banana, potato, citrus, and mango peels can be used to manufacture biodegradable films and packaging. These wastes are intriguing because they release many polysaccharides without as much processing as lignocellulosic residues.

Sugar industry byproducts like sugarcane bagasse and molasses are produced in large quantities in Brazil, India, and Thailand. As a fibrous material rich in cellulose and hemicellulose, bagasse is ideal for bio-composites and fermentation feedstock. Microbial fermentation of molasses produces bioplastic intermediates such lactic acid, ethanol, and PHAs (Selvam *et al*., 2025) [6]. Molasses comprises sucrose, glucose, and fructose. Groundnut, sunflower, and soybean oilseed cakes are another promising feedstock. These byproducts contain proteins and polysaccharides, making them ideal building blocks for chemically modified or combined biopolymers. They also provide a good use for agro-industrial byproducts that would otherwise go to inexpensive animal feed (Otoni *et al*., 2021) [7]. Getting cellulose and lignin from sawdust, wood chips, bark, and other lignocellulosic biomass and forestry byproducts is sustainable. Bio-based polymers and composites with increased mechanical strength could be used in construction, transportation, and packaging. These agricultural waste sources help produce plant-based bioplastics. They benefit the environment and foster a circular economy by manufacturing sustainable items from low-value leftovers (Arias *et al*., 2024) [8].



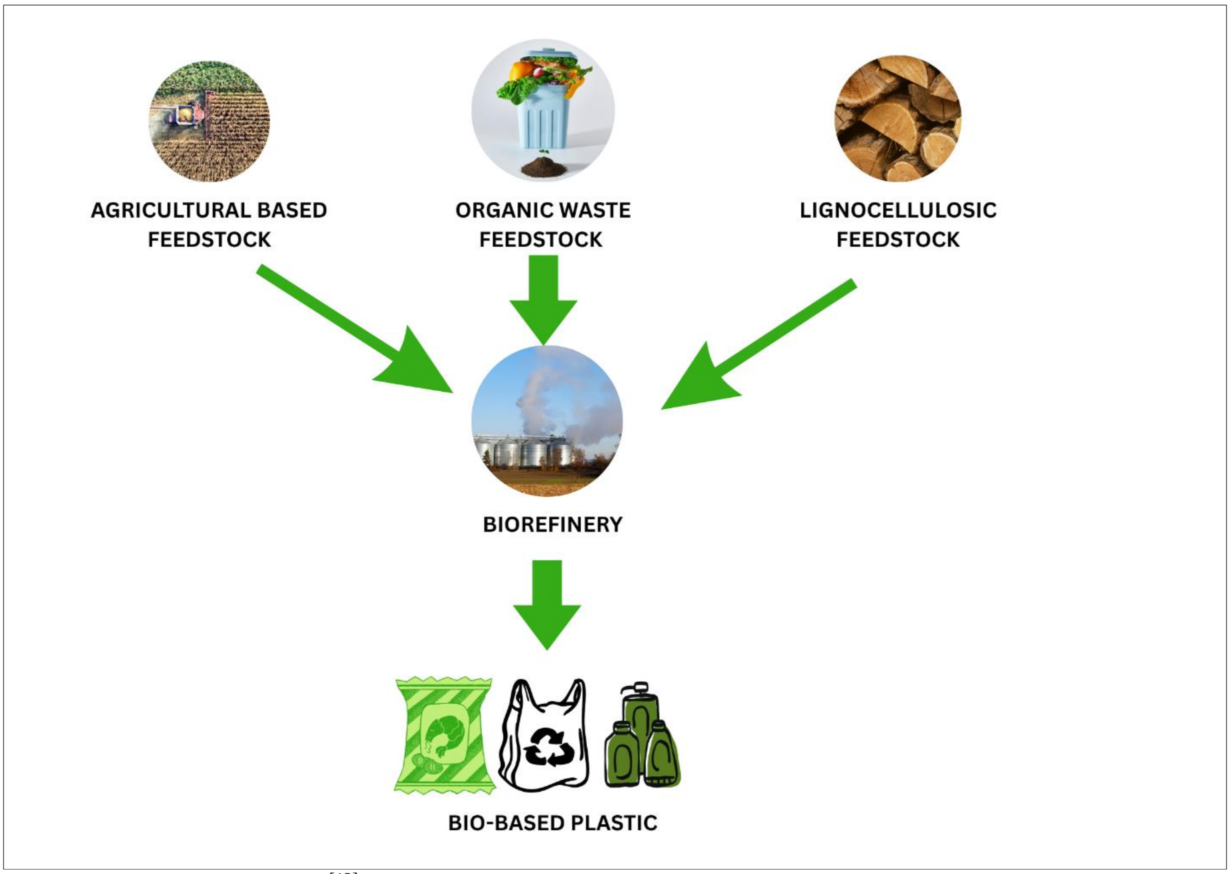
[**Source:** (Otoni *et al*., 2021)] [7]

