Impact of Bioplastics Toward Sustainable Environment

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Submitted on: 12-09-2024, Revised on: 22-11-2024, Accepted and Published on: 30-11-2024 **Review**

Abstract: The extensive use of fossil-based plastics, owing to their remarkable material properties, versatility, and low cost, has posed a major threat to global plastic waste management. The reluctance to degrade single-use plastics has led to the severe problem of plastic pollution at the global level. The demand for one-time-use plastics has increased exponentially during the COVID-19 pandemic. To combat plastic waste pollution worldwide, researchers are looking for an alternative pathway to replace traditional oil-based plastics, especially those that are difficult to recycle. Today, Bioplastics is acknowledged as a sustainable substitute for conventional plastics. Bioplastics manufactured from renewable and biodegradable polymers contribute toward a sustainable and circular plastic life cycle, reducing the dependency on oil-based plastics. Bioplastics offer a promising solution to plastic pollution because they have a lower carbon footprint and noteworthy physicochemical and biological properties. In this review article, we have focused on Bioplastics' properties, advantages, and challenges in transitioning toward sustainability to foster a circular economy. Furthermore, we discuss potential applications of Bioplastics in various fields. However, to ensure circularity, it is necessary to realize the role of bio-based plastics, their disposal, and recycling, thereby making a sustainable impact on the bio-plastic market.

***Keywords**: Bioplastics, sustainability, circularity, plastics.*

INTRODUCTION

Plastic materials comprise a wide range of polymeric composites with polymers as the main unit. For the past 50–60 years, commercial petroleum-based polymers have significantly ruled our daily routines. Plastics have many advantages, including low production costs, good strength, durability, and high chemical and corrosion stability. From 1950 to 2018, there was a significant rise in plastic production, varying from 1.5 to 359 million metric tons (Vlasopoulos et al., 2023). However, significant problems arise owing to the extensive use of plastics and their dependability on them, which is a grave threat to the physical world and the World Bank of Natural Resources, which in turn is associated with severe health risks.

Thermoplastics and thermosetting are two categories of polymeric materials. Thermoplastics soften when heat is provided and stiffen again when cooled, and thermoset polymers cannot be remolded. Currently, most polymeric materials (thermoplastics and thermosetting) are petroleum-derived, unsustainable, and even limited to the polymer market (Bîrcă et al., 2019). Currently, plastic materials can be made renewable through the convergence of consumer needs, improvement of technology, and making them easier to obtain than before.

Therefore, many countries are looking for Bioplastics as an alternative to nonrenewable plastics because they are not environmentally friendly and nonbiodegradable; hence, Bioplastics can be a sustainable solution to plastic pollution.

Bioplastics are a type of bio-based, biodegradable polymer material that is completely dependent on the source from which they are manufactured. Bioplastics were discovered about a century ago with galatith and polyhydroxyalkanoates (PHAs) (Quero, 2016). Bio-based methods indicate that bio-based polymers are entirely or partly obtained from renewable biomass materials derived from natural reusable materials of bio-origin or natural waste such as plants, bacteria, and algae (Coppola et al., 2021). Forex biopolymers derived from animals, plants, and natural fibers such as jute, bamboo, hemp, and flax have the potential to replace traditional nonbiodegradable petrochemical resins (Elfaleh et al., 2023). Define the term "biodegradable," it can be explained as a substance that naturally breaks down into simpler components with time, including CO_2 and H_2O, or is degraded by the action of microorganisms. Plastics that break down naturally maintain specific biodegradability standards (Folino et al., 2020). Likewise, compostable plastics undergo natural degradation in commercial composting capacities with certain biodegradability standards to meet requirements.

With upcoming discoveries, to compete with traditional plastics, such as polystyrene, polypropylene, and polyethylene terephthalate, more sustainable and eco-friendly plastics are being designed with unique physical and esthetic qualities. To minimize environmental concerns, modern natural bio-originated substances are gaining advantages and have become increasingly popular because of their ability to reduce environmental issues without compromising the demand for polymers and composites. As part of the circular economy, Bioplastics degrade sustainable commercial plastics, whereas pristine polymers are derived from renewable or recycled feedstocks, as illustrated in Figure 1 (Ali et al., 2023).

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DOI:10.70130/RCS.2024.0101002

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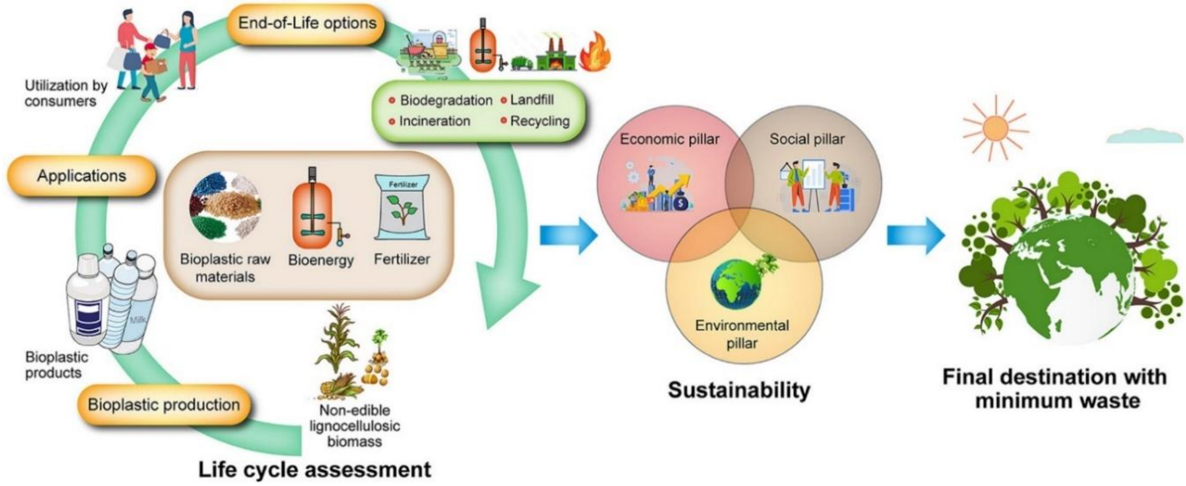


Figure 1. **Life cycle analysis of Bioplastics (Ali et al., 2023)**

Although Bioplastics can be designed to perform better than traditional plastics, they can act similarly throughout the production process. Plastics are produced worldwide, whereas Bioplastics account for only a small percentage of total plastic production. The key concern of bio-based plastics is cost, as industrial manufacturing processes are quite expensive, and the manufacturing cost can be reduced by mixing biodegradable waste or reducing the biodegradable polymeric fraction required to produce bio-based plastics (Rosenboom et al., 2022). It is possible that, in the future, Bioplastics will gain dominance in the market and replace petroleum-based products. In addition, we must consider social demand for a sustainable daily lifestyle. It is necessary to adopt suitable green alternatives to reduce ecologic degradation caused by pollution, climatic changes, and related health risks. We must focus on the various aspects required for transformation by promoting the technologies necessary for introducing bio-based plastics as superior alternatives to nonbiodegradable plastics. Achieving this concept requires fine-tuning of the extensive knowledge developed in research laboratories and scaling it up for industrial implementation.

CLASSIFICATION OF BIOPLASTICS

Bioplastics are a category of plastics synthesized from renewable biomass sources such as microbes, polysaccharides, or agricultural products, either exclusively or partially. They limit the use of fossil-based plastics because of their natural recyclability through biological processes. Biodegradable plastics are of two types: agriculture-based polymers (protein, starch, and chitin) and bio-based polyesters such as polylactic acid (PLA) and PHA (Dilshad et al., 2021). The chemical structure of a polymer determines its biodegradability rate. However, biodegradability does not depend on the monomer (Siracusa & Blanco, 2020). The main categories of bio-based plastics include bio-based and biodegradable, fossil-based and biodegradable, bio-based and nonbiodegradable, and fossil-based and nonbiodegradable plastics (c/a as plastics). The characteristics of some Bioplastics are shown in Figure 2. summarizes the different types of Bioplastics (Siddiqui et al., 2024). Table 1. Contains the chemical structures of some commonly used Bioplastics.

