

Review Article Bio-Based Disposable Containers for Food Services

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Currently, petrochemical plastics dominate the food service industry due to their good mechanical properties and barrier against heat, water vapor, carbon dioxide, and oxygen. This widespread use is not only harmful to humans but also to the ecosystem as synthetic plastics disrupt ecological balance and deplete petroleum-based oil resources. Researchers and manufacturers are continuously addressing this problem by developing bio-based alternatives that provide numerous advantages including structural flexibility, biodegradability, and effective barrier properties. However, the high cost of production and unavailability of equipment for batch processing impede the potential for widespread manufacturing. Natural fibers mixed with bio-based adhesives derived from plants provide one of the biggest potential sources of bio-based materials for the food container industry. Not only does this address the issue of high raw material cost but it also has the potential to become sustainable once processing steps have been optimized. In this review, the current findings of several research related to the production of bio-based disposable food containers, packaging, and composites made from bio-based materials and bio-based adhesives are critically discussed. Several properties and characteristics important to the production of food service containers and primary packaging, as well as the existing challenges and future perspectives, are also highlighted.

1. Introduction

In 2020, the food packaging market size in North America was valued at USD 19.29 billion and is projected to increase at a compound annual growth rate (CAGR) of 4.9% from 2020 to 2028 [1]. This growth is primarily driven by the increasing reliance of consumers on packaged food products and expanding food processing companies throughout the region. Among all the North American countries, the United States holds the largest market share. Rigid packaging production overweighs flexible packaging with a share of more than 60% in 2020 alone. However, the demand for flexible packaging solutions is expected to increase considerably in the coming years as end-use companies are transitioning to flexible packaging products that require less materials and processing, and with biodegradable nature for an increased sustainability profile. Bioplastics and other bio-based products remain one of the key raw materials for flexible packaging production.

Alongside the increasing market size for food packaging is the rising bio-based biodegradable plastics production. Quince Market Insights [2] reported a global market value of USD 7.5 billion in 2021 with a projected CAGR of 25% from 2021 to 2030. Some of the factors that drive the increase in the demand include government policies on single-use plastic utilization and stringent rules on conventional plastic products use. However, the production of bio-based food containers is impeded by its high cost of production over its conventional counterparts. For example, the cost of producing conventional petroleum-based plastics is eight times cheaper than producing polylactic acid (PLA)-based bio-plastics [2].

Still, plastic accounts for the largest share of food packaging market size due to its flexibility and wide array of applications [3]. Petrochemical plastics are known to have good mechanical and tensile properties, and provide an effective barrier against water vapor, carbon dioxide, and oxygen [4]. Several types of petroleum-based plastics include



FIGURE 1: Classification of bio-based materials, polymers, and composites used in the food packaging industry.

polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP) and polystyrene (PS). In addition to these plastic types, crystallizable polyethylene terephthalate (CPET), linear low-density polyethylene (LLDPE), ultra-low-density polyethylene, medium-density polyethylene (MDPE), polycarbonate (PC), polyvinylidene chloride (PVDC), and polyamide or nylon are also used for various food service applications.

The dominance of synthetic, nonbiodegradable plastic products in the food service industry presents a widespread problem of plastic pollution and unsustainable production. Although extremely beneficial, massive utilization of conventional plastic products causes irreversible damage to the environment, which includes harmful emissions from incineration, decreasing landfill spaces, pollution of bodies of water and sewer systems, disruption of ecological balance, and depletion of oil and petroleum resources [5, 6]. Plastics that leak out of recycling and sorting systems usually end up in soil and ocean which, after a long time, degrade into micro- and nanoparticles that penetrate into living organisms such as fishes and small animals. These plastics eventually go high up the food chain upon human consumption of the plastic-infested animals and cause long-term deleterious effects [7].

There are two main reasons that drive the research on bio-based packaging materials. One is the replacement of nonrenewable materials by renewable resources for sustainability purposes, and the other is the reduction of the amount of nonbiodegradable plastic waste that fills the landfills by producing biodegradable and compostable alternatives [8]. Compostability is one property that is critical for polymer resources as it exploits the biodegradability of organic matter present in the bio-based products without using energy compared to recycling [9]. Bio-based materials commonly used in food packaging may either be polymers, nanomaterials, or fibers and their composites. A schematic diagram of this classification is depicted in Figure 1. Other classifications may also be done based on chemical composition, economic importance, method of synthesis, applications, etc.

The main objective of this review is to highlight the use of bio-based materials in the production of primary packaging materials in food service industries, specifically the current status and advancements of bio-based disposable containers. Several reviews [8–11] have been published about bio-based food packaging but the focus of these reviews is mainly the production of biofilms, bioplastics, or biocoatings for food packaging. Based on extensive literature search, there is currently no review dedicated for the production of bio-based food containers alone. Hence, this review will shed light on the current advancements, challenges, and future trends of the production of bio-based disposable containers for food services.

2. Bio-Based Disposable Containers for Food Services

2.1. Polylactic Acid (PLA). PLA has gained popularity in the food service industry as a replacement for traditional plastics due to its eco-friendly and biodegradable characteristics. It is an aliphatic biodegradable polymer produced via ringopening polymerization. The process uses lactide, present in several forms such as L-lactide, L, D-lactide or mesolactide, and D-lactide stereocomplex, as an intermediate substance to synthesize PLA. The lactic acid monomers are commonly derived from the fermentation of carbohydrates like starch and cellulose, with large proportions produced from renewable materials like sugarcane, cassava, wheat, corn, and other feedstocks. PLA has high transparency and molecular weight. Some of its desirable characteristics include compostability, recyclability, and short degradation time compared to most petroleum-based plastic containers [12]. Figure 2 shows the general steps in the production of PLA-derived products from renewable resources [13].



FIGURE 2: Polylactic acid production process.

PLA is currently commercialized under different names that include GalacidTM, NatureworksTM PLA, LactyTM, and Ecoplastic[™] [11]. In food packaging applications, they are mostly utilized for fresh products that are not affected by PLA oxygen permeability. Among these products, rigidthermoformed containers and high-value films receive the most attention. PLA as food packaging materials offers a desirable combination of chemical and physical characteristics including dead fold and twist retention, clarity, stiffness, low-temperature heat sealability, and barrier properties for flavor and aroma characteristics, at a competitive price [14]. Since the production of PLA-made food containers is already ubiquitous and managed by several companies, there are only very few publications regarding the utilization of PLA for food packaging. Almenar et al. [15] found out that highbush blueberries packaged in nonventilated PLA containers prolonged the shelf life of blueberries stored at 10°C for 18 days and at 23°C for 9 days. Zhou et al. [16] also reported desirable results after observing that the overall quality of the Rupia red melon cultivar was maintained better after storing in PLA than in PET containers at 10°C during 10 days of storage. Although PLA is not soluble in water, marine microbes under the phylum Actinobacteria such as Saccharothrix waywayandensis, Kibdelosporangium aridum, and Actinomadura sp. can easily degrade PLA into water and carbon dioxide [17]. The general steps in the biodegradation process are shown in Figure 3.

