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Bio-based and sustainable food packaging systems: relevance, challenges, and prospects

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ABSTRACT

Packaging materials are critical in ensuring the safety and quality of foods. Conventional packaging materials from non-renewable sources have revolutionized the food packaging industry, driven largely by convenience, low cost, good moisture barriers, and exhibition of excellent mechanical and handling properties. However, the growing ecological crisis and health burden emanating from heterogenous plastic waste demands sustainable and biodegradable alternatives, which promote circularity and lead to responsible material consumption. Beyond protection and containment, sustainable food packaging materials, unlike their traditional fossil cousins, leave minimal environmental impact and low carbon footprint from birth to dust. There is, therefore, a growing body of research on sustainable food packaging systems from different classes of natural polymers derived mainly from plants and animals. Bio-based packaging materials have been identified as possible renewable sources that can potentially replace conventional packaging materials. They can be extracted from biomass, chemically synthesized, or produced by microorganisms. Besides, they can be processed using wet and dry processes, and other complementary processes. Bio-based materials are generally abundant in nature, and their sources can be broadly categorized into polysaccharides, proteins, and polyhydroxyalkanoates. Though noted as renewable sources, their application has some limitations, such as difficulty in processing and poor performance. However, they can be blended with other materials to overcome these limitations, improving their intrinsic and extrinsic properties, thereby increasing their applicability in the food industry. This review aims to provide an overview of bio-based packaging materials and their consideration for sustainable food packaging. Besides, it discusses the properties critical for their application in the food industry, their limitations, and prospects.

1. Introduction

Packaging is a critical component of food processing that offers many benefits to the food it holds. Most importantly, packaging helps to improve the shelf life of foods by preserving the quality of the food and preventing the entry of substances and compounds (oxygen (O_2), moisture, light, microbes, etc.) that could cause spoilage and release of toxins during storage and distribution processes. Not only is packaging necessary for shelf life, but it is also crucial for reducing food wastage due to post-harvest losses. Food packages do not only protect food products from chemical, biological, and physical damages (Ruban, 2009), but even for the processor, they must be cost-effective (Khan et al., 2017) to support the business goals of providing good food at minimum cost. Some examples of these food packaging materials are polyethylene terephthalate (PET), polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP), and polyethylene (PE). Over the years, packaging materials stemming from petroleum-based sources have been dominant and have become a part of our daily lives due to their versatility (Mohan et al., 2022). The shelf-life characteristics of foods and drinks can be preserved using plastic packages (De Marchi et al., 2020). About 380 million tons of plastics are produced around the world. In fact, the European Union (EU) statistics showed 16 million tons of plastic packaging waste in 2016 (Jang et al., 2020). Plastics constitute 60 % to 80 % of global waste (De Marchi et al., 2020) as a large amount of them are not well recycled, exerting pressure on the environment (Zhou et al., 2023). Nilsen-Nygaard et al. (2021) also indicated that

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plastics have been flagged to have a negative impact on human health and the ecosystem. These petroleum-based food packaging materials come at a low cost and are easy to process, among other properties, but cannot degrade, which poses excellent environmental issues. Although petroleum-based packaging materials have been predominant in recent years, one major problem has been their disposal and recycling (Bullock et al., 2021). These increasing issues have raised more concern to propose ways to mitigate these impacts. In recent times, increased global knowledge on the impact of packaging materials on the environment has led to food materials with less environmental impact, referred to as sustainable packaging. Sustainable food packaging integrates functional and innovative materials into the packaging to improve environmental health/ impact and the economy (Ncube et al., 2020). For food packages to be classified as sustainable, several considerations are made, including their potential to be recycled or reused, their ability to be made from renewable sources, and less air pollution, among others (Jabeen et al., 2015; Attaran et al., 2017; Herbes et al., 2018; Mendes & Pedersen, 2020; Sid *et al.*, 2021). Growing concern for sustainable food packaging systems has created the need for and development of bio-based materials instead of petroleum sources (Reichert et al., 2020).

This growing consideration for biobased packaging materials can be seen from the increasing progressions in the subject area. A quick search in Scopus showed a progressive increase in sustainable food packaging (Fig. 1).

According to Fortunati et al. (2018), bio-based polymeric materials are considered an alternative to petroleum-derived polymers in the future, considering that fossil resources are getting exhausted. It can be seen from Fig. 1 that the topic is gradually gaining momentum, particularly in the last decade. However, progress exceeds the numbers indicated in the graph because of Scopus's constraint on the search word (bio-based AND packaging).

