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Advances in Biodegradable Plastic Production: Exploring Strategies and Technologies using Renewable Resources

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Plastic pollution has escalated to critical levels, threatening terrestrial and marine ecosystems due to their persistent and non-degradable nature. Recent global initiatives, such as the UNEA resolutions advocating a legally binding treaty to address plastic pollution across the product life cycle, highlight the necessity for international cooperation to combat this crisis. Effective solutions remain elusive, hindered by cross-border coordination challenges, inadequate waste management, and the absence of integrated disaster risk reduction strategies. Biodegradable plastics offer a promising alternative to mitigate environmental impacts. These materials achieve substantial biodegradation within six months under specific conditions.

This review examines production methods of biodegradable plastics utilizing renewable resources such as cassava, corn starch, and banana plant materials. This emphasizes their potential as sustainable alternatives to conventional plastics. Additives such as chitosan, glycerol, and polyvinyl alcohol (PVA) play pivotal roles in enhancing mechanical properties while addressing the inherent limitations of starch-based plastics. An analysis of multi-objective optimization techniques demonstrates how to reconcile conflicting goals while benchmarking efficacy against industrial requirements. The review advocates for hybrid optimization models that simultaneously target mechanical, environmental, and economic objectives. This work highlights the potential of biodegradable plastics as sustainable alternatives to mitigate the environmental impacts of synthetic plastics.

1. Introduction

The current state of plastic pollution has reached alarming levels, with significant impacts on both terrestrial and marine ecosystems, as plastics are notoriously difficult to degrade naturally. International cooperation on plastic pollution is increasingly recognized as essential to address this global crisis effectively. Recent initiatives, such as the resolutions from the United Nations Environmental Assembly (UNEA) such as UNEA Resolution 5/14 advocating for a legally binding treaty to end plastic pollution, reflect a growing consensus including the need for coordinated action across borders, the establishment of comprehensive waste management systems, and the integration of disaster risk reduction strategies to protect vulnerable communities from the adverse impacts of plastic pollution (Alaghemandi, 2024).

This environmental crisis has prompted a pressing need to produce biodegradable plastics, which can mitigate the adverse effects of plastic waste by breaking down more efficiently in natural environments. Transitioning to biodegradable alternatives not only addresses the growing plastic waste problem but also aligns with global sustainability goals, emphasizing the importance of innovative materials that reduce reliance on traditional petrochemical plastics (Pilapitiya and Ratnayake, 2024).

This paper aims to discuss how the use of renewable resources benefits recyclability, conversion efficiency, and conversion time of plastics.

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2. Biodegradable Plastics

Global plastic production reached 412 Mt in 2020, with packaging constituting 40 % of output (Pilapitiya and Ratnayake, 2024). Different types of plastics are used based on their properties and intended applications. High-density polyethylene (HDPE) is strong and chemical-resistant, ideal for containers and pipes. Low-density polyethylene (LDPE) is flexible and used in bags and wraps. Polyethylene terephthalate (PET) is favored for bottles and textiles due to its barrier properties. The rigidity of polyvinyl chloride (PVC) suits construction and medical uses. Selection depends on performance needs, cost, and environmental factors. It has been projected that plastic waste accumulation would be equal to the amount of marine line in the ocean (Stubbins et al., 2021). Biodegradable alternatives have potential use for packaging, as it accounts for 59 % of plastic waste (Sardon et al., 2021).

According to the International Union of Pure and Applied Chemistry (IUPAC), biodegradable plastics are defined as polymeric substances that are vulnerable to biological decomposition which lower the molar masses of the macromolecules composing of the substance (Vert et al., 2012). Biodegradation is a phenomenon of biotic degradation mostly brought about by an enzymatic process that stems from the activity of cells. It continues until mineralization occurs, producing new biomass, water, and either CO_2 or CH_4 in an aerobic or anaerobic environment. It must achieve a specified degree of biodegradation of 90 %, after a predetermined amount of time, six months. This can be verified, monitored, and quantified using established assays. Various media such as compost or soil can be used in relation to the targeted uses. Compostability is related to the biodegradability analysis of compost. Based on their macromolecular structures, these polymers can then also be recycled as other polymers. The decision regarding the use, production, or disposal of biodegradable plastics by the stakeholders such as policymakers, manufacturers, and researchers must be based on the outcomes of their individual life-cycle assessments (LCAs), which evaluate the various approaches (Sardon et al., 2021). There are also problems with recycling materials with complex polymer composition, as they need additional resources to decompose. When conventional plastic composites are recycled, harmful gases such as CO_2 and SO_x/NO_x gases are released into the atmosphere.