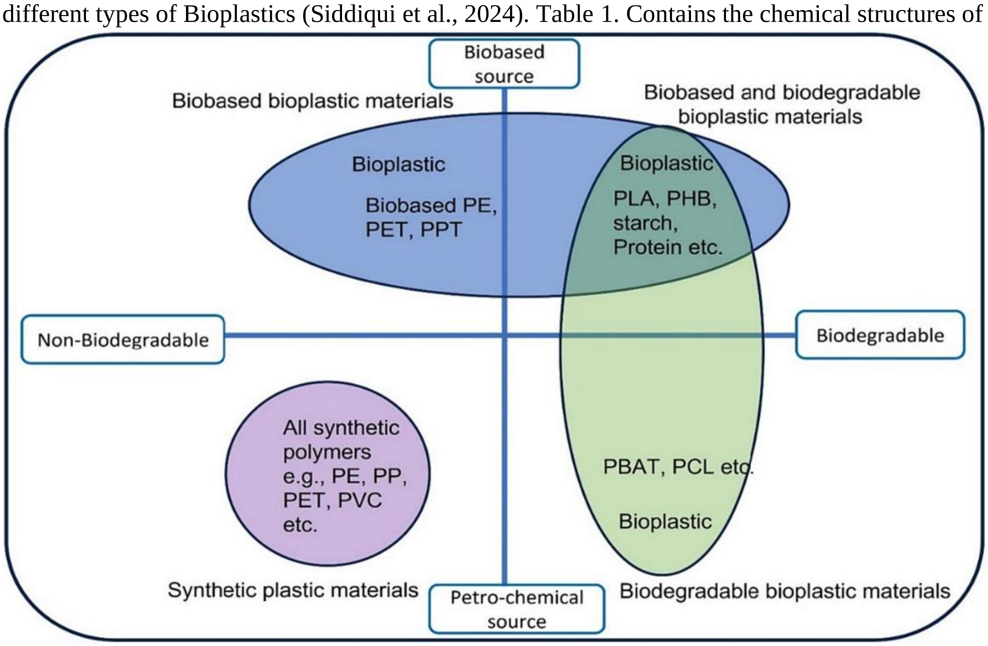


Figure 2. **Classification of Bioplastics (Siddiqui et al., 2024)**

STARCH BASED POLYMERS

Starch-based polymers contain starch moieties that are either pristine or functionalized. This type of biopolymer attracts consumers owing to its low availability, environmental friendliness, and renewability. Starch is considered the most studied biopolymer and is used in the production of edible coatings and films because of its low cost. Compared to plastic-based Bioplastics, starch-based biopolymers have the same mechanical and optical characteristics (Hassan et al., 2019).

POLYHYDROXYALKANOATE

PHA, a form of thermoplastic polyester and elastomeric material prepared using monomeric (R)-3-hydroxyalkanoic acid molecules, is produced by some bacterial organisms to convert intracellular energy and carbon (Pradhan et al., 2020). The biocompatibility, biodegradability, and environmental friendliness of this polyester class make them noteworthy. PHA and PHA-based materials have been shown to have multiple potential uses, including memory enhancers, drug transporters, biodegradable implants, tissue engineering materials, biocontrol agents, and anticancer and antibacterial agents. Different microorganisms produce PHAs when given carbon sources, regulated nitrogen, oxygen, and phosphorus concentrations in the growth medium, and an ideal pH. Certain bacteria convert carbohydrates and lipids into linear polyesters, such as polyhydroxyalkanoate, which are used as carbon and energy storage molecules. These polyesters, combined with a range of other functional monomers in an optimized manner, provide novel materials with customized and enhanced physicochemical characteristics (Ojha & Das, 2021).

POLYLACTIC ACID

Unlike other synthetic polymers, PLA is a thermoplastic polymer that is produced from natural resources. Lactides, that is, lactic-acid monomers, are building components that polymerize to produce PLA. PLA has attracted significant interest because of its superior mechanical properties compared to conventional polymers, including polyethylene (PE), PET terephthalate, and polystyrene. Furthermore, PLA has favorable properties such as better thermal flexibility, nontoxicity, greater mechanical strength, biocompatibility, and biodegradability. PLA is widely used in various industries, including buildings, agriculture, transportation, furniture, electronics, home goods, textiles, and fibers, as well as for degradable packaging materials for food materials because of its low manufacturing cost, degradable natural precursors, mechanical characteristics, flexibility, chemical and thermal stability, ability to heat seal at lower temperatures, and resistance to flavor and scent changes (Andrew & Dhakal, 2022).

POLY-3-HYDROXYBUTYRATE

The PHA group includes PHB (poly-3-hydroxybutyrate), a well-known biodegradable and biocompatible polymer. The microbial fermentation of renewable glucose sources yields PHB (Koller). Several enzymatic stages are involved in this synthesis pathway.

- β-ketothiolase mediates the condensation of acetoacetyl-CoA (acetoacetyl-CoA) to produce acetoacetyl-CoA.
- Acetoacetyl-CoA is converted into 3-hydroxybutyryl-CoA.
- Poly-3-hydroxybutyrate synthase catalyzes 3-hydroxybutyryl-CoA polymerization, resulting in the formation of poly-3-hydroxybutyrate.

PHB is created by this process and has applications in drug delivery systems, medical implants, and biodegradable polymers. When mixed with different antimicrobial agents, poly-3-hydroxybutyrate films show a notable reduction in the growth of microorganisms. Several studies have shown that antimicrobial agents, if used, can increase the efficacy of poly-3-hydroxybutyrate films. Vanillin has been proven to be more efficient than bacteria (Briassoulis et al., 2021).

In addition to considerable antifungal effects against *Botrytis cinerea*, PHB (poly-3-hydroxybutyrate) films containing 2.5–3% eugenol demonstrated significant radical-scavenging activity (~92%). These results imply that eugenol-infused poly-3-hydroxybutyrate films have potential as bio-composite materials for use in the food packaging sector owing to their antifungal and antioxidant properties (Nanda et al., 2022).

The production of PHB (poly-3-hydroxybutyrate) by microorganisms (such as prokaryotes, actinomycetes, algae, archaea, and bacteria) is of great commercial (Behera et al., 2022). In response to acute stress, marine microbial species produce intracellular poly-β-hydroxybutyrate (β-PHB), which utilizes carbon and energy. These aquatic organisms have extraordinary resilience, which helps reduce the harm caused by cellular freezing and dehydration. PHB sourced from marine microorganisms has garnered significant interest because of its cost-effectiveness. Furthermore, the high amounts of salt found in maritime areas aid in lowering the possibility of infection by other microbes (George et al., 2020).

NYLON 11

Nylon-11 (polyamide 11) is a bio-derived polymer that is part of the nylon group. 11-aminoundecanoic acid was polymerized to prepare Nylon-11. Castor oil and other bio-based renewable materials are the main sources. Owing to its remarkable mechanical and chemical resilience, polyamide 11 is desirable from both industrial and environmental perspectives. Compared to other polyamides, polyamide 11 is thought to be a better reinforcement material for natural fibers because of its high melting point of approximately 200 °C (Carter, 2022). Composites made of polyamide 11 are recyclable even though they are not biodegradable. It is especially well suited for applications that require long-term endurance. It is used in many different manufacturing industries to produce wires, clips, cables (electrical), tubing (water tubing), pipes to carry natural gases, aerospace, coatings, and strings used in sports goods. Nylon is used as a bristle in toothbrushes and fabrics in the textile industry (Chang et al., 2020).

According to recent studies, the mechanical characteristics of polyamide 11 modified using lignocellulosic fibers are similar to those of polypropylene composites reinforced with glass fibers (Lods et al., 2022). Both biopolymers and wood-fiber-based wood-plastic composites provide substantial durability gains and carbon footprint reductions. PA 11 appears to be promising for the creation of bio-based wood-plastic composites reinforced with beech fibers and was studied by Zierdt et al. They found that the materials had better mechanical and thermal qualities, such as high elastic and storage moduli, which made them easier to use in the production of door handles and other interior automobile components (Oliver-Ortega et al., 2021). However, polyamide 11 composites use a large amount of energy, similar to composites made of polypropylene.