2.2. Polyhydroxyalkanoates (PHA). The PHA class of biopolymers consists of a large group of polymers that exhibit various characteristics and performance, and are chemically synthesized by biobased or natural bacterial fermentation of lipids and sugars [19]. They accumulate as an energyreducing power storage material in several microorganisms, especially when there is a growth-limiting element such as oxygen, nitrogen, phosphorus, sulfur, and other trace elements (e.g., iron, calcium, magnesium) in the presence of excess carbon source. PHA is generally classified based on chain lengths resulting from hydroxy fatty acids with different numbers of carbon atoms—short chain length (*scl*), medium chain length (*mcl*), and long chain length (*lcl*), which consist of 3–5, 6–14, and >15 carbon atoms, respectively. *Scls* are synthesized by several bacteria like *Cupriavadus necator* and *Alcaligenes latus*, while *mcls* are usually produced by *Pseudomonas putida*, a type of fluorescent *Pseudomonas*. There are also a few bacteria that synthesize copolyester in the form of *scls* and *mcls*. These include *Thiococcus pfennigii* and *Aeromonas hydrophila* [20].

PHAs are commercially derived from different sources including marine sediments, palm oil mill effluent, municipal sludge, gas effluents, solid wastes, cellulosic, and others. They are biodegradable, thermoprocessable, and biocompatible with flexible strengths. Currently, nine different PHA product families are produced which indicates that PHA cannot be described as a single product alone. Among them, polyhydroxybutyrate (PHB), p-hydroxybenzoate hydroxylase (PHBH), and poly (3-hydroxybutyrate-co-3-hydroxyvalerate) are the most commonly utilized. One characteristic that is common to all PHA product families is their biodegradability in soil and water and in both aerobic and anaerobic conditions in the presence of bacteria or fungi. The biodegradation behaviors are tunable to suit desired requirements, making them more versatile [21]. PHA polymers are commonly used in the food packaging industry in the form of foams, fibers, coatings, films, and boxes. Molded PHA products are used as food servicing items, vegetable crates, food containers, and egg crates. The bubble sheets are usually used for vegetable and fruit packaging. The films, on the other hand, are used to package short-life and perishable food products such as dairy, fruits, and vegetables.

2.3. Paper. Paper food containers are made from an interlaced network of cellulose fibers pulped from wood extracted using sulfite and sulfate, which are further treated and bleached with chemicals during the process. Paper and paperboard are used





FIGURE 3: Biodegradation process of PLA [18].

in producing milk cartons, corrugated boxes, bags, and sacks, wrapping paper, and folding cartons [22]. Among paperbased food container materials, cartons are superior in terms of durability and functionality. It can accommodate printed explanations on its exterior and offers easy handling and food protection. It can be made with appropriate stiffness to hold food intact and prevent fragile food products from compression, which is also advantageous for transport and stacking of containers [23].

Paper-based food containers are prone to lose their form due to poor resistance to water. The cellulose content of paper-based food containers is hydrophilic in nature, thus favoring water absorption. Its surface functionality can be improved by putting barrier in between the contact of pulp material and food. In this way, the wettability of the surface is changed using sizing agents and hydrophobic materials. For instance, hydrophobic sizing agents that can be used include paraffin wax emulsions and styrene- or polyurethane-based copolymers, which are in its molted form when applied on the container surface. In order to improve adhesion and lowtemperature resistance and prevent cracking due to bending and folding of the container, plastic polymers or resins may be added to the wax [24].

Paper-based food containers have been used for many years in the food industry. Alongside with its promising functionality in this application is the human health safety and environmental concerns due to various additives added during its production process. Toxic chemicals, such as phthalates, bleaching agents, surfactants, hydrocarbons, and printing inks, may contaminate the food packed in paper-based containers [25].

2.4. Starch-Based. Expanded bead foams, such as expanded polystyrene (EPS), have been the most used material in manufacturing food containers and packaging due to their low cost, high rigidity, and availability [26]. The market for EPS has an expected compound annual growth rate of 4.8% from 2021 to 2028 driven by the increasing demand for food containers such as food trays, clamshell containers, and drink cups [27]. This is an alarming issue as polystyrene is included in the list of packaging materials released by the U.S. Plastics Pact and U.K. Plastics Pact that are labeled as "problematic or unnecessary" [28]. A promising substitute for EPS is thermoplastic starch (TPS) foams, which are nontoxic, compostable, good quality, widely available, and inexpensive [29]. In this kind of material, starch is heated and molded with water and other additives to prepare foams. TPS is a viscous mixture obtained through the breakage of hydrogen bonds from granular starch. However, starch is naturally hydrophilic and fragile and its physical and mechanical properties are easily affected by water absorption [30]. Some of the strategies employed to improve these aspects of starch as a raw material for TPS foams include (1) addition of micro- and nano-sized fibers or agro-industrial residues; (2) mixing with polymers such as chitosan, poly(lactic acid), and poly(vinyl alcohol); (3) addition of nanoclays; (4) starch

modification; (5) coating with beeswax or chitosan; and (6) addition of bioactive compound [27]. In the study of Hoyos Mireles et al. [31], oca starch foam was formed with filler agents and banana and achira leaves at 2.5%, 5%, and 7.5% concentrations. At a 2.5% concentration of banana leaf, the properties of oca starch-based foams, in terms of flexibility, water resistance, puncture resistance, and tensile strength, were improved [31].

The addition of bioactive compounds in starch-based foams has been found to extend food shelf life without affecting product quality. A study on starch-based foam added with bioactive compounds is the cassava starch/spent coffee ground (SCG) foam supplemented with zinc oxide and oregano essential oil (OEO)/palm oil. Optimal formulation in terms of bioactive agents and lowest density was achieved at 4% SCG, 1% zinc oxide, and 7:3 OEO–palm oil ratio, while in terms of flexural strength and flexural modulus is at 6% SCG, 7% zinc oxide, and 7:3 OEO–palm oil ratio [32].

2.5. Bio-Based Nanofibers. Bio-based nanofiber, also known as nanocellulose or nano-structured cellulose, is another potential renewable and sustainable alternative to plastic food containers. It is characterized by its nano size fibers (<100 nm) in at least one dimension. This material is a homopolysaccharide with $(\beta$ -1–4)-linked-glucopyranose units and nanostructures, which is of high interest due to its biodegradability and renewability [33, 34]. Other advantages as a material include high degree of polymerization, high mechanical strength, high biocompatibility, low density, and nontoxicity [35]. Sources of bio-based nanofibers include tomato peels, garlic straw, raw cotton linter, barley waste, coconut husk fiber, pine, mengkuang leaves, forest residues, corncob residues, industrial waste cotton, cassava root bagasse, sugar palm fibers, and corn straw. The purity and properties of nanofibers from these sources may differ depending on the plant source and extraction method [36].

2.6. Potential of Biomass Composites for Food Containers

2.6.1. Issues with Current Containers. As a low-cost option, plastic-based food containers are still preferred by most food stores and manufacturers despite safety concerns. They offer functional advantages such as thermosealability, optical properties, microwavability, and ability to be formed into various shapes and sizes over reusable glass and tinplate alternatives [37]. Various types of plastics are used in making food containers such as polyolefin, ethylene vinyl alcohol, polyamide, polyester, polyvinyl chloride, and polyvinylidene chloride [38].

One of the major problems caused by plastic use is continued entrapment and destruction of habitat. Specifically, about 21% of seabirds and 45% of marine mammals have either been ingested or entrapped by plastic floating in bodies of water [39]. Plastics pollute and contaminate bodies of water, thus destructing the habitat of these animals. The transport of plastic container waste facilitates the transport of pathogens and invasive species [40]. As bodies of water accumulate plastic waste, it may cause flash flooding after extreme hydrologic events may occur, which further increase the probability of floatable plastic contamination in a specific area. Even irrigation canals where water flows for crop management may be contaminated if proper waste management of food containers is still observed [41].