2.1 Production of Biodegradable Plastic using Renewable Resources

There have been various studies that have investigated using renewable resources. The study by Moro et al. (2017) demonstrated that cassava starch, corn starch, and passion fruit peel flour can be effectively combined to produce biodegradable plastics with desirable mechanical and environmental properties. In contrast, the biodegradable plastic material created by Abera et al. (2023) utilized banana plant materials, specifically the pseudo-stem for fiber extraction and the peel for starch extraction, both obtained from Musa Cavendish species. A study by Ago et al. (2016) showed that nanocellulose extracted from oil palm empty fruit bunches could reinforce bioplastics, enhancing mechanical and thermal properties. Furthermore, Chia et al. (2020) explored the use of algal biomass as a sustainable feedstock, producing bioplastics with rapid biodegradability in marine environments. Research by Haghighi et al. (2020) demonstrated that chitosan could be combined with gelatin to form biodegradable films with antimicrobial properties. It should be noted that a major concern regarding biodegradable plastics is their inferior mechanical strength compared to conventional synthetic plastics. While renewable resource-based bioplastics offer environmental benefits, their tensile strength, flexibility, and durability often fall short of petroleum-based alternatives (Singh et al., 2024).

2.2 Mechanical Properties

Starch-based biodegradable plastics naturally possess poor mechanical properties, which entail drawbacks in comparison to its synthetic polymer counterparts (Tafa et al., 2023). These challenges include controlling miscibility problems at high starch content, avoiding deterioration of mechanical properties at high starch content, and reducing costs at low starch contents (Gadhave et al., 2018). It also has water absorption, high moisture content, and swelling (Oluwasina et al., 2021). Additives such as plasticizers can enhance elongation up to 90 % (Lindriati et al., 2021). Hydrophobic agents such as chitosan reduce water absorption by 30–40 % (Tan et al., 2022). Despite these improvements, trade-offs persist. Starch blends degrade rapidly from 85–100 % in 3–6 months, whereas synthetic additives such as PVA slow biodegradation at 60 % in 6 months (Zhang et al., 2021). Empirical studies confirm that starch-based plastics can degrade by up to 90 % within 3–6 months under composting conditions, as outlined by Vert et al. (2012). For instance, Moro et al. (2017) observed 85 % mass loss in four months, while Abera et al. (2023) reported complete degradation in soil within six months. However, blends containing polymers such as PVA exhibit slower breakdown rates due to their resistance to microbial action, with some studies noting only 60 % mineralization after six months Zhang et al. (2021). These findings underscore the trade-offs between mechanical performance and environmental impact, necessitating effective material design for specific applications.

2.3 Additives

The following subsections discuss common additives used in biodegradable plastics to enhance their mechanical properties, flexibility, and functionality. These additives, such as chitosan, glycerol, and polyvinyl alcohol (PVA), are categorized based on their roles as copolymer reinforcements, plasticizers, and synthetic polymer modifiers, respectively. Each additive is examined in terms of its mechanism of action and effects on tensile strength and elongation.

2.3.1 Chitosan

Chitosan is derived from chitin, a natural polymer found in many living organisms including insect exoskeletons, fungal cell walls, invertebrate shells, fish scales, and eggshells. As a copolymer additive, chitosan is one of the most suitable additives for starch-based biodegradable plastics as it reduces the hydrophilic characteristics of the film and improves its mechanical properties in a non-toxic and low-cost way (Tan et al., 2022). It is also used as a reinforcement and as a protective edible coating to block contamination (Syaubari et al., 2022).

The relationship between chitosan and tensile strength can be attributed to the molecular weight of chitosan, which considers the degree of deacetylation when deriving chitosan. The lower the molecular weight, the lower the tensile strength value. This could be due to entanglement being less likely to occur with shorter chitosan molecules (Chen and Hwa, 1996). Increasing the amount of chitosan added to starch-based film blends leads to higher tensile strength and lower elongation. In a study published by Lestari et al. (2020), chitosan percentage and tensile strength are directly proportional due to the increase of hydrogen bonding.

