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BIOPOLYMERS: A SUITABLE REPLACEMENT FOR PLASTICS IN PRODUCT PACKAGING.

Kunle Babaremu[1], Oluseyi Oladijo[3], Esther Akinlabi[2]

[1] Mechanical Engineering Department, University of Johannesburg, South Africa.
[2] Department of Mechanical and Construction Engineering, Faculty of Engineering and Environment, Northumbria University.
[3]Department of Chemical, Materials and Metallurgical Engineering, Botswana International University of Science and Technology, Botswana

Corresponding Author Email:

Abstract

Plastics are the most utilized materials for product packaging in most manufacturing industries, from electronics to food and fashion accessories. However, numerous challenges surround plastics because of their non-biodegradability, which poses a severe threat to the environment. This study has uncovered the possibilities of replacing and discouraging the use of plastics in the packaging of products. A few scholarly articles have successfully proven that biopolymers which are valuable polymers obtained from plant-based and organic materials are better for packaging products. Unlike plastics, biopolymers are biocompatible and biodegradable within a short period, which would help preserve the ecosystem and are healthier for humans. More specifically, biopolymers have found valuable applications in consumer products, medical, electrical, and structural products. Numerous studies on plastic are still ongoing, owing to the increasing demand and quest for removing plastics from human communities, making this area of study very prolific and grey.

Keywords: Polymers, Bioplastic, Product Packaging, Biopolymers, Biodegradable

1. Introduction

In one era of human existence, plastic packaging was a major breakthrough [1]. Plastics were discovered to have several properties that made them revolutionary for preserving, protecting, and transporting several goods [2]. Plastic packaging is relatively inexpensive, lightweight, hygienic, versatile, shatter-resistant, and sealable. Plastics also prevents waste as products can affordably be divided into small quantities [2]. Furthermore, plastics provide durable surfaces to print product information. Using non-plastic alternatives in packaging and consumer goods will cost four times more than plastics [3]. Biodegradable plastics cost twice as much to manufacture as conventional plastics [4]. If plastics are so helpful, what is wrong with them? Plastics take over 400 years to degrade [5]. Plastics are becoming a major feature in the current geological era, the Anthropocene, and it has created a new microbial habitat called the plastisphere [6], [7]. There are several alternatives to plastic packaging and advanced forms of plastics. Bioplastics, plastics partly or entirely made from bio-based materials, are promoted as the solution to plastic waste. However, not all bio-based plastics are biodegradable [8]. Biodegradable and compostable plastics are problematic in recycling as they are treated as impurities in conventional plastic feedstock [9]. Scientists have examined various constituents of plastics and polymers, particularly biopolymers and advanced polymer composites have claimed significant attention in the past few years [10]. Biopolymers, bio-based degradable polymers, still require significant improvement before claiming considerable market share. This paper examines the current scenario in plastic packaging, highlights various alternatives, narrows down on biopolymers as a suitable alternative, and points out the challenges of each packaging alternative. Relevant datasets from OECD have been visualized in charts to illustrate plastic use [11]. The use of biopolymer in packaging is a voluminous topic. Hence, the present work highlights biopolymers, the popular types of biopolymers in packaging, and the challenges associated with the commercialization of biopolymers in packaging. The work discusses plastic pollution and the actual benefits and setbacks of bioplastics.

2. Plastic Packaging

Plastic packaging is ubiquitous across industries. Rigid plastic packaging was $267.38 billion in 2021 and will grow at 5.55% to reach $429.13 billion by 2030 [12]. Flexible plastic packaging was valued at $160 billion in 2020 [13]. About 33.6 million tons of flexible plastic packaging were sold in 2021 [14]. The UNEP estimates that 1 million plastic bottles are bought per minute, and an annual 5 trillion plastic bags are used globally [6]. In total, the world produced 460 million tons of plastics in 2019, contributing to 3.4% of greenhouse gas emissions [15]. Around 36% of these plastics (165.6 million tons) are used in plastic packaging [6]. About $80-120 billion is lost annually in sorting and processing plastic packaging [6]. Food and beverage packaging claims about 60% of plastic packaging [16]–[18]. Recent research shows that fresh food spoils faster in plastic packages [19]. The research showed that £2.1 billion of fresh food is thrown away annually in the UK because of molds, squishiness, or the expiry date labels on plastic packages. If these fresh products were sold outside plastic wrappers, the UK would save 100,000 tons of food and 10,300 tons of plastic [19]. However, industry experts argue that if plastic packaging is removed entirely from the equation, the increase in food waste will pose a worse environmental threat than that of plastic packaging [2]. Also, due to their lightweight, plastics save energy in transportation [20]. For example, a glass container of yoghurt weighs 85 grams, and its plastic counterpart 5.5 grams. Since glass drinks account for 36% of the load, and plastic drinks are 3.56%, only two lorries will be used to transport the plastic yogurts while 3 lorries for the same amount of glass drinks [20]. Packaging contributes to most of the plastic use globally, as shown by OECD datasets illustrated in Figure 1 [11].