Bio-based materials used in packaging technology can be divided into three main categories based on their origin, chemical nature, and means of production. Although these materials have the potential to replace petroleum-based conventional materials, there are some drawbacks associated with their physical properties and processing. These drawbacks include their weak barrier properties and short life, which hamper their ready application in food packaging (Zinoviadou et al., 2016; Fortunati *et al.*, 2018). In other words, bio-based materials should meet technical specifications before they can serve as alternatives to petroleum-based conventional materials (Nesic et al., 2020b). Therefore, this paper aims to provide an overview of bio-based packaging materials, the different classifications, properties, prospects, and challenges associated with their application to sustainable food packaging. A schematic representation of the overview followed for the review paper is shown in Fig. 2 below.

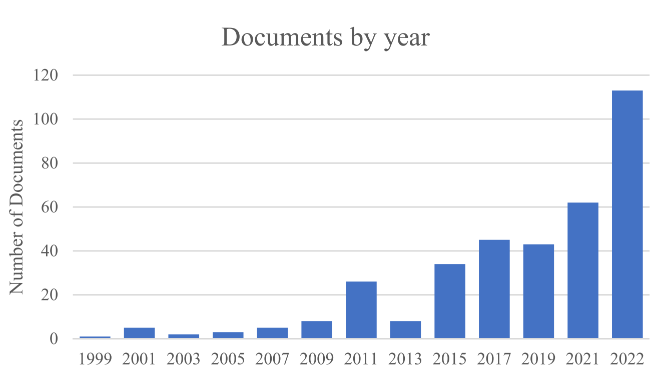

Fig. 1. Progress made in bio-based food packaging in the last two decades.

2. Bio-based sustainable packaging

The ASTM D7075–04 standard definition of bio-based packaging materials, according to Attaran et al. (2017), are materials that contain a carbon-based compound(s), and the carbon is obtained from a modern biological source (non-fossil). These packaging materials derived from renewable sources are environmentally friendly (have a low carbon footprint and are biodegradable) and used for food applications (Ruban, 2009; Siraj et al., 2023; Wu et al., 2023). Though these materials are renewable, they are not always degradable (Attaran et al., 2017; Herbes et al., 2018). Sudesh and Iwata (2008) explained that bio-based materials apply to naturally occurring polymeric materials and to natural substances polymerized by chemical and/or biological means, resulting in high molecular weight substances. According to Aung et al. (2021), most bio-based food packaging materials use biomass residues as raw inputs. They further stated that there is a worldwide demand capacity of about 7.85 million tonnes as of 2019 for these materials, making it a recent focus for recent developments in food packaging systems.

2.1. Classifications of bio-based food packaging systems

Based on historical developments, bio-based packaging materials have been classified into three main generations. The first-generation bio-based packaging materials are used as shopping bags and contain synthetic polymers like low-density polyethylene (LDPE) with about 5 – 15 % start fillers and pro and auto-oxidative additives (Robertson, 2008). The second-generation bio-based materials are made up of about 40 – 75 % gelatinized starch and LDPE with the addition of hydrophilic copolymers like poly (vinyl alcohol) (PVOH), vinyl acetate, and acrylic acid (compatibility agents) (Robertson, 2008). The third-generation materials constitute completely bio-based packaging materials and are further classified into three main categories based on their origin, chemical composition, economic importance, production, and application (Robertson, 2008; Pan et al., 2016). These three-category classifications are polymers directly extracted or removed from biomass, the polymers obtained from classical chemical synthesis of monomers of natural origin, and polymers produced by microorganisms or genetically modified bacteria (Weber et al., 2002; Robertson, 2008; Pan et al., 2016; Nesic et al., 2020). Details of the different categories under the third generation of bio-based packaging materials are shown in Fig. 3. Further discussions of biobased packaging materials are focused on those classified in the third generation. This is because the third generation is more advanced and aligns with sustainability objectives than the first and second generations. For example, the first and second generations have some amounts of synthetic polymers like low-density polyethylene (Ivanković et al., 2017).