Out of 906 chemicals used in plastic food packaging, 63 chemicals are proved to be hazardous to human health and 68 chemicals are detrimental to the environment [42]. Various polymers and its additives affect human health, specifically can cause cancer, endocrine disruption, and neurological, hepatological, renal, and cardiological issues resulting from acute chronic exposure. This exposure may be through inhalation and ingestion. Micro- and nanoplastics are usually transported as raw materials for food containers, which can become a pathway to expose humans that could reach the respiratory system, circulatory system, and lymphatic system [43]. As it traverses through these systems, deposition in internal body organs can happen, including liver, kidney, and gut [44].

2.6.2. Potential of Bio-Based Materials. Packaging plays a vital role in maintaining the quality of food products during transportation, storage, and end use. It prevents deterioration caused by environmental stressors and human tampering and increases the efficiency of food handling, sales, and consumption. Food containers, coatings, films, and lids are some of the major components that constitute a well-made food packaging. In recent years, there have been many new developments for packaging design systems such as biopolymer packaging, edible films and coatings, and active packaging. The drive for these developments arises from increasing attention to environmental concerns and sustainability. Conventional packaging materials such as chlorine-based plastics, packaging polymers (e.g., polyvinyl chloride, polyvinylidene chloride), and aluminum-based structure are now perceived as environmentally degrading [45]. Hence, a push toward the use of bio-based materials for food packaging, especially for food containers that balance the availability of raw materials, low production cost, and biodegradability has been one of the focus in the food packaging manufacturing industry.

Natural fibers provide one of the biggest potential sources of bio-based materials for food containers industry. They may be derived from animals (wool and silk), plants (sisal, cotton, hemp, flax, vegetable fibers), and geological process (asbestos). Lignocellulosic fibers from plants are commonly utilized as reinforcing fillers in biocomposites, which are embedded in a matrix of a full bioplastic such as proteins and polysaccharides [46]. For food packaging, some advantages of using natural fibers include biodegradability, low raw material cost, low tool wear, excellent mechanical strength properties, and low density per unit [46, 47]. However, the hydrophilic nature of natural fiber composites poses a critical problem similar to paper-based packaging. Several studies involving various fiber origins and processing techniques such as the use of 10% coconut fibers with poly(3-hydroxybutyrate-co-3-hydroxyvalerate) [48]; 20% wheat straw fibers as reinforcing agent [49]; almond shell, rice husk, and seagrass [50]; betel nut [51]; sugarcane bagasse, barley straw, and corn cob husk [52]; and cellulose extracted from cocoa pod husks with sugarcane bagasse as reinforcement [53] were also conducted.

3. Bio-Based Adhesives for Biomass Composites and Containers

3.1. Plant Protein Adhesives. Bio-based adhesives specifically proteins have been used in the industry for many years but have been replaced with synthetic ones in the early 20th century due to improved moisture resistivity. The most common synthetic adhesives are fossil-derived polymers, which are classified into four major synthetic thermosetting resinspolymeric diphenylmethane diisocyanate (pMDI), methyl formaldehyde, urea formaldehyde (-acidic catalyst salt), and phenol formaldehyde (-alkaline catalyst salt) [54]. In the woodworking industry, more than 90% of synthetic thermosetting adhesives are based on melamine, phenol, and urea. Among these, UF-based adhesives are the most prevalent in internal applications like medium-density fiberboards and particle boards due to several desirable characteristics such as high dry bonding strength, colorless glue line, rapid curing, and relatively low raw material cost. However, these types of resins have been proven to be detrimental to health upon exposure during production and service due to slow adhesive hydrolysis during hot and humid conditions and the unreacted formaldehyde residual [55, 56]. Urea formaldehyde (UF) is also classified as a Group 1 carcinogenic substance by the International Agency for Research on Cancer [54], hence the growing emphasis on the production of bio-based adhesives that will not cause any detrimental health and environmental effects.

Various types of biomass have been utilized for the production of natural adhesives including vegetable oils [57], starch [58, 59], tannins [60–63], and lignin [64–67]. However, the most common and widely studied are protein adhesives derived from plant proteins. There are two main reasons behind the use of protein-based adhesives—first, it allows the production of materials with specific physical and chemical properties needed for industrial utilization and second, it replaces synthetic adhesives leading to a reduction in the carbon footprint [54]. Common plant proteins utilized for adhesive preparation include soy protein [68–71], wheat gluten [69, 72, 73], cotton protein [68, 74], rapeseed (or canola) protein [75–77], and zein protein from corn [77, 78].

Among all other plant-based protein adhesives, soy protein is the most common and most well-used due to its low cost, biodegradable nature, and availability. It is made up of roughly 90% globulins and 10% albumins that can be easily extracted with moderate salt solutions and water, respectively. Compared to wheat gluten, soy protein has a more hydrophilic characteristic and more globular. However, in its raw form, the protein possesses limited water resistibility, poor wettability, and is highly sensitive to microbial degradation. Soy protein enhancements such as alkali treatment, chemical denaturation, and addition of cross-linkers and other additives increase the adhesive performance including adhesive strength and thermal resistivity [54].

Wheat gluten, a by-product from wheat starch processing, can be used as wood adhesive. Its cohesiveness and viscoelastic properties arise from a complex combination of 80% wheat protein, lipids, polysaccharides, and minerals. The two main protein groups found in wheat gluten include glutenin and gliadin with the ratio varying among gluten sources [79]. Wheat gluten is one of the cheapest and most abundant protein sources with high amounts of hydrophobic amino acid and can be easily dispersed in both alkali and acid media.

3.2. Enhancement of Protein Adhesives. Despite the high potential of plant proteins for adhesive use, the protein in its purest form does not achieve superior characteristics in terms of adhesion strength and water resistance. Modifications and enhancements need to be done to change the molecular conformations and improve the properties of proteins, such as stickiness of the protein dispersion, wetting ability, flowability, and storage ability [80]. These methods may include enzymatic modification, acidic and alkali treatment, chemical denaturation, cross-linking, and the addition of various chemical additives. In addition, several physicochemical properties must also be controlled such as resistance to degradation under different environmental conditions. Shown in Table 1 are select studies involving the enhancement of protein-based adhesives from soybean, wheat, cotton, canola, and corn proteins.

4. Biomass Composites and Containers for Food Services

4.1. Biomass Composites and Production. Bio-based composites are a class of materials that combine the benefits of having good mechanical performance and low environmental impact [7]. The process of manufacturing these materials varies depending on the desired end use and properties of the final product, as well as the type of biomass materials utilized. Most biomass is lignocellulosic, which consists of three primary polymeric components-cellulose, hemicellulose, and lignin [99]. Cellulose is a long-chain polysaccharide consisting of D-glucose units that are linked by β -1,4 glycosidic linkages, with both amorphous and crystalline components. The presence of intermolecular hydrogen bonds between the oxygen atom in the pyranose ring of one anhydroglucose residue and the hydrogen atom in the hydroxyl group in the next anhydroglucose residue stabilizes each cellulose chain and groups them into a flat network of highly ordered crystal-like structure [100]. The grouped chains result in elementary fibrils or microfibrils (with diameters around 3.5 nm), which are further arranged in bundles forming microfibrillar cellulose (diameters of 20-50 nm). These bundles altogether create the component part of cellulose fibers, which are then associated with other components such as hemicelluloses, pectin, and lignin as well as trace amounts of proteins and fats [99].