CELLULOSE-BASED BIOPOLYMERS

Cellulose, a common natural biopolymer found in large amounts in lignocellulosic biomass, is obtained from forestry and agriculture. Cellulose is formed from a combination of glucose monomers joined by strong β-1,4 glycosidic bonds. The biodegradability, durability, strength, and stiffness of cellulose-based biopolymers are the main reasons for their increasing popularity. Cellulose-based reinforced composites are inexpensive, nonabrasive, and have a low density. Weak hydrogen bonds can impair mechanical qualities such as strength and flexibility, even though they are present in cellulose-based Bioplastics, which accelerates deterioration (Tedeschi et al., 2020). It has been demonstrated that the addition of chitosan and pectin to cellulose can increase its transparency, elasticity, and stability. However, the lack of heat stability, interfacial adhesion, and water sensitivity of cellulose makes cellulose-based composites less desirable.

Bioplastics prepared using cellulose-based raw materials (e.g., cellulose acetate) are widely used as packaging films for food items, eyeglass frames, and other speciality products. The demand for cellulose-based Bioplastics is driving the market for these materials, which are used to make transparent dialers, screen protectors, and comfortable electronics, such as headphones, cosmetic boxes, and interior parts of vehicles (Aida et al., 2021). Furthermore, three-dimensional printing, biological applications, and medicine make use of cellulose and its derivatives. Phenylpropane polymer lignin, which is naturally present in lignocellulosic materials, is also a suitable raw material (as a precursor) for producing bio-based plastics (Choi et al., 2022). u

PROTEIN AND LIPID-BASED BIOPOLYMERS

A range of proteins (both plant- and animal-based), including gluten (wheat-based), protein (Soy-based, Whey, zein, casein), collagen, and gelatin, can be used to create Bioplastics. Peptide bonds bind amino acids to form proteins with better mechanical characteristics than polysaccharides. Protein-based films are composed of globular or fibrous structures organized by ionic, covalent, and hydrogen bonds. Proteins are frequently used as packaging materials because of their quantity, nutritional value, biodegradability, and superior film-forming ability (Hadidi et al., 2022). Protein-based films outperform lipid and polysaccharide films in terms of mechanical strength and gas and scent barriers.

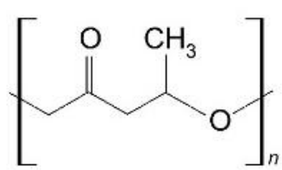
Because protein-based biopolymers have better mechanical qualities than polysaccharides, they are often used in edible films. Keratin protein-infused synthetic elastomers exhibit better mechanical properties, flame resistance, and thermal stability. When soy protein is combined with latexes, the resulting materials exhibit characteristics similar to those of elastomers filled with carbon black.

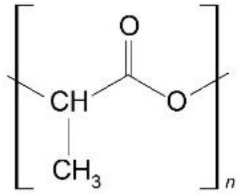
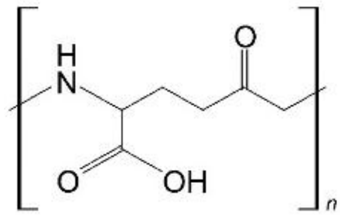
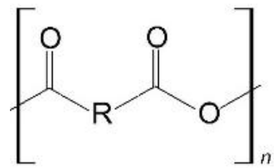
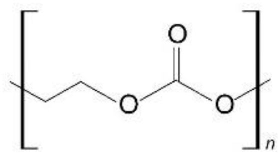
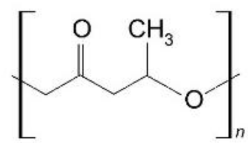
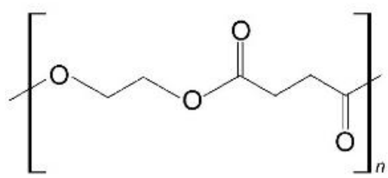
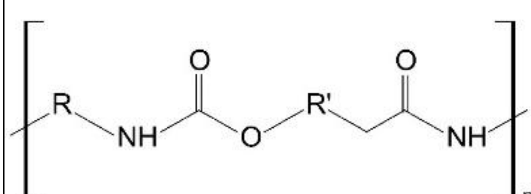
The main components of lipids, such as long-chain fatty acids and alcohols, terpenes, glycerides, and phospholipids, in lipid-based edible coatings and films are responsible for benefits, including cost-effectiveness, retention of moisture, and a glossy appearance. Oil- and fat-based bio-polymeric films are transparent, elastic, and water-resistant, making them ideal for packaging edible products. Furthermore, the use of essential oils in coatings and films enhances their antibacterial properties. Plant-based resins also help to increase emulsion stability, providing a glossy surface that prolongs the shelf life (Chen et al., 2019).

Owing to the hydrophobic nature of lipids, food industries have advanced significantly by adding lipids to edible coating films to prevent moisture from moving through food to preserve food goods. Owing to their antibacterial properties and hydrophobicity, essential oils such as terpenoids and aromatic compounds are used in the food sector to produce biopolymers. Similarly, waxes are frequently used as coatings for edible vegetables and fruit packing sheets (Bhaskar et al., 2023).

Table 1

Chemical Structure of Commonly Used Bioplastics

S. No.	Name	Structure
1	poly(3-hydroxybutyrate)	

2	poly(lactic acid)	
3	poly(γ-gluatmic acid)	
4	polyanhydride	
5	poly(ethylene carbonate)	
6	poly(3-hydroxybutyrate)	
7	poly(ethylene succinate)	
8	polyurethane	

ADVANTAGES AND DISADVANTAGES OF BIOPOLYMERS

ADVANTAGES OF BIO-BASED PLASTIC:

Renewable Resource

unlike conventional plastics, which come from limited fossil fuel supplies such as petroleum, Bioplastics come from degradable biomass reservoirs, including corn, sugarcane, and vegetable oils. By using renewable resources, the negative environmental effects of fossil fuel extraction are reduced and concerns about resource shortages are mitigated.

Biodegradability:

the capacity of some Bioplastics to break down into less complex substances when exposed to environmental conditions, such as heat, moisture, and microbial activity, is known as biodegradability. Compared to conventional plastics, which can withstand prolonged exposure to the environment, this degradation process occurs more quickly. Particularly in delicate ecosystems such as marine habitats, biodegradable Bioplastics show promise in lowering litter and environmental contamination (Altalhi, 2022).

Decreased greenhouse gas Emissions:

When compared to traditional plastics, Bioplastics may have a lower carbon footprint, particularly if they are produced using energy-efficient processes and come from biomass reservoirs that are managed sustainably. Growing biomass crops offers benefits such as reducing greenhouse-gas emissions and sequestering CO_2. Bioplastics contributes to the mitigation of climate change, thereby reducing the reliance on conventional fuel-based plastics by encouraging sustainable production methods (Ashter, 2016).

Diversification of Feedstock:

diversification of feedstock involves broadening the biomass sources from which Bioplastics can be synthesized. Probable feedstock sources for bio-plastic production include agricultural residues, nonfood crops, algae, and biomass reservoirs. This reduces the sole dependence on certain crops or sources, thereby promoting sustainability. This also helps agriculture become more resilient (Friedrich, 2021). Utilizing nonedible biomass feedstock reduces competition for food production and the manufacturing of Bioplastics using the same biomass resource.

Biocompatibility:

The biocompatibility of a few Bioplastics allows them to be used in pharmaceuticals, drug delivery systems, medical devices, and so on, without causing any negative side effects. Biocompatible Bioplastics support advances in medical technology and healthcare as well as better patient outcomes and lower chances of infections or allergic reactions (Reddy et al., 2013).

Innovation and Research

Advances in materials science, polymer chemistry, and biotechnology have been fueled by the development of Bioplastics. The goal of ongoing research on new biomaterials, processing methods, and the use of Bioplastics is to improve their efficiency, affordability, and sustainability. This invention promotes the development of sustainable and environmentally favorable substitutes for traditional plastics, advancing toward a circular economy (Costa et al., 2023).