3. Third-generation bio-based packaging materials

3.1. Polymers directly removed or extracted from biomass

This class of polymers is mainly extracted from marine and agricultural products. These polymers are polysaccharides, for example, starch and cellulose, and proteins, for example, casein and gluten. They can be used alone or in a mixture with an artificial biodegradable polymer like polycaprolactone (PCL) or polyester-like polylactic acid (PLA). These polymers have excellent gas barrier properties but are hydrophilic in nature, causing processing and performance problems (Robertson, 2008; Ruban, 2009; Pan et al., 2016).

3.1.1. Polysaccharides

Polysaccharides form the most abundant raw materials because they originate from the biomass of plants and marine organisms. They are biocompatible, biodegradable, and nontoxic to living organisms. They can be broadly classified as starch and non-starch, further classified as cellulose and derivatives. The shelf-life of fruits, vegetables, shellfish, or

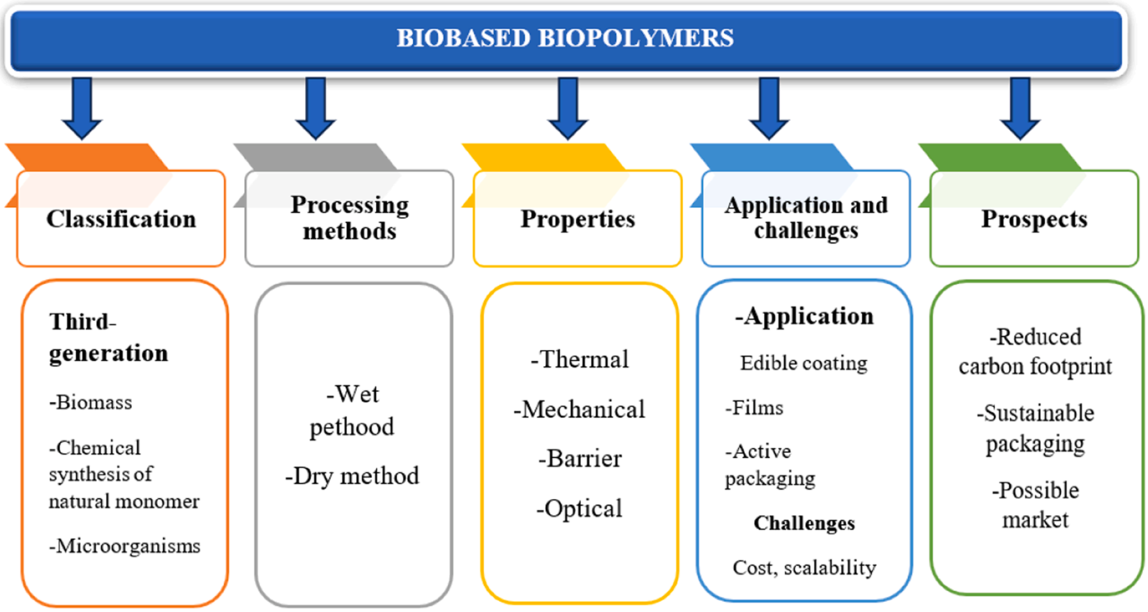

Fig. 2. Schematic representation of the scope of overview presented in this paper.

meat products can be prolonged using polysaccharide-based films. These films can be used to coat the food, and they are colourless and have an oil-free appearance with slight caloric content. Cellulose derivates, chitosan/chitin, starches, and gums are raw materials used in packaging food for preservation and edible coating purposes (Caźon et al., 2017; Nešić et al., 2020a; Anis et al., 2021).

3.1.1.1. Cellulose. This group of polysaccharides constitutes the most plentiful polymer resource in nature. This renewable resource is said to be one of the raw materials for producing biodegradable films because it comes at a low cost and is biocompatible, nontoxic, and chemically stable (Caźon et al., 2017; Torres et al., 2019). It is a linear chain with two (2) anhydroglucose rings [$(C_6H_{10}O_5)_n$] that are covalently linked through oxygen (O_2) in a β1 – 4 glycosidic bond (Caźon et al., 2017; Torres et al., 2019). When cellulose is undergoing polymerization, van der Waal and intermolecular hydrogen between hydroxyl groups and O_2s of head-to-head molecules encourage parallel piling of multiple cellulose chains to form fibrils (Caźon et al., 2017; Torres et al., 2019). The degree of polymerization is around 10,000 – 15,000 units, and it is insoluble in a few solvents (Caźon et al., 2017; Torres et al., 2019).