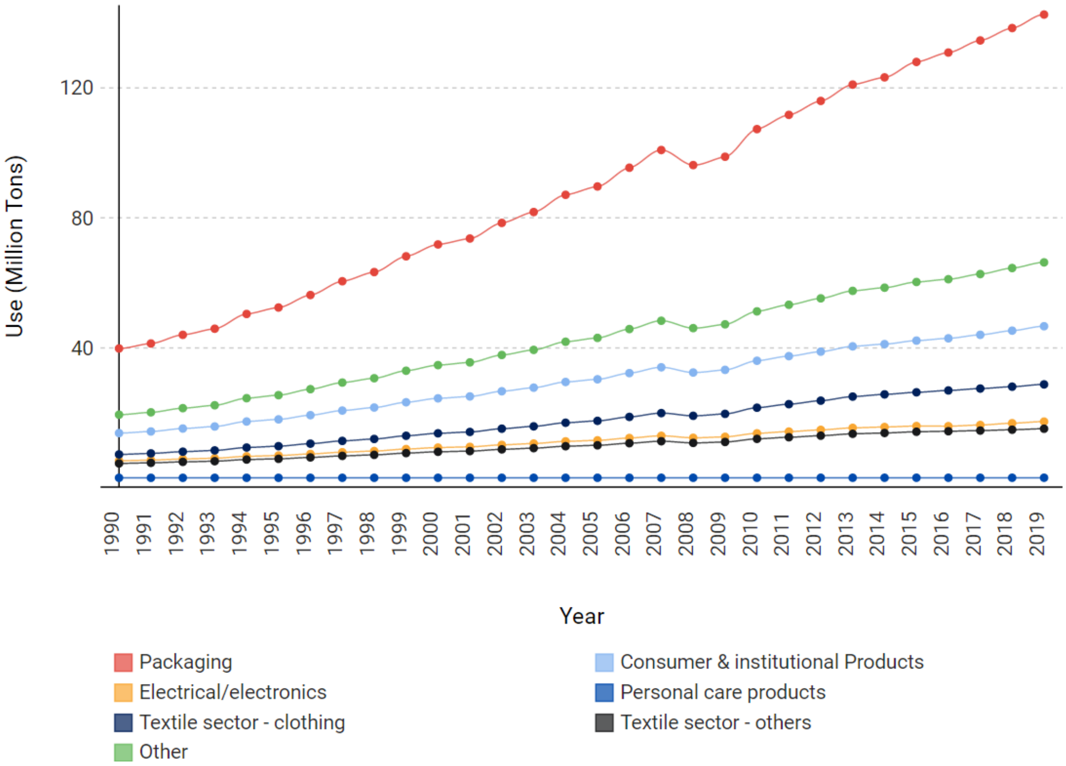
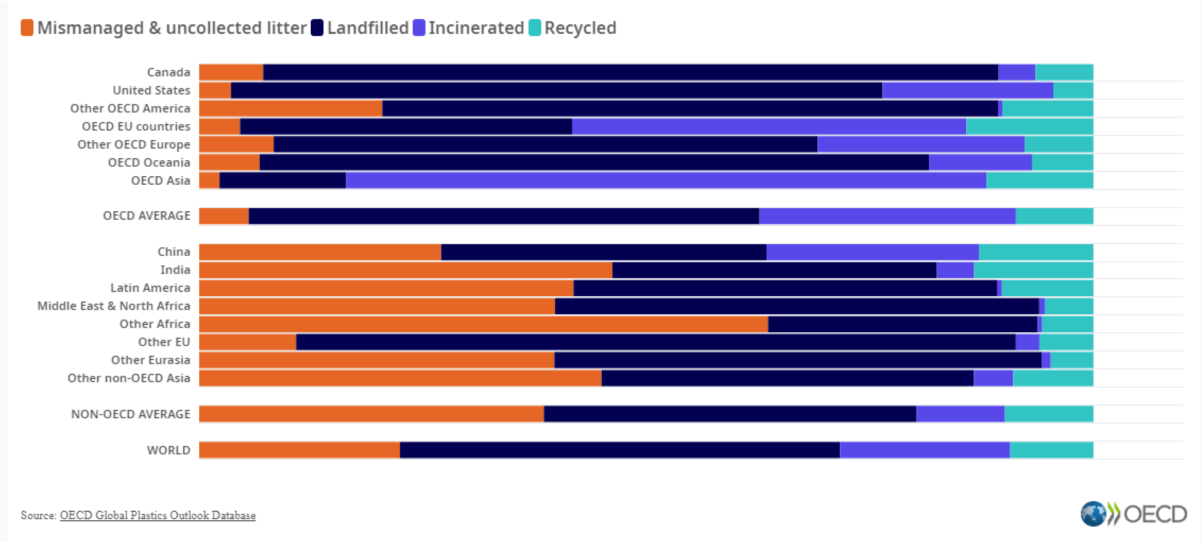