SHORTCOMINGS OF BIO-BASED PLASTIC

Resource Competition

Growing crops on a large scale for the manufacture of Bioplastics may put food production and other agricultural operations in competition, which could put more strain on arable land, water resources, and biodiversity. Sustainable bio-plastic manufacturing depends on striking a balance between the need for biomass feedstock and priorities including food security, land conservation, and fair resource distribution (Abe et al., 2021).

Limited Biodegradability

Although certain Bioplastics are designed to break down naturally under certain circumstances, others can require anerobic digestion or industrial composting. The natural degradation of bio-based plastics is affected by moisture, temperature, and microbial activity. Incomplete or partial degradation of Bioplastics results in the formation of microplastics, which further contributes to environmental pollution (Abe et al., 2021).

Performance and Durability

Generally, Bioplastics possess low mechanical strength, such as lower tensile strength, impact resistance, and thermal stability compared to conventional plastics. This shortcoming restricts the use of Bioplastics, especially in areas where durability is foremost. Therefore, it is necessary to manufacture Bioplastics with comparable functionality and robustness, without compromising their environmental impact (Ibrahim et al., 2021).

Increased manufacturing expenses

Compared to plastics, the manufacturing of Bioplastics involves high cost, specialized equipment, renewable and biodegradable feedstock, and infrastructure. This may make the bio-plastic manufacturing industry less competitive in the market owing to its high cost (Wellenreuther et al., 2022). However, it is essential to overcome this high-cost barrier through technological advancements and process optimization by making Bioplastics affordable and feasible.

Compatibility and Recycling Issues

Owing to the differences in material qualities and processing methods, waste management and recycling in the case of Bioplastics might be different from conventional plastics. However, recycling petro-based plastics and Bioplastics disturbs the recycling stream and produces low-quality products. The lack of standardized labeling and collection methods makes it difficult to distinguish Bioplastics from fossil-based plastics, thereby affecting the circularity of recycling. Therefore, it is necessary to develop appropriate recycling methods and labeling guidelines (Lamberti et al., 2020).

Concerns about Land Use and biodiversity

Extensive monoculture plantations of biomass feedstock for bio-plastic production may lead to a reduction in soil fertility, nutrient depletion, soil erosion, habitat degradation, deforestation, and biodiversity loss, thereby affecting the natural ecosystem. Additionally, the use of fertilizers and pesticides has a negative effect on water pollution and greenhouse-gas emissions (Lamberti et al., 2020). Therefore, it is essential to protect natural ecosystems by incorporating agroecologic approaches and sustainable land management techniques.

Although Bioplastics offers many benefits such as renewable feedstock, biodegradability, and biocompatibility, they also have shortcomings as mentioned above (Atiwesh et al., 2021). To overcome these drawbacks, technological advancements, sustainable practices, and stakeholder participation in business expansion must be followed. This transition toward sustainable-circular Bioplastics has the potential to create a balance between social, environmental, and economic demands (Merchan et al., 2022). Polymer composites of Bioplastics with the desired characteristics can be fabricated by tailoring various mechanical properties. However, these composites did not exhibit the desired stability and durability. Therefore, the following mechanical properties must be manipulated to enhance durability to meet the requirements for a particular application.

PROPERTIES OF BIO-BASED PLASTICS

The characteristics of bio-based plastics can be understood through the evaluation of their mechanical properties, including tensile properties, flexural properties, impact, and hardness. These tests help determine the applications of Bioplastics based on their mechanical behavior.

Tensile Properties: tensile properties represent how a material responds to tensile stress. The tensile properties are assessed through processes that exert steady pressure and pull apart a material to witness its breaking point (Rajeshkumar et al., 2023). The tensile strength provides information about the ductility, Young's modulus, modulus of elasticity, elongation at break, and elasticity of the material, and reveals the maximum strength that the polymer can withstand before failing (Nandiyanto et al., 2020).

Flexural Properties: flexural properties are useful for analyzing polymers for structural applications. Flexural testing, also known as the transverse beam test, is used to measure these properties. To conduct this test, a rectangular specimen must be bent in either a three- or a four-point manner. Factors, including the tension transmission between the fiber and matrix and their interfacial connections, affect the flexural characteristics (Boey et al., 2024). The ratio of the applied stress to the deflection is shown by the flexural modulus, whereas the flexural strength measures the highest stress at failure.

Impact Properties: Izod (Charpy) impact tests are generally used for impact testing to assess the toughness, notch sensitivity, and impact strength of a material. Impact strength indicates how well a material can tolerate high loading rates, whereas toughness quantifies the energy absorbed per unit volume until breakage. Materials with higher toughness are more resistant to breakage (Aldas et al., 2020). Impact testing is crucial, especially for polymer materials, to evaluate product performance, safety, liability, and service life.

Hardness: The resistance of a material to wear and tear characteristics, such as indentation, abrasion, compressive deformation, and scratching, is indicated by its hardness. Numerous techniques, including Shore hardness testers, Brinell (Zhou et al., 2023), Vickers hardness testers, and Rockwell hardness testers, can be used to quantify surface hardness. Greater resistance to other materials penetrating the material, as indicated by the higher hardness levels, makes the material less prone to wear and erosion. This feature is useful in technical applications in which resistance to friction and durability are critical factors.

MECHANICAL CHARACTERISTICS OF SPECIFIC BIOPLASTICS

The mechanical characteristics of Bioplastics depend on factors such as their composition, processing method, and intended application. The mechanical characteristics of some Bioplastics are summarized as follows:

PLA:

a. Tensile Properties: the tensile strength of polylactic acid varies from 50 to 70 MPa, which is equivalent to the tensile strength of PET terephthalate.
b. Flexural Strength: the flexural strength of PLA varies from 70 to 100 MPa and thus finds application in making products that require rigidity and stiffness.
c. Impact Strength: PLA generally has poor impact properties compared to other polymers. However, the impact properties of PLA can be improved by the addition of modifiers.
d. Elongation at Break: PLA has low elongation at break, which signifies lower flexibility before failure (Aworinde et al., 2021).

PHAs, or polyhydroxyalkanoates:

a. Tensile Strength: PHB tensile strength varies from to 20–60 MPa that varies with the composition and processing parameters.
b. Flexural Strength: PHA has a moderate flexural strength between 30 and 70 MPa, which allows it to withstand deformation and bending.
c. Impact Strength: PHA exhibits excellent impact strength and frequently shows outstanding resistance to impact, making it ideal for use in terms of toughness and longevity.
d. Elongation at break: PHA exhibits moderate elongation at break, suggesting a certain level of flexibility before failure (Behera et al., 2022).

Bio-based PE and bio-based polypropylene (PP):

a. Tensile Strength: the tensile strength of bio-based PE and bio-based PP varies from 20 to 40 MPa for PE and 30–50 MPa for PP, which is comparable to conventional plastics.
b. Flexural Strength: the flexural strengths of bio-PE and bio-PP were 20–50 MPa and 30–60 MPa, respectively.
c. Impact Strength: depending on the formulation and processing techniques, Bioplastics based on PE and PP may show comparable impact resistance to conventional plastics (Ali et al., 2023).
d. Elongation at Break: bio-PE and bio-PP exhibit moderate flexibility, and the elongation at break is comparable to that of conventional plastics.

Starch-based Bioplastics:

a. Tensile strength: starch-based Bioplastics have low tensile properties, such as a tensile strength of 10–30 MPa.
b. Flexural Strength: the flexural strength varies from 10 to 40 MPa depending on the formulation and processing methods.
c. Impact Strength: starch-based Bioplastics generally exhibit low impact strength but can be modified to the compared value of traditional plastic forming blends, composites, and so on.
d. Elongation at Break: Bioplastics derived from starch usually exhibit considerable elongation at break, indicating some flexibility before failure (Nandiyanto et al., 2020).

These mechanical characteristics provide broad insight into the behavior of various types of Bioplastics. When assessing their applicability, it is important to consider their precise formulation, processing characteristics, and intended use. Research is still being conducted to modify the mechanical characteristics of Bioplastics so that they can be used in more applications and outperform conventional plastics.