3.1.1.2. Starch. Due to its availability, price, and good film-forming ability, it is considered one of the most applicable materials for packaging. Khan et al. (2017) stated that starch biopolymers are cheap and abundantly available. Primarily derived from cereal grains, potatoes, or tapioca, it has interlinked glucose molecules that store energy. Starch can be processed through wet and dry means and has two (2) macromolecules: amylose and amylopectin. They have a highly ordered hydrogen-bonded network structure in which the amylose and amylopectin form crystalline and non-crystalline regions in alternating layers. Films can be formed from starch by plasticizing them with small molecular weight compatible constituents, blending, or chemical modification (Ruban, 2009; Zinoviadou et al., 2021; Caźon et al., 2017; Fortunati et al., 2018; Sid et al., 2021). Edible packaging films formed from starch are odorless, tasteless, nontoxic, biologically absorbable, semi-permeable to carbon dioxide (CO_2), and exhibit resistance to O_2, with a brittle nature (Ruban, 2009; Zinoviadou et al., 2021; Caźon et al., 2017; Fortunati et al., 2018; Sid et al., 2021). To overcome the resistance from the intermolecular forces between hydrogen bonds in starch during processing, plasticizers are added to make them deformable, creating materials called thermoplastic starches (TPSs) (Khan et al., 2017).

3.1.1.3. Chitin and chitosan. Chitin is a cellulose-like biopolymer found in the exoskeleton of crustaceans, fungi, insects, and yeast cell walls, acting as a supportive and protective material for biological systems (Kumar, 2000) and is considered an important polysaccharide (Garrison et al., 2016). It is a polymer that contains differing amounts of N-acetylglucosamine (β – 1, 4 – linked 2 – acetamido-D-glucose) (Aranaz, et al., 2009). Traditionally, chitin is isolated from crustacean shells (Kumar, 2000) by demineralization with diluted acid and deproteinization in a hot base solution. Chitosan is a derivative formed when chitin undergoes partial deacetylation to about 50 % in the presence of alkali (concentrated NaOH) (Rinaudo, 2006). A chitosan copolymer consists of β – (1→4) – 2 – acetamido – D – glucose and about 80 % of β – (1→4) – 2 amino – D – glucose units (Hudson & Smith, 1998; Fernandez-Saiz, 2011; Song & Zheng, 2014; Caźon et al., 2017). A simple schematic representation of chitosan extraction and application is displayed in Fig. 4.

Chitosan is considered a very abundant biopolymer (Bangyekan, Aht-Ong & Srikulkit, 2006) used in different fields with an emerging area in food packaging as antibacterial and sensing films (Wang, Qian & Ding, 2018). Honarkar and Barikani (2009) added that these biocompatible natural polymers are nontoxic and biodegradable, with their applications not only in food packaging but also in areas such as medicine, membranes, drug delivery systems, and water treatment. A review of antimicrobial biopolymers indicated that using these polymers will enhance the effectiveness of existing antimicrobial agents and reduce problems associated with conventional antimicrobial agents (Kenawy, Worley & Broughton, 2007). Chitosan, insoluble in water and other common organic solvents, displays good film and coat-forming properties when cast from an organic acidic water solution. Films formed from chitosan have good mechanical properties and selective permeability to CO_2 and O_2, with inherent antimicrobial character against the growth of pathogenic organisms (Hudson & Smith, 1998; Fernandez-Saiz, 2011; Song & Zheng, 2014; Caźon et al., 2017).

Bangyekan et al. (2006) prepared a composite film by coating chitosan on cassava starch containing glycerol. A good adherence was observed between these two due to the compatible water activities. An assessment of the film showed improved mechanical properties, water vapor barrier capability, and surface properties, indicating that it can be