Fig 1: Sources of Agricultural Waste for Bioplastics

3. Production Technologies and Processes

Pretreatment of raw biomass, changing it into polymers, and changing its commercial properties are the steps. Agricultural waste is turned into plant-based bioplastics using a process with several steps. The environmental impact and economic viability of bioplastic manufacturing rely on how well and how long these processes last (Zimmermann *et al*., 2020) [9]. The complicated structure of crop residues made up of lignin, starch, proteins, cellulose, and hemicellulose must be broken down during pretreatment. Some mechanical preparation methods, like milling, grinding, and extrusion, make it easier to work with materials by increasing their surface area and decreasing their particle size. Using acids, alkalis, or solvents to prepare the plant breaks the links between lignin and cellulose and turns polysaccharides into sugars that can be fermented. For instance, Álvarez-Castillo *et al*. (2021) [10] say that dilute acid hydrolysis is used to get glucose back from lignocellulosic waste. Chemical ways are faster, but biological preparations based on enzyme mixtures or fungi are better for the environment. Several pretreatment methods are used together to get the most sugar and inhibitory effects. Bioplastic monomers or polymers are made by pretreated biomass conversion methods. Lactic acid, polyhydroxyalkanoates (PHA), and other chemicals are made when Lactobacillus or Ralstonia eutropha are fermented. Lactic acid is used to make polylactic acid (PLA), a biodegradable material that is popular in business. PHAs, on the other hand, are naturally biodegradable polyesters that have many uses (Merino *et al*., 2022) [11].

PLA and starch-based plastics need to be made chemically. During the production of PLA, ring-opening polymerization or condensation changes lactic acid into long polymer chains that are good at both mechanical and heat properties. Thermoplastic treatment can be used to make stronger, more flexible films from starch found in leftovers like corn or potato peels. It can also be mixed with other plastics. For these methods to work, they usually need catalysts, temperature control, and the right reaction conditions (Rajendran *et al*., 2025) [12]. Enzymatic processes are becoming more well-known because they are selective and safe for the environment. A group of enzymes called amylases, cellulases, and lipases break down complex carbohydrates and proteins into bioplastic building blocks that can then be fermented or polymerized. Enzymatic catalysis is a good environmentally friendly choice because it cuts down on chemical waste and makes processing less harsh. Bioplastics made from farm waste are much better now thanks to nanotechnology and composites. Nanofillers like lignin nanoparticles, nanoclays, and cellulose nanocrystals make things stronger, better at blocking heat, and more stable. Problems with brittleness, durability, and being sensitive to moisture can be fixed by mixing polymers made from farm waste with biopolymers or environmental additives. Because of these findings, bioplastics might be able to be used in more demanding applications like food packaging, auto parts, and medical gear (Zhang & Sablani, 2021) [13]. To fully use agricultural waste for making bioplastic, methods like pretreatment, conversion, and nanocomposite are needed. Continuous innovation is needed to make replacements to plastics made from oil that are sustainable, scalable, and cost-effective.



[**Source:** (Rajendran *et al*., 2025)] [12]