CHALLENGES IN PRODUCTION AND USE OF BIOPOLYMERS

Approximately 4% of global annual crude oil consumption is used to produce synthetic plastics. The production of synthetic plastics may be adversely affected by changes in the demand for crude oil and its prices. Furthermore, compared to synthetic polymers, Bioplastics consume less energy for production. Compared to the energy required to produce petrochemical-based plastics, which can require between 78 and 88 MJ/kg of resin, the energy input from fossil fuels in the case of Bioplastics is projected to be 44 MJ/kg of bio-resin (Nadda et al., 2022). Bioplastics have many benefits, but they also have several drawbacks and technological difficulties, such as the formation of intermediate products in the production process of Bioplastics, which may pollute the conventional plastic recycling process if not appropriately separated and processed. Furthermore, the vast majority of Bioplastics manufactured now come from (first-generation) feedstock, including cassava, wheat, sugarcane, corn, and potatoes. The use of (first-generation) feedstocks, especially starch-based materials, for producing biofuel, bio-based chemicals, and bio-based materials is controversial because it competes with food supplies, arable land, agricultural energy, and financial investments. To overcome this problem, research into nonfood consisting of lignocellulosic feedstocks, including waste biomass, invasive plants such as weeds, and agricultural crop residues, is required to extract fibers, natural polymers, and resins (Alias et al., 2022).

Bioplastics frequently exhibit unpredictable biodegradation, especially polymers, which require regulated environments to break down effectively. Furthermore, extra steps for end-of-life management may be necessary for Bioplastics that consist of synthetic polymers derived from petrochemicals (de Souza & Gupta, 2024). In essence, the necessary environmental factors, including pH, temperature, and humidity, are not easily met in landfills required for the degradation of Bioplastics. In addition, the establishment of bio-plastic disposal facilities requires the following: setting aside land, maintaining a controlled environment, regular monitoring, encouraging microbial development, introducing microorganisms that break down polymers along with their food source, periodically extracting intermediates and by-products, and initial capital expenditure (Bhatia et al., 2021). The major challenges are presented in Figure 3. are discussed below:

Material Performance and Characteristics: obtaining material properties that are on par with or better than those of conventional plastics is a major research challenge for Bioplastics. Compared to plastics made from petroleum, Bioplastics frequently exhibit worse tensile, thermal, and barrier qualities. Improving the performance of Bioplastics while maintaining their sustainability requirements is a significant scientific challenge (Attallah et al., 2021).

Availability and Competition of Feedstocks: obtaining sustainable biomass feedstock is a critical challenge for the manufacture of Bioplastics. Competition for resources and land between food and nonfood crops raises questions regarding the ecologic and social sustainability of Bioplastics. Reducing the environmental impact of feedstock agriculture and finding alternative feedstock sources that do not interfere with food production are ongoing issues (Wellenreuther et al., 2022).

Biodegradability and Management of end of life: even though some Bioplastics have the desirable property of being biodegradable, it can be challenging to ensure proper end-of-life management. Improper disposal techniques can lead to pollution and environmental harm, whereas biodegradable plastics may require specific conditions to break down. For effective waste management, a standardized infrastructure for the labeling, collection, and composting of biodegradable Bioplastics is essential (Sikorska et al., 2021).

Processing and Manufacturing: owing to differences in material qualities and processing requirements, bio-plastic processing and manufacturing present technical hurdles. Significant progress in processing technology, additives, and formulation strategies is needed to ensure consistency and quality in bio-plastic production, particularly on an industrial scale (Rosenboom et al., 2022).

Cost Competitiveness: because of many considerations, such as processing methods, economies of scale, and feedstock availability, the cost of Bioplastics is still higher than that of regular plastics. The cost-effective production of Bioplastics without compromising their mechanical properties and sustainability is a major challenge that needs to be addressed (Wellenreuther et al., 2022).

Durability and Stability: durability and stability are the major characteristics of Bioplastics that should be improved to make them popular in the market. Factors such as temperature change, moisture exposure, and environmental elements should have no effect on the functionality of the material (Alias et al., 2022).

Regulatory and Standardization Issues: standards must be set for bio-plastic labeling, certification, and mechanical testing to avoid confusion, complexity, and unpredictability in the global bio-plastic market (Stoica et al., 2022).

Ecological Assessment and Ecological Measures: to evaluate the environmental impact of Bioplastics through life cycle assessment, various factors such as resource consumption, end-of-life scenarios, and greenhouse-gas emissions should be considered. It is essential to formulate standardized strategies and sustainability indicators to develop policies that can distinguish between Bioplastics and conventional plastics (Bishop et al., 2021).

Research and Innovation: there is much scope for innovation and technological advancement in this area, including finding novel renewable feedstock, improved mechanical and material properties, cost-effective processing techniques, and inventive applications of Bioplastics in several fields for commercialization (Garcia-Garcia et al., 2022).

The use of Bioplastics is closely related to their long-term sustainability. It is important to disseminate knowledge about Bioplastics in both urban and rural communities. This includes information on their use, composition, environmental effects, composting, and waste segregation at the consumer or household level. Such initiatives are crucially important for determining the future course of the bio-plastic market and encouraging expansion in the agricultural industry to satisfy the need for raw materials. Strict regulations that prohibit the utilization of single-use plastics and encourage the use of Bioplastics, from large-scale industrial applications to commercial packaging, can significantly help solve environmental problems.

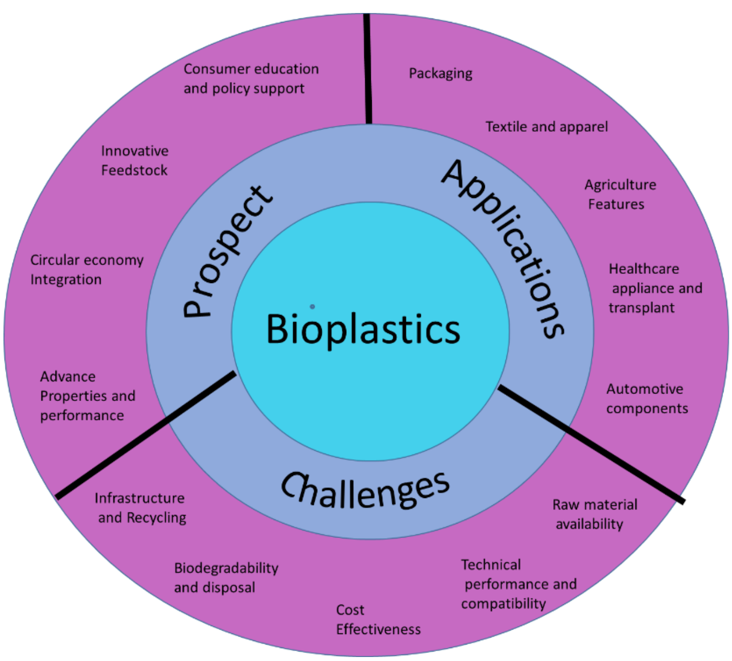


Figure 3. **Applications, challenges and prospects of Bioplastics**

STRATEGIES TO COMBAT CHALLENGES OF BIOPLASTICS

Various stakeholders and solutions must be involved in a complete strategy to address issues surrounding Bioplastics. This is a thorough approach for overcoming these obstacles.

A. *Advancement of research in Polymer Chemistry*: exploring cutting-edge catalysts and polymerization strategies to promote the production of Bioplastics with enhanced mechanical, thermal, and barrier properties. Live radical polymerization, ringopening polymerization, and metathesis polymerization are examples of controlled/living polymerization techniques that can be used to produce polymers with precisely regulated structures and characteristics (Gao et al., 2020).

B. *Biopolymer Blending and Modification*: to customize the performance of Bioplastics, blending techniques that mix biopolymers with distinct characteristics have been investigated. Chemical modification techniques such as cross-linking, grafting, and copolymerization result in composites with improved stability, processability, and mechanical properties (Palacios et al., 2023).