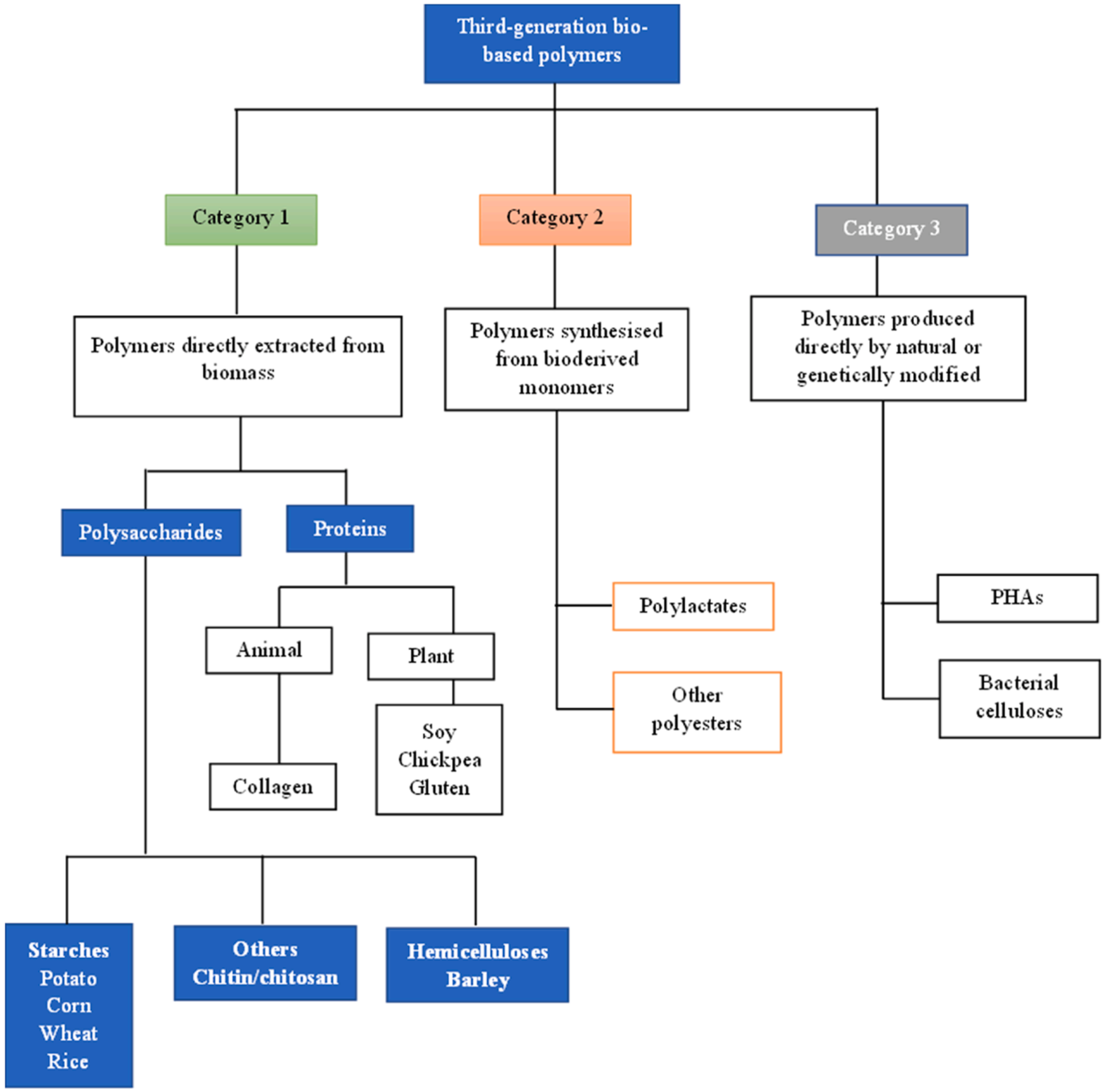

Fig. 3. Classification of third-generation biobased packaging materials based on their origin and method of production. PHA – polyhydroxyalkanoates. Reproduced with permission from Zinaviadou et al., (2016).

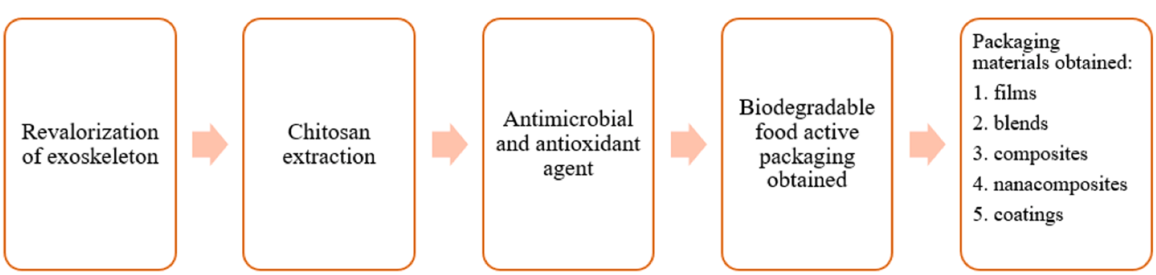

Fig. 4. Schematic presentation of chitosan extraction. Reproduced with permission from Fortunati et al., (2018).

a good preferred packaging film.