Cellulose fibers derived from plants such as hemp and flax grown in Europe, and bamboo and jute grown in Asia are the most common materials used for composites. The fibers from these plants are long and can be easily extracted, making preforms with desired fiber orientations for composites possible. In addition, the relatively high cellulose content in the form of aligned crystalline microfibrils improves the mechanical properties while maintaining low density. In the past decades, a large number of studies reported the mechanical and technical performance of composites made

| Protein type | Enhancement done | References |
|---------------------------|---|------------|
| | Soy proteins modified by 0.5% and 1% sodium dodecyl sulfate and 0.5% and 1% sodium dodecylbenzene sulfonate enhanced the water resistance and tensile strength of soy protein adhesives applied on walnut, cherry, and pine plywood. | [81] |
| | (ii) Soy proteins modified by 1 and 3 M urea and 1 M guanidine hydrochloride improved the water resistance and tensile strength of soy protein adhesive applied on walnut, cherry, and pine plywood. | [82] |
| | (iii) Soy proteins modified with higher hydrophobicities under moderate alkaline conditions (pH of 10.0 at 50°C) and the addition of trypsin enhanced adhesive strengths and water resistance properties. | [83] |
| | (iv) Urea modified soy proteins resulted to higher water resistance properties compared to adhesives containing alkali-modified and heat-treated proteins when applied to plywood. | [84] |
| Soy protein | (v) Moderate esterification using ethanol yielded the maximum increase in adhesion strengths and water resistance of soy protein adhesives. The optimum esterification condition was found to be 10 hr with no catalyst. This condition increased the dry, wet, and soaked strengths by 20.6%, 61.6%, and 48.1%, respectively. | [85] |
| | (vi) The use of 20μ M optimum glutaraldehyde concentration as a protein cross-linker enhanced the dry, wet, and soak strengths of soy protein isolate applied to cherry wood. | [86] |
| | (vii) Soy protein isolate modified with three cationic detergents (hexadecyltrimethyl ammonium bromide, ethylhexadecyldimethyl ammonium bromide, and benzyldimethylhexadecyl ammonium chloride) at a concentration of 2.6 mM improved the dry tensile strength and water resistance of soy protein. | [87] |
| | (viii) Decreasing the carbohydrate content and extent of Maillard reaction at high temperatures improved the degree of cross-linking and hydrophobicity of soy-based adhesives. The highest bonding strength was observed for soy-based adhesives with a glucose content of 71%. | [88] |
| | (ix) The shear strength and water resistance of sorghum lignin and extruded sorghum lignin blended with soy protein improved the shear strength and water resistance of soy protein adhesive. | [89] |
| | (i) The addition of triacetin to phenolic resins containing wheat protein improved the performance of thermoset wood adhesives. | [90] |
| | (ii) Alkaline hydrolysis (pH of 13 with concentrated sodium hydroxide solution) improved the dry and wet bonding strength of wheat protein adhesive by forming smaller peptides after longer treatment times. | [72] |
| Wheat protein (gluten) | (iii) The addition of polyamidoamine-epichlorohydrin as cross-linker for wheat gluten proteins dispersed in sodium hydroxide instead of citric acid enhanced the internal bonding strength, reduced thickness swelling, and water absorption capacity of particleboards bonded with wheat protein adhesive. | [91] |
| | (iv) Thick spent sulfite liquor, an industrial by-product from sulfite pulp mills, combined with wheat flour at an 84:16 dry weight ratio and preheated to 94°C prior to application yielded an internal bonding strength higher than the standard requirements for particleboard type P2 (boards for interior fitments for use in dry conditions). | [92] |
| | (i) Hexane-extracted cottonseed meal glue yielded comparable shear strength values with commercial casein glue and peanut meal glue. | [93] |
| Cotton protein | (ii) Cottonseed protein isolate modified with adipic acid, butyric acid, acetic acid, glutamic acid, and aspartic acid enhanced the adhesive strength and water resistance of cottonseed protein adhesive tested on maple wood veneer. | [94] |
| | (iii) Cottonseed protein modified with sodium dodecyl sulfate showed improved shear strength and superior retained strength on a hot water test. | [94] |
| | (i) Chemical modification with SDS, CaCO ₃ , ZnSO ₄ , and OSA improved the dry and soak strengths of canola proteins adhesives. However, the combined chemical modifications of canola protein using SDS and CaCO ₃ , and SDS and ZnSO ₄ did not improve the shear strength. | [75] |
| Canola (rapeseed) protein | (ii) Canola proteins modified with ammonium persulfate (APS) at optimum conditions (1% w/w APS/protein) followed by nanomaterial exfoliation improved wet and dry adhesion strengths. | [95] |
| | (iii) Canola protein isolate-poly(glycidyl methacrylate) conjugates synthesized by free radical polymerization showed can be produced with good adhesive strength and water resistance. | [96] |
| | (i) Zein-based adhesive modified with 5 wt % FeCl ₃ aqueous solution (Fe(III)@zein/SDS adhesive) showed high adhesive strength. | [97] |
| Corn protein (zein) | (ii) Using acetic acid rather than ethanol as solvent, zein can be cross-linked by glutaraldehyde for improved water resistance and strength. Zein adhesives added with 5% cellulose nanofibrils also enhanced the adhesive bonding strength. | [98] |



FIGURE 4: Injection molder parts and components.

from bio-based fibers. A majority of these studies have focused on the composites with random in-plane fiber orientation due to their applications in semistructural panels in large-scale construction and automotive industry [101].

Composite materials consist of two main componentsa continuous matrix and a dispersed phase in the form of sheets, fibers, or particles that are embedded in the matrix for reinforcement. The matrix is typically a polymer like highdensity polyethylene [99]. The fibers used in the dispersed phase have mechanical and physical properties that depend on the type of biomass and source of biomass. Typically, the density, elastic modulus, tensile strength, and elongation at break of the natural fibers are within the range $0.8-1.5 \text{ g-cm}^{-3}$, 5-50 GPa, 140-900 MPa, and 1.5%-30%, respectively [101, 102]. The weak adhesion at the fiber polymeric matrix interphase limits the amount of fillers added in the composite. This is further worsened by poor mechanical properties and complexities in processing [103, 104]. Hence, compatibilizers (in the case of PLAs) like itaconic or maleic anhydride are used to increase filler loading in the polymeric matrix. Enzymatic, chemical, or coating approaches, as well as the pretreatment of fillers, may also enhance the matrix-filler compatibility. Furthermore, the properties and amount of coupling agents should be considered as these affect the properties of the resulting composites [105].

4.2. Production of Containers

4.2.1. Injection Molding. There is a plethora of methods applied for the production of rigid containers. Among them is injection molding, which is commonly carried out for polymeric thermoplastic materials. The main principle behind the process involves melting the polymer in a heated barrel and injecting it into a mold with desired shape and size. Injection molding is typically employed in the production of jars for cosmetics, bottle caps, coffee capsules, and hard food containers. It consists of three main stages—injection, pressure holding and plastification, and ejection. Figure 4 shows an injection molder with its parts and components.

The first stage of injection molding is injection where the mold is partially filled with the molten polymer. Here, understanding the rheological behavior of the polymer as a function of temperature is critical to facilitate good processing. To allow rapid and perfect filling of the mold, the polymer viscosity should be very low while maintaining a high shear rate. This can be achieved by using and controlling appropriate temperature at all times. Moreover, it is necessary to determine the melt flow index at the injection molding temperature. Thermoplastic polymers used for injection molding have typical melt flow indices greater than 10 g min⁻¹ [106]. A precise dimensioning of the filling channel as a function of the melt rheology of the thermoplastic polymer is also employed in some cases.