Fig 2: Flowchart of Agricultural Waste to Bioplastics

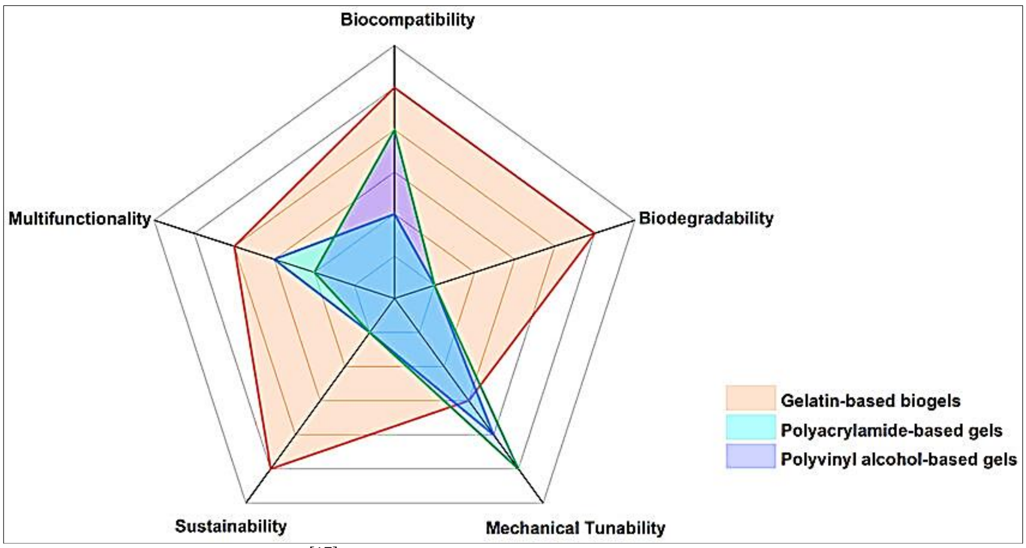
4. Properties and Performance of Plant-Based Bioplastics

Plant-based bioplastics are widely used due to their renewable source and superior functionality. Their versatility comes from biodegradability, thermal stability, elasticity, and mechanical strength. Life cycle assessments provide further information on their environmental impact, including pros and cons. Mechanical properties are crucial to bioplastics' usage. Polylactic acid (PLA), a plant-based bioplastic, is robust and rigid like PET. They are too brittle and have limited elongation at break for flexible usage (Maraveas, 2020) [14]. Starch-based polymers and polyhydroxyalkanoates PHAs) are more flexible but less durable. Many investigations have attempted mixing the material with different polymers or plasticizers or adding nanofillers like cellulose nanocrystals to overcome these limits. Processing and end-use performance depend on thermal stability. PLA's low glass transition temperature (55-65°C) and melting point of 150-170°C make it better for extrusion and injection molding than PP and PE, which are better for high-temperature situations. PHAs can break down in high temperatures, yet they may be more thermally resilient (Ortega *et al*., 2022) [15]. Because they are heat and moisture sensitive, starch-based polymers must be changed or blended to improve performance. Compostable plant-based bioplastics are biodegradable. In a good industrial composting environment, PLA, PHAs, and starch composites can breakdown into carbon dioxide, water, and biomass in months. Biodegradation rates depend on temperature, humidity, and microbial activity. Compostability is good for waste management because it breaks down partially in seas and landfills, but composting infrastructure and standards need improvement (Osemwegie *et al*., 2022) [16].

Table 2: Comparison of Bioplastics and Conventional Plastics)

Property	PLA (Polylactic Acid)	PHA (Polyhydroxyalkanoates)	Starch-Based Plastics	PET (Conventional)	LDPE (Conventional)
Mechanical Strength	High	Medium	Low	High	Medium
Flexibility	Low	Medium	High	Medium	High
Thermal Stability	Medium (Tg 55-65°C, Tm 150-170°C)	High	Low	High	Medium
Moisture Sensitivity	Moderate	Low	High	Low	Low
Biodegradability	Yes (Industrial composting)	Yes (Soil & water)	Yes	No	No
Cost	High	High	Medium	Low	Low
Typical Applications	Packaging, films, rigid containers	Packaging, biomedical devices, films	Biodegradable bags, films	Bottles, packaging	Bags, flexible packaging

Bioplastics are recyclable and environmentally beneficial, but they lack petrochemical plastics' long-term stability, cost-effectiveness, and durability. PLA is comparable to PET in tensile strength but not thermal resistance or durability. Low-density polyethylene (LDPE), used for flexible packaging, is more adaptable than starch-based polymers. Finally, life cycle analysis (LCA) provides a complete environmental assessment. Plant-based bioplastics utilize much less energy, greenhouse gas emissions, and non-renewable resources than typical plastics, according to research. These benefits can be reduced by land use changes, energy-intensive pretreatment, and a lack of composting infrastructure. Utilizing agricultural waste as feedstock reduces landfill waste and helps the food vs. material issue (Kulanthaisamy *et al*., 2023) [18]. Plant-based bioplastics need continual materials engineering and waste management system innovation to improve performance across applications. They have room for improvement despite their promising characteristics and environmental benefits.