C. I*ncorporation of fillers and functional additives*: incorporation of fillers and additives of renewable biomass origin improves mechanical strength and thermal stability. Some of the commonly used biomass sources include natural fibers, lignin derivatives, nanocellulose, and bio-based fillers (Tan et al., 2022).

D. *Boosting Biodegradation*: biodegradation of Bioplastics can be improved by various methods, such as the incorporation of biodegradable additives or compatibilizers. Designing Bioplastics capable of enzyme or microbial degradation will improve the decomposition rate of Bioplastics in marine habitats as well as in soil (Meereboer et al., 2020).

E. *Green Solvents and Processing Methods*: use of green solvents and environmentally benign processing methods such as supercritical fluid technologies, solvent polymerization, and aqueous-based processing techniques for the manufacture of Bioplastics reduces energy consumption, waste production, and environmental impact (Ramchuran et al., 2023).

F. *Bio-Based Monomer Synthesis*: designing catalytic procedures for the synthesis of monomers such as terpenes, fatty acids, and sugars from biomass feedstock makes the entire process of bio-plastic manufacturing more sustainable and resilient (Dourado Fernandes et al., 2022).

G. *Principles of Green Chemistry*: the principles of green chemistry must be considered while processing, designing, and manufacturing Bioplastics. This leads to a reduction in waste, utilization of renewable feedstock, minimal consumption of electricity, and development of safer products. This ensures environmental safety and security (Sheldon & Norton, 2020).

H. *Improving End-of-Life Care and Biodegradability*: issues related to the end of life of Bioplastics should be properly evaluated by studying different options for waste disposal. Common end-of-life scenarios include composting, recycling, and upcycling. Proper guidelines, standardizing regulations, labeling, and certification processes for biodegradable plastics should be issued. This provides information to experts and customers regarding the appropriate handling and disposal of Bioplastics postuse and thus helps in reducing the ecologic footprint (Sikorska et al., 2021).

I. *Making Sure of Market Penetration and Cost Competitiveness*: providing financial assistance such as grants and subsidies encourages the commercialization of Bioplastics (Iles & Martin, 2013).

J. *Encouragement of Research and Innovation Projects*: provide money and resources to support basic and applied studies on bio-plastic materials, technology, and uses (Iles & Martin, 2013). Cooperation and information sharing across government, business, and academic research organizations should be encouraged to tackle important technical issues and hasten the development and commercialization of Bioplastics. Governments, industries, and financial institutions should work together to encourage investment in bio-plastic production and innovation.

CONCLUSION

Owing to their complex and heterogeneous compositions, conventional synthetic polymers pose challenges for recycling and contribute to plastic waste contamination in the environment. Bioplastics offer an alternative solution to the problem of using renewable resources to prepare bio-based polymers. Various renewable materials, including cellulose, hemicellulose, lignin, proteins, and vegetable oils obtained from crops, such as wheat, rice, potatoes, maize, sunflower, sugar beet, and sugarcane, can be used as bio-plastic raw materials. The properties of Bioplastics are similar to those of standard polymers synthesized from petrochemical raw materials. However, based on the challenges posed by Bioplastics, several parameters, such as processing, stability and durability, material performance, and biodegradability of Bioplastics, their eir life cycle from production to ultimate disposal or recycling must be considered. Properties including tensile properties, flexural properties, impact strength, hardness, suitable processing conditions, and posttreatment can be optimized to evaluate the mechanical performance.

Bioplastics, driven by technological improvements, can transition plastic-intensive industries toward circular economies. The wide availability of feedstock makes it advantageous for the synthesis and application of Bioplastics. Deep-characteristic analysis of the properties of these materials provides insightful information that can be further tailored to fabricate Bioplastics with varying properties that can be used for applications such as packaging, films, and filters. These attempts to develop sustainable Bioplastics as replacements for typical plastics have minimized the environmental impact.

REFERENCES

Abe, M. M., Martins, J. R., Sanvezzo, P. B., Macedo, J. V., Branciforti, M. C., Halley, P., Botaro, V. R., & Brienzo, M. (2021). Advantages and disadvantages of Bioplastics production from starch and lignocellulosic components. *Polymers*, *13*(15), 2484. https://doi.org/10.3390/polym13152484

Aldas, M., Ferri, J. M., Lopez-Martinez, J., Samper, M. D., & Arrieta, M. P. (2020). Effect of pine resin derivatives on the structural, thermal, and mechanical properties of Mater-Bi type bioplastic. *Journal of Applied Polymer Science*, *137*(4), 48236. https://doi.org/10.1002/app.48236

Ali, S. S., Abdelkarim, E. A., Elsamahy, T., Al-Tohamy, R., Li, F., Kornaros, M., Zuorro, A., Zhu, D., & Sun, J. (2023). Bioplastic production in terms of life cycle assessment: A state-of-the-art review. *Environmental Science and Ecotechnology*, *15*, 100254. https://doi.org/10.1016/j.ese.2023.100254

Alias, N. H., Abdullah, N., Othman, N. H., Marpani, F., Zainol, M. M., & Shayuti, M. S. M. (2022). Sustainability challenges and future perspectives of biopolymer. In *Biopolymers* (pp. 373–389). Springer. https://doi.org/10.1007/978-3-030-98392-5_17

Altalhi, T. (2022). *Handbook of Bioplastics and biocomposites engineering applications*. John Wiley & Sons. https://doi.org/10.1002/9781119160182

Andrew, J. J., & Dhakal, H. N. (2022). Sustainable biobased composites for advanced applications: Recent trends and future opportunities–A critical review. *Composites Part C*, *7*, 100220. https://doi.org/10.1016/j.jcomc.2021.100220

Ashter, S. A. (2016). *Introduction to Bioplastics engineering*. William Andrew Publishing. https://doi.org/10.1016/C2014-0-04010-5

Atiwesh, G., Mikhael, A., Parrish, C. C., Banoub, J., & Le, T. T. (2021). Environmental impact of bioplastic use: A review. *Heliyon*, *7*(9), e07918. https://doi.org/10.1016/j.heliyon.2021.e07918

Attallah, O. A., Mojicevic, M., Garcia, E. L., Azeem, M., Chen, Y., Asmawi, S., & Brenan Fournet, M. (2021). Macro and micro routes to high performance Bioplastics: Bioplastic biodegradability and mechanical and barrier properties. *Polymers*, *13*(13), 2155. https://doi.org/10.3390/polym13132155

Aworinde, A. K., Emagbetere, E., Adeosun, S. O., & Akinlabi, E. T. (2021). Polylactide and its composites on various scales of hardness. *Pertanika Journal of Science and Technology*, *29*(2). https://doi.org/10.47836/pjst.29.2/34

Barzic, A. I. An introduction to engineering applications of Bioplastics. *Handbook of Bioplastics and biocomposites engineering applications*. (2023): p. 1–22. https://doi.org/10.1002/9781119160182.ch1

Behera, S., Priyadarshanee, M., Vandana, S., & Das, S. (2022). Polyhydroxyalkanoates, the Bioplastics of microbial origin: Properties, biochemical synthesis, and their applications. *Chemosphere*, *294*, 133723. https://doi.org/10.1016/j.chemosphere.2022.133723

Bhaskar, R., Zo, S. M., Narayanan, K. B., Purohit, S. D., Gupta, M. K., & Han, S. S. (2023). Recent development of protein-based biopolymers in food packaging applications: A review. *Polymer Testing*, *124*, 108097. https://doi.org/10.1016/j.polymertesting.2023.108097

Bhatia, S. K., Otari, S. V., Jeon, J.-M., Gurav, R., Choi, Y.-K., Bhatia, R. K., Pugazhendhi, A., Kumar, V., Rajesh Banu, J., Yoon, J.-J., Choi, K.-Y., & Yang, Y.-H. (2021). Biowaste-to-bioplastic (polyhydroxyalkanoates): Conversion technologies, strategies, challenges, and perspective. *Bioresource Technology*, *326*, 124733. https://doi.org/10.1016/j.biortech.2021.124733

Bîrcă, A. et al. (2019). Introduction in thermoplastic and thermosetting polymers. In *Materials for biomedical engineering* (pp. 1–28). Elsevier.