Figure 1: Plastics Use by Application [11]

Plastic pollution is majorly derived from poor disposal of macroplastics (large plastic debris), and a significant amount from industrial leakage of microplastics (polymers less than 5mm) [15]. Synthetic textiles, plastic pellets, tire wear, and road markings contribute significantly to plastic pollution. Out of the 15% of plastics collected for recycling, 40% went back into the waste cycle as residues [15]. Only 9% of plastic waste is recycled globally. About 221kg of plastic waste is generated per person in the United States, 114 kg in EU OECD members, and 69 kg in Japan and Korea [15]. Marine organisms can ingest plastic, get trapped in plastic waste, or suffer long-term injury and physiological change from chemical substances in plastics [1]. OECD data showing the final destination of plastics is visualized in Figure 2.



Source: OECD Global Plastics Outlook Database

Figure 2: Final Destination of Plastics by Region [11]

According to the Chemicals associated with Plastic Packaging database, 906 chemicals are in plastic packaging. Out of these, 63 are hazards to human health, 68 are environmental hazards, seven are persistent, bioaccumulative, and toxic (PBT), and 34 are endocrine-disrupting chemicals (EDC) or potential endocrine-disrupting chemicals. These dangerous chemicals are present as solvents, monomers, plasticizers, intermediates, biocides, accelerators, surfactants, stabilizers, flame retardants, and colorants [18]. 50% of plastics went to landfills in 2019 [15]. Aquatic environments claimed 6.1 Mt of plastic waste and the oceans 1.7 Mt in 2019, resulting in about 30 Mt accumulated in oceans and seas and 109 Mt in rivers [15]. In the plastic packaging industry, 85% of the packages end up in landfills [6]. Figure 3 shows the most common kinds of plastic in packaging.