This results in stronger and harder-to-break biodegradable plastic. When the chitosan concentration in the blend is at 30 %, the tensile strength was close to zero. As the concentration increased to 50 %, the tensile strength reached a maximum of 31.8 MPa. Excessively increasing the chitosan content in the blend can reduce the tensile strength as 60 % chitosan added resulted in a decreased tensile strength of 3.33 MPa. In terms of elongation, however, the increase of hydrogen bonds leads to closing the distance between molecules, consequently losing stretchability.

2.3.2 Glycerol

In the production of starch-based biodegradable plastic, plasticizers are used to control the brittleness of the film, which can be attributed to high intermolecular forces. Glycerol is regarded as the best plasticizer as it possesses hydroxyl groups which are responsible for controlling and reducing internal hydrogen bonds in intermolecular bonds (Syaubari et al., 2022).

The study by Lestari et al. (2020) revealed that a higher glycerol content added to the film blend would result in a lower tensile strength, but higher elongation. Its innate ability to reduce intermolecular bonds causes the tensile strength to decrease. Conversely, depleting hydrogen bonds allows the distance of biopolymer molecules to become tenuous. This state of strain among the molecules increases the flexibility of the biodegradable plastic. With a basis of 2 % elongation, a 10 % glycerol content in the blend leads to a 1.3 % increase in elongation percent. Further increasing the glycerol percent to 45 % then reached an elongation of 4 %. High elongation yield was expected as the function of glycerol as a plasticizer is to aid in the flexibility of the plastic. Increasing plasticizers would also result in increased water resistance.

The utilization of glycerol plasticizer in processing biodegradable plastics proves to be advantageous as glycerol does not evaporate when added to the blend in comparison to other plasticizers such as water, ethanol, or low-molecular-weight polyethylene glycol (PEG), which can volatilize during thermal processing, leading to inconsistent plasticization and material defects (Syaubari et al., 2022).

2.3.3 Polyvinyl Alcohol

Polyvinyl alcohol (PVA) is a water-soluble synthetic polymer usually prepared by the hydrolysis of polyvinyl acetate. Mixing PVA with natural polymers proved to be an effective way to obtain a biopolymer with improved mechanical properties and biological performances (Elsaeed et al., 2023). It is important in additive-making water-soluble films as it can form films, emulsifiers, and adhesive properties. Similar to glycerol, PVA strengthens hydrogen bonds in starch-based biodegradable plastics. Higher amounts of PVA added to the film blend would lead to an increase in tensile strength and a decrease on elongation.

Based on the study conducted by Lestari et al. (2020), the tensile strength of the starch-based biodegradable plastic increased at an estimate of 0.5 % per g of PVA added. The study obtained the highest tensile strength of 2.2 MPa for 3 g of PVA. Testing the effect of 3 g of PVA on the film resulted in around a 4.2 % elongation, whereas 1 g of PVA increased the elongation to 7 %.

Table 1: Summary of pertinent mechanical properties of biodegradable plastic studies.

Material	Parameter	Results	Reference
Chitosan, Glycerol	Elongation	Increases as glycerol increases	Syaubari et al. (2022)
Chitosan	Tensile Strength	At 30 %, tensile strength at 0. At 50 %, tensile strength at maximum of 31.8 kPa	Lestari et al. (2020)
PVA	Tensile Strength	Tensile strength increased as PVA increased	Lestari et al. (2020)
Glycerol	Elongation	A 45 % increase of glycerol increases elongation to 4 %	Lestari et al. (2020)
Chitosan	Tensile, Elongation	There is a 35.55 MPa increase of tensile strength, but decrease in elongation by 1.9 %	Saputro and Ovita (2017)
Chitosan	Elongation	With an addition of 35 % w/w chitosan, the highest elongation value was 76.76 %	Ernita et al. (2020)
PVA	Tensile Strength	The additional 2 % reinforcement of PVA increased the tensile strength by 5.64 MPa	Maryam et al. (2019)
PVA	Elongation	At a 35 % PVA assistance, a 77 % elongation at break was achieved under acidic condition.	Zhang et al. (2020)
Glycerol	Tensile, Elongation	The optimum conditions had a tensile strength of 7.27 MPa, and 12.45 % elongation	Ratnawati et al. (2022)
Glycerol	Tensile, Elongation	Tensile strength at a maximum value of 14.33 MPa; Elongation at a maximum value of 94.22 %	Lindriati et al. (2021)