Mixtures of chitin and chitosan were prepared and treated on boards that contained packed starch-based food. Results obtained showed a reduction in bacteria and moulds on the treated boards, indicating that these biopolymer mixtures could be effective in improving the shelf-life of perishable products (Panariello et al., 2019).

In an investigative study by Yingyuad et al. (2006) to check the effect of chitosan coating and vacuum packing, grilled pork was dipped in chitosan solution, dried, and vacuum packed for quality and microbial analyses. Results showed smaller drops in pH, low lipid oxidation, slow microbial evolution with no significant difference, and maintained sensory properties for up to 28 days compared to the control samples. In another report, Fan et al. (2009) evaluated the effectiveness of coating carp (freshwater fish) with 2 % chitosan solution by dipping method against coated with 1 % glacial acetic acid as control and then stored these samples in plastic trays at -3 °C for 30 days. Samples coated with chitosan showed better lipid inhibition versus indicator for deterioration, which was 18.8 g mg/100 g and 30.2 mg/100 g, respectively, from an initial 7.3 mg/100 g.

3.1.2. Protein-based biopolymers

Song and Zheng (2014) defined proteins as naturally occurring linear, random heteropolymers built from up to twenty (20) basic amino acid units. Proteins can be distinguished based on the number of amino acids (polar and non-polar) and their sequencing that plays a role in bond formation. Four (4) broad categories can be used to differentiate the structures of proteins, and they are primary, secondary, tertiary, and quaternary (Gupta & Nayak, 2015; Hammam, 2019). Bourtoom (2008) explained that films obtained from protein are formed from solutions or dispersions of the protein as the solvent/carrier evaporates. Proteins undergo denaturation by applying heat, acid, base, and/or solvent to form extended structures needed for film formation. After the extension, protein chains associate through hydrogen, ionic, hydrophobic, and covalent bonding. According to Ruban (2009), protein-based films adhere well to hydrophilic surfaces, providing barriers for O_2 and CO_2, but cannot resist water (H_2O) diffusion. Sources of proteins for edible films include gelatin, whey, casein, wheat gluten, soy, etc. (Bourtoom, 2008).

3.1.2.1. Soybean proteins. Soybeans contain about 38 – 44 % of protein, according to Bourtoom (2008). Commercially available soy flour has about 50 – 59 % protein, and soy concentrate contains 65 – 72 % protein Song and Zheng (2014). Bourtoom (2008) additionally stated that most soybean proteins are insoluble in water but soluble in dilute neutral salt solutions. Fine fractionation of proteins in soybeans results in albumin, glutelin, and major globulin fractions. Globulin can further be classified into 2S, 7S, 11S, and 15S according to relative sedimentation rates, the main concepts being 7S (conglycinin) and 11S (glycinin), which have quaternary structures (Bourtoom, 2008; Song & Zheng, 2014). The polymerization of soy protein can be attributed to disulfide bonds and, to a lesser degree, hydrophobic interactions, and hydrogen bridges. Because of their hydrophilicity, films formed from soy have poor moisture resistance and water vapor barrier ability. Plasticizers can, however, impart film flexibility (Buffo & Han, 2005). Meanwhile, films from soy protein isolates have good O_2 barrier properties with moderate mechanical properties (Wang & Wang, 2017). Research by Galus (2018) showed the effectiveness of rapeseed oil in improving the water vapor barrier and sorption properties of films made from soy.

3.1.2.2. Whey and casein. The two common proteins found in milk for forming edible films are casein and whey. Whey is a co-product of cheese making and casein manufacturing in the dairy industry. They have high nutritional values, excellent mechanical, and barrier properties, are soluble in water, and act as emulsifiers (Ruban, 2009; Gupta & Nayak, 2015). Saez-Orviz *et al.* (2017) stated that these proteins are exceptional candidates for biodegradable films.