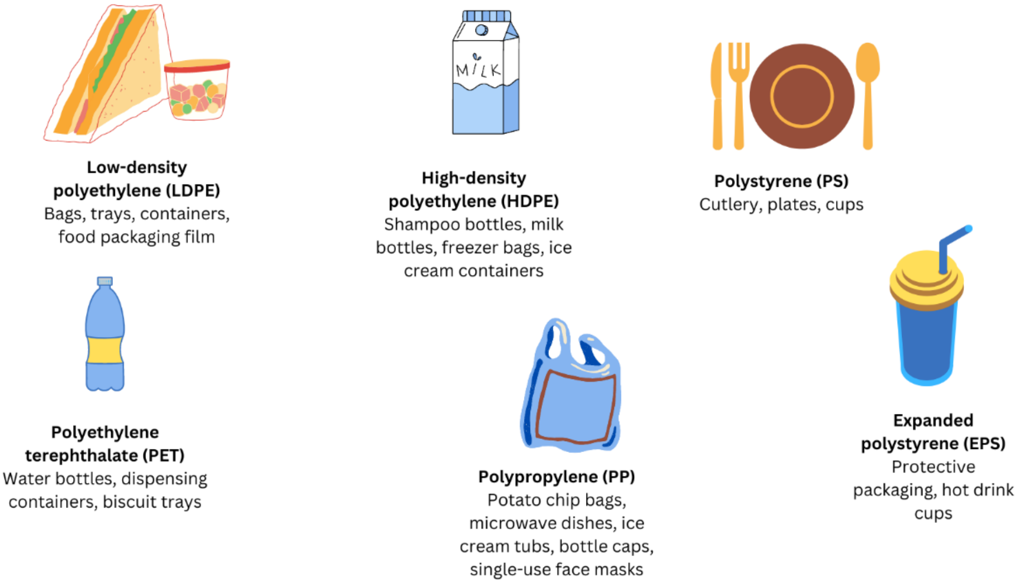


Figure 3: Different kinds of plastics and their uses [6], [21]–[24]

Single-Use Plastics

Design for Reuse and Design for Recycling are essential concepts in the circular economy and can be used separately or simultaneously [25]. Plastic packaging for reuse must be extremely durable to support its lifespan in various applications. Conversely, packaging for recycling must encourage dematerialization. Dematerialization is not explicitly sustainable. Discussions have compared the sustainability of designing for reuse and recycling [25]. A study showed that processes involved in reusability designs are less damaging to the environment than dematerialization processes by 171% [25]. Many governments and organizations are actively passing sanctions to cut down on plastic use [26]. Bangladesh was one of the first countries to ban plastic bags [26]. By July 2022, 77 countries have placed complete or partial prohibitions on plastic use. About 32 countries employed taxes and similar restrictions to limit plastic bag production and sale. Some US states implement local plastic bans. Guatemala banned single-use plastic containers, straws, and bags [26]. In 2022, India banned single-use plastic products, including straws, cutlery, earbuds, and sticks. Nonetheless, no country has braved a strict ban on single-use plastics. Several initiatives have started to reward alternatives that can be converted into energy, biomass, or water [26].

Popular Alternative Plastics

About 98% of single-use plastic packaging is made from fossil fuels [6]. Bio-based plastics are gaining popularity in recent times. Not all bio-based plastics are degradable [8]. In fact, biodegradable plastics can be made from fossil raw materials [27]. Oxo-degradable plastics are made with additives that decompose or fragment into microplastics through oxidation [8]. Three popular alternatives to conventional plastics are bioplastics, biodegradable plastics, and compostable plastics. These plastics are detailed below.

Bioplastics are plastics partly or entirely made from bio-based materials [8]. Bioplastics are marketed as great substitutes for plastics [28]. Studies show that bioplastics have the same compounds as plastics after they are produced from eco-friendly materials, resulting in the same 400 years of degradation [27].

Biodegradable plastics must fulfill the following requirements [28]:

- Degrade under natural processes, including sunlight and hydrolysis.
- Contain low amounts of heavy metals.
- Within six months of exposure, 90% of must be converted to CO2 under natural means
- 90% must be smaller than a 2 x 2 mm mesh within 12 weeks of exposure
- The biodegraded material should not harm plant life

Unfortunately, the speed at which biodegradable plastics' degrade relies on the prevailing environmental conditions where they are disposed [8]. Hence, the oxygen, moisture, microorganisms, temperature, and duration of exposure play significant roles in validating the sustainability of biodegradable plastics [29], [30].

Compostable plastics are mostly made of polylactic acid [9]. Compostable plastic is similar to biodegradable plastic, but the plastics are decomposed under industrial composting processes [8]. The two main types of compostable plastics are industrial compostable and home compostable plastics. Home compostable plastics are biodegraded using a monitored home composter. Industrial compostable plastics go through anaerobic digestion or composting plant. Figure 4 shows plastic use by polymer based on OECD data [11].