3. Evaluation of Environmental Measures

Biodegradable plastics require comprehensive environmental assessment to verify sustainability claims. While offering ecological advantages over conventional plastics, their impact varies by production method and disposal. PLA emits fewer GHGs than petroleum-based plastics but generates N_2O from agricultural feedstocks (Benavides et al., 2020). PLA uses 30-50 % less energy than PET but depends on fossil-fueled manufacturing (Kim et al., 2022). PHA production requires energy-intensive sterile conditions (Obulisamy and Mehariya, 2021). Biodegradable plastics demonstrate fossil fuel advantages, such as for PHA consuming 40 MJ/kg versus 78-88 MJ/kg for petrochemical polymers (Yu and Chen, 2008). This could reduce the annual Bt-CO_2 emissions of the plastic industry (Moshood et al., 2022). Complete adoption might cut emissions by 74 % through reduced production energy and improved recyclability. Critical challenges remain in agricultural impacts and industrial scalability. However, despite higher upfront costs, biodegradable plastics show strong potential for long-term emission reductions across manufacturing sectors when considering full lifecycle impacts. Their sustainability ultimately depends on optimized material use, renewable energy integration in production, and proper end-of-life management.

4. Applications of Optimization in Biodegradable Plastic Production

Multi-objective optimization is a model that identifies many possible calibration alternatives that help in estimating parameters by dealing with conflicting objectives. Ayyubi et al. (2022) employed RSM-BBD multi-objective optimization to enhance biodegradable plastic strength while maintaining degradation properties. Their Design-Expert analysis yielded optimal results of 25.11 MPa tensile strength (±4.8 %), 83.43 % elongation (±3.7 %), and 50.45 % soil degradation after 30 d. The study evaluated individual additives (chitosan, glycerol, PVA) to isolate their mechanical effects on starch films. In other related literature it can be observed that the film blend mixtures make use of multiple additives in one film blend. The study by Syaubari et al. (2022) explores starch film blends with both glycerol and chitosan. The study by Lestari et al. (2020) included the addition of sorbitol to PVA, instead of only incorporating PVA by itself. These studies were not able to set a proper benchmark as to how a specific additive could affect the starch film blend by itself. With the study by Ayyubi et al. (2022), one film blend was done per additive. This serves as a clear basis as to how each additive would respond to the test for tensile strength and elongation at break. The study of Ayyubi et al. (2022) does not consider the material costs when determining the optimal composition. The study is optimized to achieve a single objective as it does not consider the conflicting objectives of simultaneously maximizing tensile strength and elongation. Nwaka et al. (2024) optimized starch-chitosan-glycerol bioplastics via CCD, achieving 2.25 MPa strength and 92.31 % biodegradability in 21 d.

This shows superior degradation but lower strength than the single-additive samples from Ayyubi et al. (2022) Similarly, Adeyemo et al. (2024) used Box-Behnken RSM to develop waste-corn bioplastics (1.44 MPa strength, 12.02 % elongation) with 99.01 % model accuracy. This demonstrates the effectiveness of using CCD/RSM for balancing biodegradability and mechanical properties. It should be noted that fuzzy optimization is well-suited for handling multi-objective trade-offs, as it allows for the simultaneous consideration of conflicting objectives through membership functions and degrees of satisfaction (Zimmermann, 1978). It is also important to acknowledge that various other optimization techniques exist for multi-objective problems, each with distinct advantages. Weighted sum methods transform multiple objectives into a single objective by assigning weights, though this approach can be sensitive to weight selection (Marler and Arora, 2004). Currently RSM is a tool used for the optimization of biodegradable plastic production. The integration of other methods can further enrich decision-making frameworks. Future discussions could explore hybrid approaches to optimize trade-off of the maximization of mechanical properties, minimization of environmental impacts, and minimization of costs.

5. Conclusion

This review underscores the critical transition toward biodegradable plastics derived from renewable resources, aiming to mitigate plastic pollution while enhancing material performance. By examining key studies on cassava, corn starch, and banana-based materials, the paper highlights how optimized formulations and additives can significantly improve mechanical properties such as strength, flexibility, and water resistance. The application of multi-objective optimization emerges as a pivotal strategy for balancing performance and scalability, ensuring that biodegradable plastics meet both environmental and industrial requirements. By synthesizing recent advancements, this review serves as a valuable resource for researchers, industries, and policymakers, facilitating informed decisions in the development and implementation of sustainable biodegradable plastics. The insights provided herein aim to accelerate the adoption of eco-friendly materials, contributing to global sustainability goals and the reduction of ecological harm associated with traditional plastics.

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