After injection, the molten polymer stays in the mold for a specific amount of time while being subjected to constant pressure. Some of the critical parameters that need to be monitored and controlled include mold temperature, holding time, and holding pressure, as minimal deviation in any of these parameters may affect the mechanical strength and properties of the final container. Also, at this stage, the thermoplastic polymer (especially for bio-polyesters like PLAs and PHAs) undergoes crystallization, and the said parameters influence the distribution and amount of crystals formed. The resulting crystalline morphology then determines the final properties of the container.

4.2.2. Thermoforming. Thermoforming is another method of producing jars, blisters, plastic cups, trays, and containers with desired shapes and sizes. In the process, a plastic sheet or film is subjected to a high but pliable temperature (usually between the film's glass transition temperature and melting point) enough to form the packaging shape while maintaining barrier properties for food protection and preservation. It uses flat die extrusion with a thickness ranging from 50 to $300 \,\mu$ m and a mold that shapes the softened sheet [107]. After the molding is done, the packaging goes to a trimming station where it is trimmed and cut. Commonly thermoformed materials include PP, CPLA, PLA, PS, and PET.

For optimal material distribution and efficient forming, it is not only necessary to have a machine with appropriate parameter setting but design considerations such as efficient tooling process, consistency in forming and cutting quality, and productivity and flexibility need to be considered. Optimal air and cooling systems and efficient forming molds also affect the quality of the final product. Four major designs of plastic thermoforming are used in the food packaging industry—clamshells, cups, trays, and containers. Clamshells are transparent, easy-viewed packaging that does not require additional packaging to function. It may consist of holes for forced-air precooling process of fresh fruits and vegetables in the cold chain or a seal that goes all around the packaging and creates an airtight assembly for maintaining freshness and prevention of product tampering. Thermoformed containers (made from PET, PS, or PP) being commonly combine several features such as leak-resistant design, tight seals, and tabs for easy opening and closing. Some designs include a hinge that alerts whenever tampering has occurred. Trays, on the other hand, are similar to containers but are usually bigger in size since they are used for catering services and for holding large quantities of food products [108].

4.3. General Requirements of Containers for Food Services

4.3.1. Mechanical Strength. Various strategies can improve the mechanical properties of starch-based foams as a replacement for expanded polystyrene (EPS) used in food container production. Tapia-Blacido et al. [27] summarized processing conditions and properties of starch-based foams produced in different research studies. In one of these studies, improved mechanical properties and water resistance were observed using 13.6% glycerol and 18.4% grape stalks that were smaller than 0.18 mm in particle size [109]. Better mechanical properties of starch-based foams can be observed with smaller cell size and more uniform cell size distribution [26]. Higher density for cassava starch-PLA foams coated with beeswax solution at 0-3 g of beeswax per 100 g of solution produced by extrusion resulted in greater tensile strength and elongation until break point [110]. The highest impact strength was observed from foams with 20% and 30% esterified starch resulting in smaller average cell area (0.2358 mm^{-2}) and greater cell density $(4.49 \times 108 - 5.08 \times 108 \text{ g-cm}^{-3})$ [30].

The mechanical strength of a bio-based composite material decreases by increasing moisture content. Hence, water resistance is also directly related to mechanical strength. In the study of Ma et al. [111], biodegradable polymers mixed with starch and the addition of cross-linking agent such as tri-sodium/tri-meta phosphate have increased water resistance of composites. Another aspect related to mechanical strength is water vapor permeability. Graphene nanosheets, nanoclay, kaolinite, and carbon nanotubes were reported as potential fillers that can improve mechanical and barrier properties of nanocomposites [112].

4.3.2. Barrier Properties. Barrier properties such as resistance to water, oil, salt, and vinegar can influence mechanical strength and holding time of food containers. These compounds may penetrate the packaging and degrade not only the container but also the food or produce inside it. For example, when water penetrates through the packaging, it binds weakly and reversibly by hydrogen bonds to food. The oxygen inside will react strongly causing irreversible damage to the quality of food. Through the deposition of laminates of synthetic polymers including polyvinylidene chloride and ethylene–vinyl alcohol copolymer, better oxygen properties can be achieved. Thin layers of aluminum or inorganic compounds like SiOx may also be used as alternatives but the process requires technical efforts and expensive materials. The polymeric structure used are also nonbiodegradable and not readily recyclable, hence the increasing interest in bio-based polymers that are biodegradable and with excellent barrier properties [113, 114].

For nanofiller biodegradable composites, nanofiller orientation and dispersion uniformity in the polymer matrix play an important role in its barrier properties [115]. Diffusion pathway of fluids such as water or oil is longer and follows an irregular curve route, thus decreasing permeability of nanocomposites [116]. The gas and vapor permeability of PLA matrix was enhanced through the addition of cellulose nanowhiskers (CNW) as nanofillers with length of 60-160 nm and thickness of 10-20 nm. CNW was well dispersed in the PLA matrix, inducing formation of transcrystallinity without negatively affecting its thermal stability. CNW produced through freeze drying caused up to 82% decrease in water permeability and up to 90% decrease in oxygen permeability of PLA nanocomposites with CNW. Optimum barrier properties were observed for PLA nanocomposites added with at most 3 wt% of CNW [117].

A composite made of plasticized wheat gluten and modified potato starch (MPS) with attractive gas barrier properties was produced through extrusion [118]. In comparison to wild-type potato starch, MPS has higher amylose content and altered chain length of amylopectin. Optimum gas barrier properties under ambient conditions were achieved with a 70:30 ratio of wheat gluten and MPS plasticized with 45% glycerol.

Cellulose-based materials, such as paper and cardboards, are known to be hydrophilic and porous, which means poor resistance to water, gases, vapors, and air moisture. Improvement of barrier properties of these cellulose-based food containers can be done through lamination or coating with synthetic hydrophobic polymers. Biodegradable hydrophobic polymers include aliphatic polyesters, polycaprolactone, polylactic acid, copolyesters, and polyhydroxyalkanoates [119]. Table 2 summarizes some of the common polymeric materials and their derivatives used for the improvement of barrier properties for food packaging applications.

4.3.3. Stability to Temperature, Relative Humidity, and Heat. The stability of bio-based food containers to temperature and relative humidity is an essential consideration as poor heat stability and water resistant can cause material degradation. Since meals in food containers may be served hot, thermally stable materials should be used. PLA has a low thermal degradation temperature but can be blended with plasticizers and other polymers and incorporated with fillers to increase