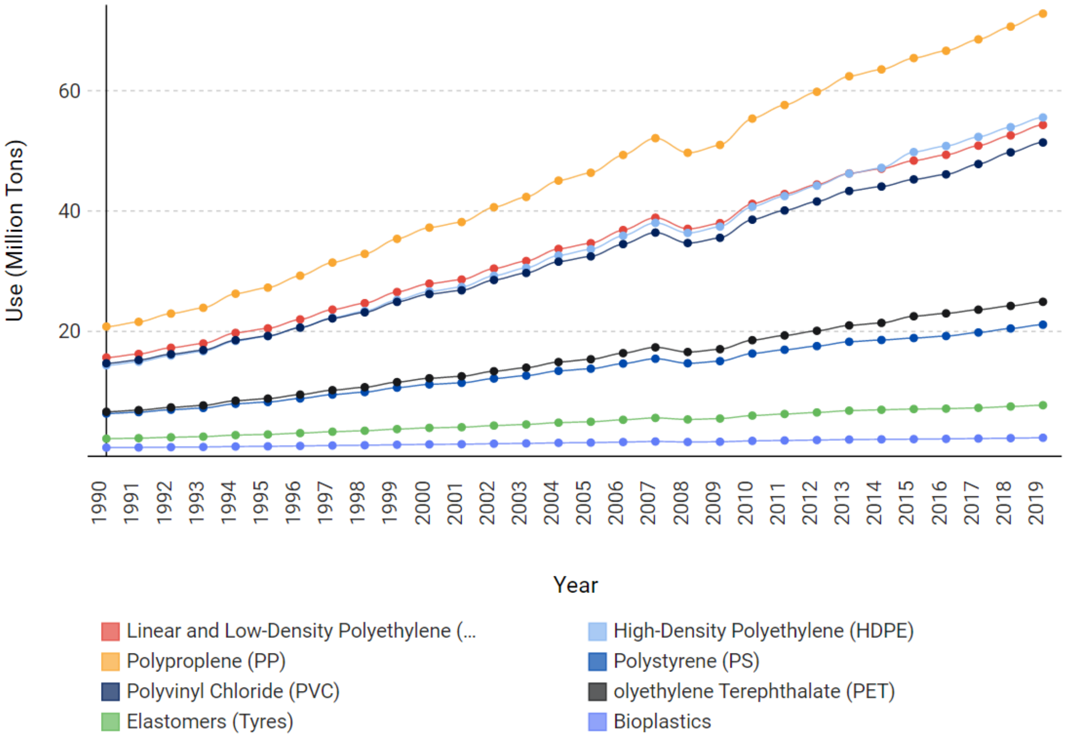


Figure 4: Plastics Use by Polymer [11], [15]

Biodegradable and compostable plastics are problematic in recycling. When collected with conventional plastics, biodegradable cannot be treated as plastics but as impurities [31]. Compostable plastics are challenging to recyclers, and most are sent to landfills [9]. There is a need to clarify the bio-related labels on plastics and set clear standards regarding plastic sustainability, such as the UK Plastic Pact's work towards unified standards around plastic sustainability targets in 2025 [32]. Some scientists have proposed a "self-destruct" mechanism, embedding polyester-consuming enzymes into plastics as they are made [9]. These enzymes are protected in polymers that break off when exposed to heat and water.

3. Biopolymer: A Sustainable Alternative

Polymers are substrates and a matrix in plastics [4]. Due to technological, cost, and knowledge limitations, synthetic polymers, such as polypropylene (PP), polystyrene (PS), linear low-density, low-density, and high-density polyethylene (HDPE, LDPE, and LLDPE), and polyethylene terephthalate (PET)] are used in packaging [33]. Figure 5 illustrates the chemical structure of common plastic polymers [33], [34].