Bishop, G., Styles, D., & Lens, P. N. L. (2021). Environmental performance comparison of Bioplastics and petrochemical plastics: A review of life cycle assessment (LCA) methodological decisions. *Resources, Conservation and Recycling*, *168*, 105451. https://doi.org/10.1016/j.resconrec.2021.105451

Boey, J. Y., Kong, U., Lee, C. K., Lim, G. K., Oo, C. W., Tan, C. K., Ng, C. Y., Azniwati, A. A., & Tay, G. S. (2024). The effect of filler loading, biological treatment, and bioplastic blend ratio on flexural and impact properties of blended bioplastic reinforced with spent coffee ground. *Polymer Engineering and Science*, *64*(7), 3319–3333. https://doi.org/10.1002/pen.26772

Briassoulis, D., Tserotas, P., & Athanasoulia, I.-G. (2021). Alternative optimization routes for improving the performance of poly (3-hydroxybutyrate)(PHB) based plastics. *Journal of Cleaner Production*, *318*, 128555. https://doi.org/10.1016/j.jclepro.2021.128555

Carter, P. (2022). Bio-advantaged polyamides from muconic acid. Iowa State University. https://dr.lib.iastate.edu/handle/20.500.12876/Nr1VXWnz

Chang, B. P., Mohanty, A. K., & Misra, M. (2020). Studies on durability of sustainable biobased composites: A review. *RSC Advances*, *10*(31), 17955–17999. https://doi.org/10.1039/c9ra09554c

Chen, H., Wang, J., Cheng, Y., Wang, C., Liu, H., Bian, H., Pan, Y., Sun, J., & Han, W. (2019). Application of protein-based films and coatings for food packaging: A review. *Polymers*, *11*(12), 2039. https://doi.org/10.3390/polym11122039

Choi, J.-H., Kim, J.-H., Lee, S. Y., Jang, S.-K., Kwak, H. W., Kim, H., & Choi, I.-G. (2022). Thermoplasticity reinforcement of ethanol organosolv lignin to improve compatibility in PLA-based ligno-Bioplastics: Focusing on the structural characteristics of lignin. *International Journal of Biological Macromolecules*, *209*(B), 1638–1647. https://doi.org/10.1016/j.ijbiomac.2022.04.090

Coppola, G., Gaudio, M. T., Lopresto, C. G., Calabro, V., Curcio, S., & Chakraborty, S. (2021). Bioplastic from renewable biomass: A facile solution for a greener environment. *Earth Systems and Environment*, *5*(2), 231–251. https://doi.org/10.1007/s41748-021-00208-7

Costa, A., Encarnação, T., Tavares, R., Todo Bom, T., & Mateus, A. (2023). Bioplastics: Innovation for green transition. *Polymers*, *15*(3), 517. https://doi.org/10.3390/polym15030517

Cubas, A. L. V., Moecke, E. H. S., Provin, A. P., Dutra, A. R. A., Machado, M. M., & Gouveia, I. C. (2023). The impacts of plastic waste from personal protective equipment used during the Covid-19 pandemic. *Polymers*, *15*(15), 3151. https://doi.org/10.3390/polym15153151

de Souza, F. M., & Gupta, R. K. (2024). Bacteria for Bioplastics: Progress, applications, and challenges. *ACS Omega*, *9*(8), 8666–8686. https://doi.org/10.1021/acsomega.3c07372

Dilshad, E., Waheed, H., Ali, U., Amin, A., & Ahmed, I. (2021). General structure and classification of Bioplastics and biodegradable plastics. In M. Kuddus & Roohi (Eds.), *Bioplastics for sustainable development*. Springer. https://doi.org/10.1007/978-981-16-1823-9_2

Dourado Fernandes, C. D., Francisco Oechsler, B., Sayer, C., de Oliveira, D., & Hermes de Araújo, P. H. (2022). Recent advances and challenges on enzymatic synthesis of biobased polyesters via polycondensation. *European Polymer Journal*, *169*, 111132. https://doi.org/10.1016/j.eurpolymj.2022.111132

Elfaleh, I., Abbassi, F., Habibi, M., Ahmad, F., Guedri, M., Nasri, M., & Garnier, C. (2023). A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials. *Results in Engineering*, *19*, 101271. https://doi.org/10.1016/j.rineng.2023.101271

Folino, A., Karageorgiou, A., Calabrò, P. S., & Komilis, D. (2020). Biodegradation of wasted Bioplastics in natural and industrial environments: A review. *Sustainability*, *12*(15), 6030. https://doi.org/10.3390/su12156030

Friedrich, D. (2021). Benefits from sustainable development using Bioplastics: A comparison between the food and fashion industries. *Sustainable Development*, *29*(5), 915–929. https://doi.org/10.1002/sd.2184

Gao, Y., Zhou, D., Lyu, J., A, S., Xu, Q., Newland, B., Matyjaszewski, K., Tai, H., & Wang, W. (2020). Complex polymer architectures through free-radical polymerization of multivinyl monomers. *Nature Reviews. Chemistry*, *4*(4), 194–212. https://doi.org/10.1038/s41570-020-0170-7

Garcia-Garcia, D., Quiles-Carrillo, L., Balart, R., Torres-Giner, S., & Arrieta, M. P. (2022). Innovative solutions and challenges to increase the use of poly(3-hydroxybutyrate) in food packaging and disposables. *European Polymer Journal*, *178*, 111505. https://doi.org/10.1016/j.eurpolymj.2022.111505

George, D. M., Vincent, A. S., & Mackey, H. R. (2020). An overview of anoxygenic phototrophic bacteria and their applications in environmental biotechnology for sustainable Resource recovery. *Biotechnology Reports*, *28*, e00563. https://doi.org/10.1016/j.btre.2020.e00563

Hadidi, M., Jafarzadeh, S., Forough, M., Garavand, F., Alizadeh, S., Salehabadi, A., Khaneghah, A. M., & Jafari, S. M. (2022). Plant protein-based food packaging films; recent advances in fabrication, characterization, and applications. *Trends in Food Science and Technology*, *120*, 154–173. https://doi.org/10.1016/j.tifs.2022.01.013

Hassan, M., Bai, J., & Dou, D.-Q. (2019). Biopolymers: Definition, classification and applications. *Egyptian Journal of Chemistry*, *62*(9), 1725–1737. https://doi.org/10.21608/ejchem.2019.6967.1580

Ibrahim, N. I., Shahar, F. S., Sultan, M. T. H., Shah, A. U. M., Safri, S. N. A., & Mat Yazik, M. H. (2021). Overview of bioplastic introduction and its applications in product packaging. *Coatings*, *11*(11), 1423. https://doi.org/10.3390/coatings11111423

Iles, A., & Martin, A. N. (2013). Expanding Bioplastics production: Sustainable business innovation in the chemical industry. *Journal of Cleaner Production*, *45*, 38–49. https://doi.org/10.1016/j.jclepro.2012.05.008

Aida, M.S., Alonizan, N.H., Hussein, M.A. et al. Facile Synthesis and Antibacterial Activity of Bioplastic Membrane Containing In Doped ZnO/Cellulose Acetate Nanocomposite. J Inorg Organomet Polym 32, 1223–1233 (2022). https://doi.org/10.1007/s10904-021-02171-2

Koller, M. *The handbook of polyhydroxyalkanoates, three volume set. 2020*. CRC Press. https://doi.org/10.1201/978100308071

Lamberti, F. M., Román-Ramírez, L. A., & Wood, J. (2020). Recycling of Bioplastics: Routes and benefits. *Journal of Polymers and the Environment*, *28*(10), 2551–2571. https://doi.org/10.1007/s10924-020-01795-8

Lods, L., Richmond, T., Dandurand, J., Dantras, E., Lacabanne, C., Durand, J.-M., Sherwood, E., Hochstetter, G., & Ponteins, P. (2022). Continuous bamboo fibers/fire-retardant polyamide 11: Dynamic mechanical behavior of the biobased composite. *Polymers*, *14*(2), 299. https://doi.org/10.3390/polym14020299