| TABLE 2: Im | provement of barrier properties of food packaging materials, conta | ners, and composites from various polymeric materials and their derivatives [120]. | |
|---------------------------|---|--|------------|
| Polymeric materials | Methods and formulation | Effect on barrier properties | References |
| | A natural formulation composed of carboxymethyl cellulose (CMC) and various contents of cellulose nanocrystals immobilized silver nanoparticles (CNC@AgNPs) was developed for paper coating. | The water vapor and air barrier properties of CMC/CNC@AgNPs coated paper improved with the increasing content of CNC@AgNPs. CMC/CNC@AgNPs 7% coated paper exhibited 45.4% decrease in water vapor permeability (WVP) and 93.3% reduction in air permeability. | [121] |
| | Nanofibrillated cellulose (NFC) was prepared from microcrystalline cellulose via a high-pressure homogenization process and deliberately employed as a coating agent. | Water retention value (WRV) decreased from 250.0 to 158.71 g/m ² when 0.40% NFC was added. The WVP exhibited a decrease from 27.50 to 25.0 g/m ² at 0.30% NFC and further to 24.0 g/m ² at 0.40% NFC. | [120, 122] |
| | Solutions of the synthesized cellulose stearoyl ester compound were coated onto the calendered paper sheets by bar coater with the coating grammage ranging from 0.5 to 23.6 gm ⁻² . | Contact angle values increased from ≈ 15 to $109 \pm 2^{\circ}$. Water vapor transmission rates (WVTR) values declined from 514.80 to $27.74 \mathrm{g}\mathrm{m}^{-2}\mathrm{d}^{-1}$. The barrier ratio of coated paper to uncoated paper was recorded as $>90\%$ | [120, 123] |
| | Multilayered hybrid thin films of cellulose nanocrystals (CNC) and gibbsite nanoplatelets built by layer-by-layer technique onto substrates selected for packaging applications. | The measurement of the oxygen transmission rate (OTR) at 23°C and 50% RH showed that the oxygen barrier properties of the bare substrates could be significantly improved. Specifically, there was a substantial improvement, with the OTR experiencing a significant decrease of approximately 75% following the application of these thin (<100 nm) multilayered hybrid films. | [124] |
| Cellulose and derivatives | An aqueous slurry base, a mixture of cellulose nanofibrils and nanoclay particles, was sprayed on a kraft writing and printing paper surface as base substrate. Upon drying, the suspension on the paper surface formed a hybrid nanocomposite layer with cellulose nanofibrils (matrix) and nanoclay (mineral filler). | WVTR reduced from 28.55 \pm 0.7 to 4 \pm 0.2 (g m $^{-2}$ day). OTR values were not improved because of the incomplete closure of the base paper. | [125] |
| | Cellulose nanofibers (CNF) were used as a coating to improve the structure and barrier properties. Two forms of CNF were used: refiner- produced material and material produced with an ultra-fine grinder. CMC was used for some samples as an additive. | CNF significantly enhanced the barrier properties of the coated papers. Gravimetric water retention values declined with an increase in solid content from 1.5% to 3%. Air resistance increased from 80 to 1,400 Gurley s. | [126] |
| | Nanocomposite films prepared from TEMPO-oxidized nanofibrillated cellulose isolated from rice straw, chitosan nanoparticles, and glycerol by solution casting. The percentage of chitosan nanoparticles ranged from 2.5% to 20% while a fixed ratio of glycerol (25%) was added. | WVP increased by $15\%,$ water absorption reduced by 33% (Cobb test), and oil penetration time increased from 6 to 78 s. | [127] |
| | Handsheets were coated on one side with 1.5 or 3 wt% cellulose nanofibils as a single or double layer. | A double layer of 1.5 wt% cellulose nanofibils resulted in better barrier properties compared to a single layer of 3 wt\% cellulose nanofibils, even though the total amount of applied cellulose nanofibils was the same. | [128] |
| | Microfibrillated cellulose coated using bar coating process. 2% microfibrillated cellulose suspension was applied on cardboards using bar coating (5 cm). The process was repeated five times to deposit five layers. | Microfibrillated cellulose did not enhance much cardboard barrier properties, although it considerably increases their water absorption from 43 ± 7 to 114 ± 7 g/m ² . KIT values increased from 0 to 2.5 ± 0.5 . | [129] |

10

| Continued. | |
|------------|--|
| TABLE 2: | |

| Polymeric materials | Methods and formulation | Effect on barrier properties | References |
|---------------------|--|---|------------|
| | PLA films incorporated with cinnamic acid (3 wt%) using casting and thermal processing. | $\rm O_2$ permeability decreased from 187 \pm 8 to 141 \pm 2 \times 10 ¹⁴ , cm ³ /m·s·Pa, while WVP decreased from 0.28 \pm 0.06 to 0.18 \pm 0.11 g \cdot mm/kPa·h·m ² | [120, 130] |
| | A synthetic, large aspect ratio Na-Hectorite is used that may be utterly delaminated in an organic solvent and composited with PLA by modification with 18-crown-6 (18C6Hec), yielding a castable, homogeneous nematic suspension. | O ₂ permeability was reduced from $17,775 \text{ cm}^3 \mu \text{m} \text{ m}^{-2} \text{ day}^{-1} \text{ atm}^{-1}$, which was reduced by 99.3% to $124 \text{ cm}^3 \mu \text{m} \text{ m}^{-2} \text{ day}^{-1} \text{ atm}^{-1}$ and swelling properties in freshwater were decreased. | [120, 131] |
| | Pure potato starch was modified by 3-APTMS (3-(aminopropyl) trimethoxy silane) to manufacture a cross-linked film. To obtain a bilayer PPS-3APTMS-PLA film, the PLA was employed with PPS-3APTMS by casting method. | WVP improved from $31.69 \pm 0.4 \times 10^{-7}$ g s ⁻¹ m ⁻¹ to $14.26 \pm 0.3 \times 10^{-7}$ g s ⁻¹ m ⁻¹ . | [120, 132] |
| | PLA/polyethylene glycol (PEG)/graphene oxide composite films with filler concentration, relative to PLA, restricted up to 2 wt%, while 10 wt% of PEG was used as a plasticizer. | O ₂ permeability decreased from 1.45 \times 10 ⁻¹⁴ to 1.05 \times 10 ⁻¹⁴ (kg m (m ² s Pa)). while WVP decreased from 3.42 \times 10 ⁻¹⁸ to 2.18 \times 10 ⁻¹⁸ (kg m (m ² s Pa)) | [120, 133] |
| PLA and derivatives | Polyester multilayer membranes with more than 2,000 alternating layers of PLA and PBS were prepared via a nanolayer coextrusion process equipped with a multiplying-element device. | Improvement in barrier performances until 30% for oxygen, 40% for water and 70% for carbon dioxide. | [134] |
| | Melt extrusion was used to plasticize PLA with 5% epoxidized karanja oil. | O ₂ permeability increased from 20.9 \pm 0.9 to 25.4 \pm 1.2 (cm ³ mm m ⁻² day ⁻¹), while WVP increased from 71.2 \pm 1.0 to 74.1 \pm 0.7 (θ_{w}). | [120, 135] |
| | Coproducts coming from mill industries, such as wheat gluten proteins (WG), were used to produce PLA-WG-PLA multilayer complexes with improved barrier performance. | The most efficient complex increased more than 20 times (or 2,000%) the barrier properties to oxygen and \sim 20% the barrier properties to water vapor, considering application conditions (50% relative humidity and 25°C). | [136] |
| | Zinc oxide nanoparticles (ZnO NPs) were synthesized using zinc chloride and NaOH and they were incorporated to prepare PLA/ZnO NPs composite films. | WVP decreased by 30.5% from 3.11 \times 10^{-11} to 2.16 \times 10^{-11} g m/m^2. Pa·s when 0.5 wt% of ZnO NPs was incorporated. | [137] |
| | Bleached bamboo kraft pulp was pretreated by 2,2,6,6- tetramethylpiperidine-1-oxy radical- (TEMPO-) mediated oxidation using a TEMPO/NaBr/NaClO system at pH = 10 in water to facilitate mechanical disintegration into TEMPO-oxidized cellulose nanofibrils (TO-CNs). | O2 permeability drastically decreased from 355 for neat PLA to $8.4 \text{ mL} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ after coating a thin layer of TO-CN with a carboxylate content of 1.8 mmol $\cdot \text{g}^{-1}$. | [138] |
| | | | |