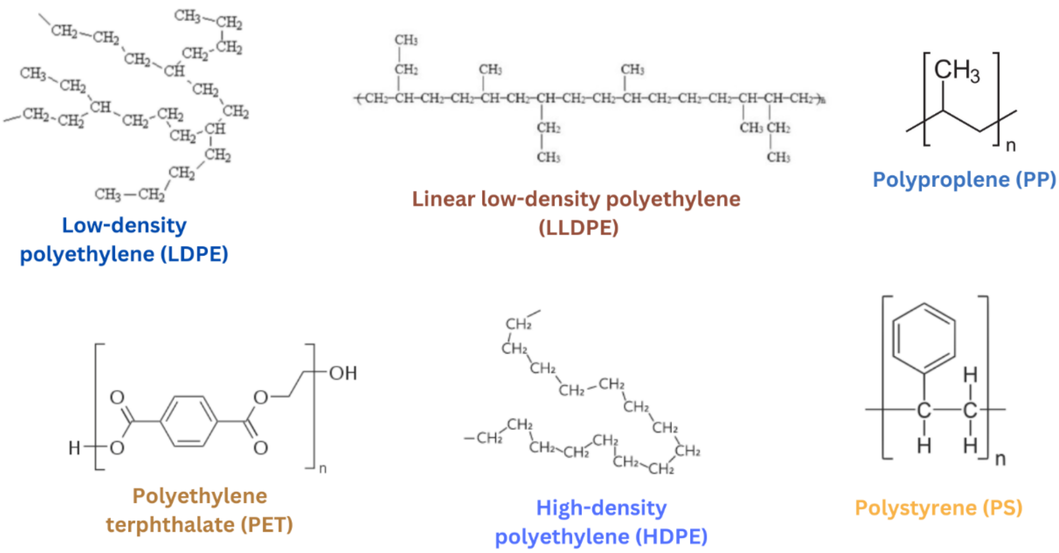


Figure 5: Chemical Structures of Common Plastic Polymers [33], [34]

Biopolymers, bio-based degradable polymers, are gaining attention as better alternatives to synthetic polymers [10], [35]–[37]. Bio-based and biodegradable polymers are classified as biopolymers [4]. These substances have biodegradable functional groups, including acetal, silyl ether, ketone, etc. [38]–[43]. The past few decades have witnessed an increase in the study of lipids, carbohydrates, and proteins to be employed in packaging [10]. Food packaging is a popular use case for biopolymers. Biopolymers are popular in food packaging because they are edible and safer for humans. The most commonly researched nanocomposite biomaterials for food packaging applications are proteins, carbohydrates, and their derivatives [44]–[47]. Agar, alginate, gluten, and pectin have shown varying levels of low barrier, processing, and mechanical properties [45], [48]–[53]. Biopolymers are cost-effective, their raw materials are relatively abundant, and producing biopolymers uses up agricultural waste [54]. Unfortunately, only 1% of plastics are classified as bio-based, biodegradable, or compostable [33]. In 2020, 2.1 million tons of bioplastics were produced globally, and 47% were channeled toward packaging [33]. Biodegradable polymeric product packaging was valued at $4.65 billion in 2019 and is estimated to grow to $9 billion by 2025 [4]. Biodegradable polymers are generally classified based on their sources [4], [55], [56]. There are:

- Chemically synthesized polymers derived from chemicals (fossil material-based or natural)
- Biomass-derived polymers
- Biosynthesized polymers obtained from microbial fermentation

Chemically synthesized polymers include polylactic acid (PLA), polycaprolactone (PCL), poly (vinyl alcohol) (PVA), poly (glycolic acid) (PGA), polybutylene succinate (PBS), and polybutylene adipate-co-terephthalate (PBAT) [4]. Biomass-derived polymers include starch, cellulose, chitin, chitosan, gelatin, collagen, and alginate. Biosynthesized polymers include polyhydroxyalkanoates (PHA) and Bacterial Cellulose (BC). Studies report that cellulose and starch produce desirable gas barriers and mechanical properties [57], [58]. Several biopolymers have non-toxicity, antifungal, and antimicrobial properties [59]. While biopolymers have various desireable properties, they have not completely replaced conventional polymers in various applications because of their weaknesses. Biopolymers are mechanically deficient for packaging applications [60]. Their mechanical properties can be improved by additives and reinforcements. Cellulose acetate, carboxymethyl cellulose, and hydroxypropylmethylcellulose have shown suitable properties for food packaging applications upon reinforcement by various additives (such as silver nanoparticles and bacterial derivatives) [61]–[63]. Studies have also proposed intelligent biopolymers that monitor and recondition food based on environmental conditions [59]. Some of these biopolymers are derived by adding active compounds to chitosan and gelatin active compounds to improve the mechanical, functional, and barrier properties [53], [59], [64]–[67].

Starch, specifically thermoplastic starch, is a popular biopolymer in the biodegradable film industry. Nonetheless, starch is very sensitive to moisture and is mechanically weak [56]. Hence scientists have mechanically and thermally modified starch molecules and added plasticizers to form gelatinized starch for processing [68], [69]. Starch-based polymers have been used to produce edible film [70]. Scientists have employed corn starch and corn husk fiber to improve strength [71]. Cassava starch has been plasticized and reinforced with clay nanoparticles as a packaging alternative [72], [73]. Sugar palm starch has been examined as another possibility [74]. Cellulose is generally derived from wood because it is a primary constituent of wood [56]. Several suppliers, including Innovia, Alce Nero, Genpak, Twinings, Amcor, Hain Celestial, Biome Bioplastics, Berkshire Labels, Bunzl, Bio4Pack, and Paperfoam use cellulose polymer packaging [23], [24], [75]–[81]. These suppliers have used it in packaging for confectionery, biscuits, tea, butter, and sealing films [56]. Cellulose-based biofilm is beneficial to food packaging. Cellulose biofilm made from maize starch, soybean oil, and microcrystalline cellulose enhanced the snacks' shelf life compared to their unwrapped counterparts. [23]. In nano form, cellulose acts as a coating, improving the moisture barrier [56].