[**Source:** (Arriaga *et al*., 2025)] [17]

Fig 3: Radar Chart of Bioplastics Performance Metrics

5. Opportunities of Agricultural Waste-Based Bioplastics

Making plant-based bioplastics from farm waste has more benefits than just replacing regular plastics. By turning low-value trash into useful resources, these new ideas help the world reach its sustainability goals, deal with environmental problems, and boost economic growth. One great thing about bioplastics made from agricultural waste is that they are good for the earth. A huge amount of pollution and greenhouse gases are released when sugarcane bagasse, wheat straw, and rice husks are burned or broken down (Nanda *et al*., 2022) [19]. By cutting down on open burning, bioplastics made from these materials clean up the air and ease the load on landfills. Bioplastics are better for land and water environments because they can break down or compost. The world is working to cut down on greenhouse gas emissions and make industry more environmentally friendly. The circular economy and sustainable growth are helped by reusing and recycling food waste. A cycle of "take-make-dispose" ends when agricultural waste is turned into valuable materials that can be used in new goods. This keeps resources from going to waste and helps reach the UN's Sustainable Development Goals (Hamed *et al*., 2025) [20] for responsible production and usage, climate action, and sustainable industrialization.

Socioeconomically, bioplastics manufacturing empowers farmers and generates rural money. Rural farmers can benefit from selling fruit peels, oilseed cakes, and crop leftovers. Decentralized collecting and processing facilities reduce economic inequality, improve rural development, and provide jobs. Smallholder farmers create a lot of biomass that isn't consumed, making this significant in agricultural economies like India, Brazil, and portions of Africa. Reducing fossil fuel use is another opportunity (Sharma *et al*., 2024) [21]. Bioplastics reduce petroleum dependence and increase sustainable feedstocks like agricultural waste, improving energy security. Since fossil fuel markets are volatile and world oil supplies are low, the plastics sector is seeking for bio-based alternatives. Bioplastics generated from agricultural waste have several industrial uses. Their biodegradable films, bags, and containers are great for packaging. Agriculture uses bioplastics as mulching films and controlled-release fertilizer carriers. They are used in wound dressings, medicine delivery systems, and surgical implants because they are biocompatible. Bioplastics are also being studied in consumer goods, textiles, and automotive parts (Aras *et al*., 2024) [22]. These materials' versatility may aid industries seeking ecologically responsible choices without losing performance. Technological innovation, economic opportunity, and environmental awareness combine in agricultural waste bioplastics. Their broad usage in business could build a durable, eco-friendly plastic economy.

6. Challenges and Limitations

Bioplastics generated from agricultural waste have immense potential, but social, economic, infrastructural, and technical barriers impede their widespread usage. Long-term competition with traditional polymers requires addressing these limits. Technology is a major impediment. Using pretreatment, fermentation, and chemical synthesis to turn agricultural waste into bioplastics can be energy-intensive and inefficient. Inefficient conversion techniques reduce scalability and increase production costs. Inhibitory byproducts from comprehensive processing of lignocellulosic biomass to obtain fermentable sugars decrease microbial fermentation efficiency (Sarkar *et al*., 2025) [23]. Industrial bioplastic production from diverse waste feedstocks is currently problematic. Material restrictions also affect bioplastic performance. Many polymers manufactured from agricultural waste, such as starch-based plastics, are highly sensitive to moisture, reducing their mechanical strength and shelf life. PLA is strong and stiff, yet it is fragile and unsuitable for flexible applications. Although PHAs break down naturally, high temperatures may accelerate their breakdown. Bioplastics have a long way to go before they can replace petrochemical plastics in high-stress industrial applications, high-temperature packaging, and long-term storage. Economic constraints hinder market expansion. The high cost of pretreatment, fermentation, and purification makes bioplastics more expensive than conventional plastics. Petrochemical plastics are cheaper due to economies of scale, lower raw material costs, and decades of infrastructure development (Lackner & Besharati, 2025) [24]. Without government subsidies, tax incentives, or low-cost manufacturing processes, bioplastics struggle in price-sensitive sectors.

Another issue is inadequate garbage collection, sorting, and supply chain management infrastructure. Collection and shipping agricultural leftovers is difficult due to their dispersion, seasonality, and bulkiness. Lack of coordinated garbage aggregation infrastructure in many countries, especially developing nations, affects large-scale bioplastic plant costs and feedstock supply. Policy and regulation also limit growth. Some governments are unable to promote bioplastics through research incentives, subsidies, and single-use plastic prohibitions due to inconsistent global standards. Because biodegradability and compostability criteria differ by country, certification and trade are complicated. Without clear regulations and labeling, manufacturers and consumers will be confused (Younis *et al*., 2024) [25]. Finally, business acceptance and customer awareness are lacking. Many countries lack understanding of bioplastics, while environmentally concerned consumers in affluent countries are ready to use them. Assumptions regarding biodegradability (e.g., bioplastics break down everywhere) and cost prevent their broad adoption. Consumers need clear and accessible information about bioplastic merits and cons to adopt those (Chauhan *et al*., 2024) [26]. In conclusion, bioplastics derived from agricultural waste have many challenges that require innovation, cost reduction, infrastructure development, and regulatory support. These challenges must be overcome to make them sustainable alternatives to fossil fuel polymers.