Advances in Polymer Technology

| | TABLE 2: | Continued. | |
|---------------------|--|--|------------|
| Polymeric materials | Methods and formulation | Effect on barrier properties | References |
| | Poly(butylene adipate-co-terephthalate), poly(butylene succinate), and linear low-density polyethylene were blended to produce bio-based packaging via blown-film extrusion. | O_2 permeability was significantly reduced in films containing PBS, and WVP was reported to be $1.5g~mm/m^2\cdot d\cdot k\cdot Pa.$ | [139] |
| | PBS/Graphene nanoplatelets (GnP) nanocomposites over a range of GnP from 0 to 1.35 wt%. were prepared by a melt process. A mixture of individual graphene nanosheets and aggregates was obtained by the addition of GnP in the PBS matrix. | Water permeability improved by 38% and dioxygen permeability by 35%. | [140] |
| | Biofilms made of poly PBS and tapioca starch (TPS) added with 1.5% or 3% of Biomaster-silver particles were made. | Small pore-size features with high barrier property for gas permeability were obtained for BM-filled PBS/TPS films. The O ₂ permeability decreased from 28,650 to 17,420 cm ³ $\mu m/m^2$ s Pa, while WVP increased from 90.17 to 95.40 g $\mu m/m^2$ with the incorporation of TPS. | [141] |
| | PBS/poly (butylene adipate-co-terephthalate films (containing 25%, 50%, and 75% PBS (w/w))). | $\rm O_2$ permeability decreased from 4.41 \pm 0.01 to 0.68 \pm 0.01 \times 10 ¹⁶ mol/m ⁻¹ \cdot s ⁻¹ \cdot Pa ⁻¹ , while WVP decreased from 7.09 \pm 0.08 to 2.90 \pm 0.02 \times 10 ⁻¹² mol/m s Pa. | [120, 142] |
| PbS and derivances | Bio-nanocomposite films were prepared using PBS as a matrix and banana starch nanocrystals (SNC) as filler by chill-roll cast film extrusion. | WVTR and OTR values of 9% wt modified SNC/PBS film (54.1 gm ⁻² day and 216.3 cc m ⁻² day) were lower than those of neat PBS film (114.5 gm ⁻² day and 560.3 cc m ⁻² day) | [143] |
| | PBS composite films with lactic acid through slit die extrusion-stretching-woven compression molding. In situ nanofibrillar networks of PLA are constructed within a PBS matrix serving as an efficient "barrier ball" and reinforcement. | Gas permeability of composite films decreased significantly, i.e., >63% reduction in PO_2 from 5.8×10 ⁻¹⁵ to 2.1×10 ⁻¹⁵ cm ³ cm ⁻² s ⁻¹ Pa ⁻¹ . | [120, 144] |
| | A confined flaking technique was used to establish the degradable nanolaminar PBS in PLA films based on PLA/PBS in situ nanofibrillar composites. The combination of high pressure (10 MPa) and temperature (160°C) during the flaking process enabled sufficient deformation of PBS nanofibrils and retention of ordered PLA channels. | O_2 permeability decreased by $87\%,$ i.e., from 1.4 to $0.6\times10^{-14}\mathrm{cm}^3\mathrm{cm}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Pa^{-1} | [120, 145] |
| | Combination of PHA-based materials and nanokeratin extracted from poultry feathers. | O_2 permeability decreased from 1.75 \pm 0.25 to 0.90 \pm 0.05 \times 10 $-$ 19 $m^3\cdot$ m \cdot $Pa^{-1}\cdot$ $s^{-1}\cdot$ m^{-2} and WVP decreased significantly from 3.54 \pm 0.40 to 1.22 \pm 0.10 \times 10^{-14} kg m s^{-1} m^{-2} Pa^{-1} . | [120, 146] |
| | Organic recyclable high-oxygen-barrier multilayer films based on different commercial PHA materials, including a blend with commercial poly(butylene adipate-co-terephthalate), which contained an inner layer of cellulose nanocrystals and an electrospun hot-tack adhesive layer of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) derived from cheese whey. | O_2 permeability decreased from 57.81 \pm 21.45 to 1.12 \pm 0.61 \times 10 $-$ 19 $m^3 \cdot m \cdot Pa^{-1} \cdot s^{-1} \cdot m^{-2}$, while WVP decreased significantly from 11.47 \pm 0.06 to 0.82 \pm 0.03 \times 10^{-11} kg m s^{-1} m^{-2} Pa^{-1}. | [120, 147] |
| PHA and derivatives | An electrospun antimicrobial hot-tack layer made of poly(3- hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) derived from cheese whey was deposited on a blown film of commercial food contact PHA- based resin. A hybrid combination of oregano essential oil and zinc oxide nanoparticles was incorporated during the electrospinning process into the PHBV nanofibers at 2.5 and 2.25 wt%, respectively. | WVP decreased from 3.22 \pm 0.12 to 0.87 \pm 0.92 \times 10^{-11} kg \cdot m^{-2} \cdot Pa^{-1} \cdot s^{-1}. | [120, 148] |
| | Enhanced thermoplastic corn starch nanobiocomposites containing bacterial cellulose nanowhiskers (BCNW) prepared by melt mixing were made. | Improved barrier to water vapor and oxygen at high relative humidity (80%) was observed, reaching the best performance at 15 wt% BCNW loading with a maximum drop of 46% and 95% for water and oxygen permeability. | [149] |
| | Three-layer films based on plasticized wheat gluten films have been developed by applying a more hydrophobic electrospun PHA layer on both sides of the protein film. A commercial PHB and a polyhydroxybutyrate-co-valerate copolymer with 3% valerate content (PHBV3) have been used. | O_2 permeability decreased from 15.10 ± 2.42 to 4.36 × 10 ⁻¹⁵ m ³ · m · Pa ⁻¹ · s ⁻¹ · m ⁻² , and WVP decreased from 16.02 ± 0.43 to 3.11 ± 0.64 × 10 ⁻¹¹ kg · m · Pa ⁻¹ · s ⁻¹ · m ⁻² . | [120, 150] |

12

Advances in Polymer Technology

its thermal stability [151, 152]. In the study of Arrieta et al. [153], PLA crystallinity was increased by dispersed nanocrystals, which in turn improved its thermal stability. A higher degree of crystallinity of a material is associated with greater resistance to high temperatures [154]. Humid conditions can alter the mechanical properties of bio-based composites, especially those with higher moisture absorption and poor water resistance [155].

Heat resistance is highly associated with the crystallinity of a material. It is attributed to the formation of polymer chains composed of crystalline and amorphous regions. The crystalline region is characterized by an ordered arrangement of crystalline platelets formed from polymer chains, whereas the amorphous region is located in between these crystalline regions. Higher temperature resistance is a characteristic of a material with a high degree of crystallinity. A material with longer polymer chains has better thermal properties. Polymer with long polymer chains is required to form crystalline platelets. Thus, short polymer chains cannot contribute to the semicrystalline structure of the bio-based polymer [154].

Different transformation temperatures influence a polymer structure and its heat resistance, including glass transition temperature, melt temperature, and crystalline temperature. Glass transition temperature is the temperature at which increased mobility of the amorphous region of the polymer structure is observed, resulting in rotation and sliding of side groups. Exceeding the glass transition temperature of a material indicates that its mechanical properties are justified by its crystalline phase [156]. Melt temperature is the temperature when a crystalline structure becomes a viscous liquid. Bio-based food containers should be made of materials with melt temperature higher than the actual maximum temperature that it is intended to be used for. Its melt temperature should also be lower than the degradation temperature [154]. Crystallization temperature is the temperature wherein the formation of crystalline regions occurs due to cooling. For a low crystalline or amorphous material, glass transition temperature is used as a measure of heat resistance as the temperature that the container will be used for should not be above this temperature. Otherwise, material deformation will occur [157]. Among bio-based materials, starch (crystalline region) and PLA (amorphous) are the materials with poor heat resistance as their melt temperature and glass transition temperature, respectively, are within the range of temperature reached during heat treatment in the food industry. Starch and PLA are also characterized by low values of heat deflection temperature and Vicat softening temperature [154]. Material deformation occurs upon application of constant load when heat deflection temperature is reached. Vicat softening temperature is the temperature at which 1 mm bio-based polymer can be penetrated by a needle under constant load [158].