Another popular biopolymer is polylactic acid. Studies have shown the possibility of using agricultural residue, corn husk, bagasse, wheat straw, industrial waste, wood chips, and by-products to produce PLA [81]–[85]. There is also significant interest in generating lactic acid through methane fermentation. Some researchers have used anaerobic digestion [22]. Producing PLA via ring-opening polymerization of lactides creates a thermoplastic film with a good water vapor barrier [80]. However, PLA is unsuitable for various production techniques. Biopolymers generally have beneficial properties, including shelf life extension and biodegradation [86]–[88]. Production technologies and processes must improve to facilitate the commercial production of biopolymer-based plastics. Specific standards are needed to determine processes and constituents for different kinds of biopolymers. The world lacks clear biodegradable standards for plastics [4]. Mechanical, thermal, and physiochemical properties and chemical stability of biopolymers must be improved.

Challenges of Biopolymers

Unfortunately, many people cannot differentiate between the different types of plastic. Several people believe that all bioplastics are biodegradable [8]. Consumers also find it difficult to distinguish between bio-related plastic labels. Many people do not know that biodegradable plastics cannot be recycled alongside other plastics. The majority of the public will put biodegradable plastics into the recycling bin. Less than 5% of the respondents to a survey said that biodegradable plastics should go into the home compost bin [89]. Surveys show that many people do not consciously recycle [32]. While durable plastic and biodegradable plastics are perceived as more positive than single-use plastic, many people say that biodegradable plastics are not as convenient and practical as other counterparts [89]. Eight in ten people are convinced that plastic-free packaging is more beneficial in the long run [32]. Some people believe that replacing plastics in several packaging scenarios will involve using more materials to get the same functionality-which will be more harmful to the environment. People are also concerned that recycling paper takes less energy than plastic [32].

Before biopolymers become serious commercial contenders, scientists must understand their physicochemical, mechanical, thermal, and chemical properties. Physicochemical properties include a gas barrier and mechanical properties that cover tensile strength, elastic modulus, and maximum elongation [10]. Scientists also need to understand how biopolymers react with various food items. Currently, biopolymers are mixed with several harmful chemicals to produce plastic [4]. Biopolymers have different properties from their resulting plastics. For example, a biopolymer may have better mechanical properties than the plastic it is used to manufacture [10]. Another primary challenge with biopolymers is product shelf life [56]. Manufacturers struggle to find durable bio-sourced packaging that will reduce the shelf life of their products. Biopolymers are usually thermal or hydro-degradable [4].

4. Conclusion

This work has examined the actual benefits and setbacks of the alleged eco-friendly alternatives to plastics. Plastics are very desirable in product packaging. The primary problem with plastic waste is that it takes more than 400 years to degrade. Thus, more research is required to explore better technologies to quicken plastic degradation without damaging the environment. Biopolymers are used as a matrix or substrates in bio-related plastics. Biopolymers differ greatly from each other. Starch, cellulose, and polylactic acid are widely used biopolymers. Biopolymers are in their foundation phase and suffer several setbacks. They are made from a variety of materials, susceptible to different challenges. The industry requires more innovations to improve biopolymers' mechanical strength and moisture affinity. All bioplastics are erroneously considered an eco-friendly alternative to plastics. Many people cannot distinguish between bio-based, biodegradable, and compostable plastics and generalize all green claims on plastic packaging labels. However, biodegradable plastics are more eco-friendly. Plastics should at least be designed for reuse. In specific industries, however, the use of plastic packaging should be reconsidered. Since plastic packaging is harmful to the fresh food industry, it is more advisable to reduce the use of such packaging, relying on the good old open-air display. In the long run, even biodegradable plastics are not quickly degraded; hence not a perfect solution for plastic waste. However, the best solution to plastic pollution is to cut down on plastic use.

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