Meereboer, K. W., Misra, M., & Mohanty, A. K. (2020). Review of recent advances in the biodegradability of polyhydroxyalkanoate (PHA) Bioplastics and their composites. *Green Chemistry*, *22*(17), 5519–5558. https://doi.org/10.1039/D0GC01647K

Merchan, A. L., Fischöder, T., Hee, J., Lehnertz, M. S., Osterthun, O., Pielsticker, S., Schleier, J., Tiso, T., Blank, L. M., Klankermayer, J., Kneer, R., Quicker, P., Walther, G., & Palkovits, R. (2022). Chemical recycling of Bioplastics: Technical opportunities to preserve chemical functionality as path towards a circular economy. *Green Chemistry*, *24*(24), 9428–9449. https://doi.org/10.1039/D2GC02244C

Nadda, A. K., Sharma, S., & Bhat, R. *Biopolymers: Recent updates, Challenges and Opportunities*. (2022): *Springer*. https://doi.org/10.1007/978-3-030-98392-5

Nanda, S., Patra, B. R., Patel, R., Bakos, J., & Dalai, A. K. (2022). Innovations in applications and prospects of Bioplastics and biopolymers: A review. *Environmental Chemistry Letters*, *20*(1), 379–395. https://doi.org/10.1007/s10311-021-01334-4

Nandiyanto, A. B. D., Fiandini, M., Ragadhita, R., Sukmafitri, A., Salam, H., & Triawan, F. (2020). Mechanical and biodegradation properties of cornstarch-based bioplastic material. *Materials Physics and Mechanics*, *44*(3), 380–391. http://doi.org/10.18720/MPM.4432020_9

Ojha, N., & Das, N. (2021). Microbial production of Bioplastics: Current trends and future perspectives. In M. Kuddus & Roohi (Eds.), *Bioplastics for sustainable development*. Springer. https://doi.org/10.1007/978-981-16-1823-9_1

Oliver-Ortega, H., Julian, F., Espinach, F. X., Tarrés, Q., Delgado-Aguilar, M., & Mutjé, P. (2021). Biobased polyamide reinforced with natural fiber composites. In *Fiber Reinforced Composites*, (141–165). https://doi.org/10.1016/B978-0-12-821090-1.00008-9

Palacios, L. M., Muñoz, G. A. A., Castillo, H. S. V., & Guarín, H. P. (2023). Bioplastics challenges and opportunities. In *Biodegradable polymers* (pp. 229–242). CRC Press. https://doi.org/10.1201/9781003230533-16

Pradhan, S., Dikshit, P. K., & Moholkar, V. S. (2020). Production, characterization, and applications of biodegradable polymer: Polyhydroxyalkanoates. In *Advances in sustainable polymers* (pp. 51–94). Springer. https://doi.org/10.1007/978-981-15-1251-3_4

Quero, A. J.. *Bioproduction of itaconic acid by biomass valorization, towards material elaboration. Biotechnology*. Université de Strasbourg. (2016). English. NNT: 2016STRAE036. tel 01561750. https://theses.hal.science/tel-01561750v1.

Rajeshkumar, L., Ramesh, M., Bhuvaneswari, V., Balaji, D., & Deepa, C. (2023). Synthesis and thermomechanical properties of Bioplastics and biocomposites: A systematic review. *Journal of Materials Chemistry. B*, *11*(15), 3307–3337. https://doi.org/10.1039/d2tb02221d

Ramchuran, S. O., O'Brien, F., Dube, N., & Ramdas, V. (2023). An overview of green processes and technologies, biobased chemicals and products for industrial applications. *Current Opinion in Green and Sustainable Chemistry*, *41*, 100832. https://doi.org/10.1016/j.cogsc.2023.100832

Reddy, R. L., Reddy, V. S., & Gupta, G. A. (2013). Study of bio-plastics as green and sustainable alternative to plastics. *International Journal of Emerging Technology and Advanced Engineering*, *3*(5), 76–81.

Rosenboom, J.-G., Langer, R., & Traverso, G. (2022). Bioplastics for a circular economy. *Nature Reviews. Materials*, *7*(2), 117–137. https://doi.org/10.1038/s41578-021-00407-8

Sheldon, R. A., & Norton, M. (2020). Green chemistry and the plastic pollution challenge: Towards a circular economy. *Green Chemistry*, *22*(19), 6310–6322. https://doi.org/10.1039/D0GC02630A

Siddiqui, S. A., Yang, X., Deshmukh, R. K., Gaikwad, K. K., Bahmid, N. A., & Castro-Muñoz, R. (2024). Recent advances in reinforced Bioplastics for food packaging – A critical review. *International Journal of Biological Macromolecules*, *263*(2), 130399. https://doi.org/10.1016/j.ijbiomac.2024.130399

Sikorska, W., Musioł, M., Zawidlak-Węgrzyńska, B., & Rydz, J. (2021). End-of-life Options for (Bio) degradable Polymers in the Circular Economy. *Advances in Polymer Technology*, *2021*(1), 1–18. https://doi.org/10.1155/2021/6695140

Siracusa, V., & Blanco, I. (2020). Bio-polyethylene (Bio-PE), Bio-polypropylene (Bio-PP) and Bio-poly(ethylene terephthalate)(Bio-PET): Recent developments in bio-based polymers analogous to petroleum-derived ones for packaging and engineering applications. *Polymers*, *12*(8), 1641. https://doi.org/10.3390/polym12081641

Stoica, M., Stoica, D., Ivan, A. S., & Dragomir, C. M. B. (2022). Biopolymers: Regulatory and legislative issues. In *Biopolymers* (pp. 55–71). Springer. https://doi.org/10.1007/978-3-030-98392-5_4

Tan, S. X., Andriyana, A., Ong, H. C., Lim, S., Pang, Y. L., & Ngoh, G. C. (2022). A comprehensive review on the emerging roles of nanofillers and plasticizers towards sustainable starch-based bioplastic fabrication. *Polymers*, *14*(4), 664. https://doi.org/10.3390/polym14040664

Tedeschi, G., Guzman-Puyol, S., Ceseracciu, L., Paul, U. C., Picone, P., Di Carlo, M., Athanassiou, A., & Heredia-Guerrero, J. A. (2020). Multifunctional Bioplastics inspired by wood composition: Effect of hydrolyzed lignin addition to xylan–cellulose matrices. *Biomacromolecules*, *21*(2), 910–920. https://doi.org/10.1021/acs.biomac.9b01569

Vlasopoulos, A., Malinauskaite, J., Żabnieńska-Góra, A., & Jouhara, H. (2023). Life cycle assessment of plastic waste and energy recovery. *Energy*, *277*, 127576. https://doi.org/10.1016/j.energy.2023.127576

Wellenreuther, C., Wolf, A., & Zander, N. (2022). Cost competitiveness of sustainable bioplastic feedstocks–A Monte Carlo analysis for polylactic acid. *Cleaner Engineering and Technology*, *6*, 100411. https://doi.org/10.1016/j.clet.2022.100411

Zhao, X., Boruah, B., Chin, K. F., Đokić, M., Modak, J. M., & Soo, H. S. (2022). Upcycling to sustainably reuse plastics. *Advanced Materials*, *34*(25), e2100843. https://doi.org/10.1002/adma.202100843

Zhao, X., Wang, Y., Chen, X., Yu, X., Li, W., Zhang, S., Meng, X., Zhao, Z.-M., Dong, T., Anderson, A., Aiyedun, A., Li, Y., Webb, E., Wu, Z., Kunc, V., Ragauskas, A., Ozcan, S., & Zhu, H. (2023). Sustainable Bioplastics derived from renewable natural resources for food packaging. *Matter*, *6*(1), 97–127. https://doi.org/10.1016/j.matt.2022.11.006

Zhou, H., Guan, Y., Yan, X., Pan, Z., Xu, J., Dai, L., Zhang, M., & Si, C. (2023). All-lignocellulose-based hard bioplastic. *Industrial Crops and Products*, *193*, 116164. https://doi.org/10.1016/j.indcrop.2022.116164