Improving the heat resistance of bio-based materials can be done through additives such as chain extenders, nanoparticles, nucleating agents, and plasticizers, which could decrease the melt and glass transition temperatures, thereby increasing crystallinity [159]. Additives should be compatible with the main bio-based material as immiscible materials have a tendency to segregate during the melting phase, which induces decrease in mechanical strength. Higher surface tension attributed to the larger difference in the chemical nature of two polymer chains results in more immiscible materials. Compatibility between two polymer chains or materials can be enhanced through chemical modification, cross-linking, or the addition of a reactive functional group [160]. For instance, a 3:1 blend of PLA and PHB has an observed improvement in thermal and mechanical properties compared to these pure polymers [161].

4.3.4. Antimicrobial Capacity. One of the main goals of packaging food in containers is to prevent them from spoilage brought by microbial and environmental contamination and tampering from untargeted consumers. The introduction of antimicrobial agents to packaging creates an environment that prevents microbial growth on the surface of the product, which leads to prolonged shelf life and improved safety. Antimicrobial agents (e.g., organic acid, biofibers, mineral clays, biopolymer, essential oil, and heterocyclic organic compounds) are incorporated into biocomposites for food containers through different methods such as coating exterior surface with bioactive materials, direct incorporation into the bio-based composite polymer, and forming composites using antimicrobial material [162].

One biopolymer with intrinsic antimicrobial activity is chitosan (CS), produced from alkaline deacetylation and made up of *N*-acetylglucosamine and glucosamine units joined together by 1–4 glucosidic bonds [163]. It is widely incorporated in edible films and was found to inhibit the growth of *Bacillus cereus*, *E. coli*, *Salmonella typhimurium*, and *Staphylococcus aureus* when combined with apple peel polyphenols [164]; *E. coli* and *Pseudomonas aeruginosa* after mixing with grapefruit seed extract [165]; and *B. substilis* and *E. Coli* when added with Quercetin–starch [166]. The incorporation of chitosan into the matrix of polyvinyl alcohol (PVA) also stimulated the oxygen and water vapor permeability and improved the mechanical characteristics of the resulting PVA–CS films [167].

Determining the antimicrobial capacity of food containers and packaging is a complex process. There is currently a growing concern for antimicrobial food packaging as laboratory data are often an extrapolation of results into that of the real world. Lab-grade tests uses food stimulants which are far less complex than the actual food systems where salt contents are higher, water activity is lower, and proteins, fats, nutrients, and other chemical composition of the food interact with antimicrobials and food packaging [168–170]. In addition, environmental conditions such as temperature, moisture content, and relative humidity affect both the antimicrobial capacity of the container and the food inside it.

4.3.5. Compostability and Biodegradability. PLA is one of the most essential biodegradable polymers as it has a wide range of applications, including the production of food containers, agricultural films, implantable biomedical devices, drug delivery systems, and disposable household items. Biodegradation of PLA involves several steps and pathways [171]. It initially breaks down into monomers or oligomers (low molecular weight), with hydrolytically cleaved ester bonds [172]. Uptake of PLA by microorganisms is facilitated only after the

molecular weight of PLA reduces as a result of the transformation to smaller water-soluble fragments [173]. At molecular weight of less than 20,000 g/mol, PLA is water soluble. As microorganisms consume these smaller fragments, successive metabolic activity converts these polymers into water and carbon dioxide, and specific quantities of carbon are converted into biomass as end products [174]. Hydrolysis and microbial activity induce environmental composting of PLA under adequate conditions [175]. Hydrolysis of PLA is also hastened at temperatures above 50°C [176]. Microorganisms produce extracellular enzymes that cleave PLA chains, thus contributing to the degradation process [177].

The biodegradability of PHA is dependent on the length of the side chain, with longer side chain PHAs associated with a higher degree of biodegradability [178]. Depolymerization of PHA occurs in two phases. Initially, the binding domain of PHAs depolymerase is adsorbed onto the surface of PHAs, followed by polyester chain hydrolysis through catalytic domain of the enzyme [179]. Oligomers of PHAs produced after hydrolysis are further depolymerized by oligomer hydrolase yielding organic acid. Microorganisms convert the produced organic acid into water and carbon dioxide under aerobic condition [180].

Other naturally occurring polymers such as starch, protein, and cellulose are biodegradable over a wide array of environmental conditions. The biodegradability mechanism is influenced by the combined factors of pressure, water or moisture content, oxygen concentration, temperature, light, and environmental parameters such as the presence of other microorganism like fungi and microbiome [181]. For example, containers and packaging materials produced from potato starch may be made to be industrially or domestically compostable by varying the purities of bio-based carbon contents [182]. However, one of the biggest issues on compostable packaging materials is the possible increase in littering and undegraded compostable plastic residues [183, 184].

5. Conclusions and Future Perspectives

This review highlighted the current findings and research related to the production of bio-based disposable food containers, packaging, and composites made from bio-based materials such as PLAs, PHAs, paper, starch, bio-based nanofibers, and naturally occurring plant fibers. Several properties and characteristics that include mechanical strength, barrier properties, water resistance, stability to temperature, heat, and relative humidity, antimicrobial capacity, and compostability and biodegradability were discussed for containers with different components and reinforcements. Undoubtedly, the food container manufacturing industry has come a long way in utilizing bio-based raw materials for the development of environmentally friendly and sustainable food service products. However, synthetic, nonbiodegradable plastic products are still dominating the market due to good overall performance (e.g., good mechanical and tensile properties, effective barrier against water vapor, carbon dioxide, and oxygen).

Another important aspect highlighted in this review is the use of bio-based adhesives for biomass composites and containers. Discussions about the existing applications of plant-based protein such as zein, soy protein, wheat gluten, canola or rapeseed, and cottonseed proteins were provided as well as the enhancements (e.g., enzymatic modification, acidic and alkali treatment, chemical denaturation, cross-linking, and addition of various chemical additives) made to improve adhesive strength and water soaking characteristics. The use of bio-based adhesives in conjunction with bio-based materials for composite and container manufacturing doubles the beneficial effect in the environment as the sources for both raw materials are renewable and their utilization reduces the carbon footprint.

The biggest challenge that prevents the commercialization of bio-based materials is the balance between cost and energy utilization during production, extraction, and processing and the value of the final product. Since the majority of processing techniques are not yet optimized and applied in large scale, the initial cost and maintenance is undeniably high. It is therefore demanded to have more adaptable and accessible commercial techniques and equipment that can match the large-scale production. Another perspective to be considered is the long-term sustainability of the products after end use. Although, most of the products are biodegradable and have good composting properties, overproducing them may also hurt the environment as biodegradation takes time for some products. Increasing efforts toward developing processes that require less energy and use nontoxic organic solvents is also recommended.

Data Availability

The data supporting this review paper are from previously reported studies and datasets, which have been cited in the text and listed in the reference.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported on this paper.

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