7. Global and Regional Perspectives

Government legislation, industrial ecosystems, consumer awareness, and biomass feedstock availability affect agricultural waste-derived bioplastic uptake, which varies by area. We can learn from regional and global bioplastic production practices in other countries. Europe leads the bioplastics market due to strong laws and increased customer demand for sustainable products. EU directives on limiting single-use plastics and building a circular economy have accelerated agricultural waste valorization investments. Large plants in Germany, Italy, and the Netherlands create PLA, PHA, and starch-based plastics from agricultural and industrial waste. Horizon Europe, which supports biopolymer manufacturing and life cycle evaluations, is one of many EU finance projects that support new ideas. According to Italian case studies, biodegradable packaging films made from agricultural waste like potato peels link sustainable packaging with agriculture. With some aid from federal and state legislation, consumer demand and private sector activities drive US bioplastics research and development. USDA's BioPreferred Program promotes bio-based materials and offers labeling and procurement support to certified items. NatureWorks (PLA maker) and Danimer Scientific (PHA producer) use maize stover and other agricultural byproducts as raw materials. Startups that exploit fruit and vegetable waste as bioplastic, notably in packaging, have also become famous.

China is a major bioplastics market due to government initiatives and fast industrialization. In 2020, the country will phase out single-use plastics, creating strong incentives for alternatives. Agricultural waste like maize leftovers and rice husks is increasingly used for bio-based packaging. China has invested heavily in industrial production, and state-owned enterprises and private startups are collaborating to create affordable, scalable solutions. China wants to boost its bio-economy and reduce pollution. Rice husk, oilseed cakes, sugarcane bagasse, and India's vast agricultural base all bode well for its future. India has banned some single-use plastics, allowing bioplastics to become mainstream. New enterprises and academic organizations are developing environmentally friendly polymers from food leftovers. Early-stage industries confront challenges in scalability, infrastructure, and client awareness. Bio-based company subsidies and rural entrepreneur support could boost India's position in this industry. Globally and regionally, regulatory support, industrial cooperation, and innovation ecosystems encourage bioplastics uptake. India and China use agricultural waste and government controls, whereas the US and Europe emphasize public-private partnerships and academic research. If we collaborate globally, we can replace traditional plastics with agricultural waste-based alternatives faster.

8. Conclusion

Researching agricultural waste as a bioplastic source highlights the challenges and opportunities that must be overcome before broad application. This research indicates that bio-based polymers may be manufactured from rice husk, sugarcane bagasse, corn stover, and wheat straw, reducing waste and fossil fuel use. Due to advances in material engineering, enzymatic processing, and microbial fermentation, bioplastics with improved mechanical and thermal properties have been produced for various uses. Risk-reward balance is also stressed in the study. Bioplastics derived from agricultural waste have clear environmental benefits, but processing costs, scalability, feedstock availability, and end-of-life management remain issues. Energy intensity in some industrial processes, limited biodegradability in nature, and varying material quality highlight the complexity. To use agricultural leftovers sustainably, competing applications including animal feed, bioenergy, and soil enrichment must be regulated. Bioplastics generated from agricultural waste have good long-term sustainability prospects despite these challenges. By integrating biotechnology and synthetic biology with renewable energy sources and creating high-performance mixes and composites, efficiency and material quality should improve. Policies like subsidies, standards, and public-private partnerships can accelerate commercialization and customer acceptance. A circular economy strategy that promotes biodegradability, recycling, and appropriate waste management is needed to make bioplastics environmentally friendly without burdening other businesses. To conclude, bioplastics derived from agricultural waste help reduce plastic pollution, boost rural incomes, and satisfy global sustainability goals. Academics, industry, governments, and consumers must collaborate to unlock these materials' full potential. This is the only path. With smart legislation and technology, agricultural waste-based bioplastics could replace standard plastics. This would promote circularity and sustainability.

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10. Conflict of Interest
The authors declare that there is no conflict of interest regarding the publication of this paper.

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