Liquid bovine milk has approximately 3.6 % protein composed of 20 % whey and 80 % casein. The whey is separated from the casein by acidification to pH 4.5–4.8 or by the action of rennet, a casein-coagulating enzyme preparation (USDA, 2015). There are five major fractions of whey protein, and they are 50 % β-lactoglobulin, 20 % α-lactalbumin, 15 % glymacropeptide, 10 % immunoglobulin, and 8 % bovine serum albumin Kandasamy et al. (2021). It has different combinations of cross-sulfur bonds, which are sensitive to heat and less sensitive to calcium (Hammam, 2019). Procedures used to produce whey protein are based on the studied behavior of the whey components under certain defined conditions (Matthews, 1984). The cohesion forces between polymer molecules of whey protein and the adhesive forces between the film and its substrate enable film formation. Denaturing and cross-linking additives promote molecular order and increase the cohesion and rigidity of films formed from whey protein Banerjee and Chen (1995). Kandasamy et al. (2021) added that whey protein edible films are primarily dry, highly interacting polymer networks with a three-dimensional gel-type structure. Films prepared from whey protein concentrates exhibited good water vapor barrier and mechanical properties (Banerjee & Chen, 1995).

Casein, on the other hand, contains four main subunits: kappa-casein, beta-casein, alpha S1-casein, and alpha S2-casein, which constitute about 13 %, 36 %, 38 % and 10 % of casein compositions, respectively (Chen et al., 2019). Casein randomly coils to form electrostatic, hydrophobic, and hydrogen bridges, giving it an easy film-forming ability (Saez-Orviz et al., 2017). Casein-based films are used in packaging to form edible films for fruits and vegetables (Gupta & Nayak, 2015).

3.1.2.3. Collagen and gelatine. Collagen and gelatine biopolymers are proteins that can be extracted from animals like their tendons, scales, bones, eggshells, etc. (Asgher et al., 2020; Sehgal et al., 2023). Collagen obtained from connective tissues of animals is the most common type (Tapia-Blácido et al., 2023), and it can be extracted mainly by acid or enzyme hydrolysis and is used in many industries, including food (Tapia-Blácido et al., 2023). Subhasri et al. (2023) indicated that collagen coatings are used to prepare edible sausage casings. Gelatine can be obtained when collagen is thermally hydrolyzed, breaking the hydrogen bridges between the polypeptide molecular chains (Tapia-Blácido et al., 2023). Asgher et al. (2020) further indicated that films obtained from gelatine usually through the wet processing method possess poor mechanical and barrier properties. Furthermore, collagen films are said to have better optical properties because they exhibit brightness above 80 % in the visible spectrum (Atta et al., 2022).

3.2. Polymers obtained from classical chemical synthesis of monomers of natural origin

A wide range of 'bio-polyesters' can be derived from classical chemical synthesis for polymer production. Among these 'bio-polyesters' is the production of poly(lactic) acid (PLA), a polymer that currently has the highest potential to produce renewable packaging materials on a commercial basis (Weber et al., 2002; Robertson, 2018). PLA is one of the most applied biopolymers for food packaging. Many packaging companies are veering into the production of PLA by setting up plants for that purpose (Weber et al., 2002; Robertson, 2008).

3.2.1. Poly(lactic) acid (PLA)

Poly(lactic) acid (PLA) is an aliphatic (non-cyclic and non-aromatic) thermoplastic formed by the polymerization of lactic acid/ lactide, acquired when sugars from different agricultural biomass sources undergo microbial fermentation (Sid et al., 2021; Nesic et al., 2020). PLA is considered a good biopolymer because it is biodegradable, exhibits good mechanical properties, and has a low cost (Muthuraj et al., 2018). Nesic et al. (2020) mentioned that PLA could be (Fig. 5a) obtained through fermentation or chemical synthesis. PLA consists of lactic acid monomers, a chiral molecule with two stereoisomers, L- and D- lactic acids, produced via biological or chemical synthesis. The fermentation of carbohydrates can obtain lactic acid by lactic bacteria or fungi. For the fermentation process to occur, a bacterial strain is required, a carbon source (carbohydrate), a nitrogen source (for example, yeast, extract, peptides), and mineral elements to support the growth of the bacteria, which will yield lactic acid, existing almost exclusively as L-lactic acid (Pan *et al.*, 2016). Directly poly-condensing the lactic acid monomers obtained will yield PLA (Jabeen, Majid & Nayik, 2015). Pan et al. (2016) further noted that poly (L-lactic) acid obtained from the poly-condensation process is low weight. PLA can also be obtained via chemical synthesis by ring-opening polymerization (ROP) reactions, which yields high molecular weight polymer (Pan et al., 2016; Nesic et al., 2020). Nesic et al. (2020) further stated that the properties of PLA

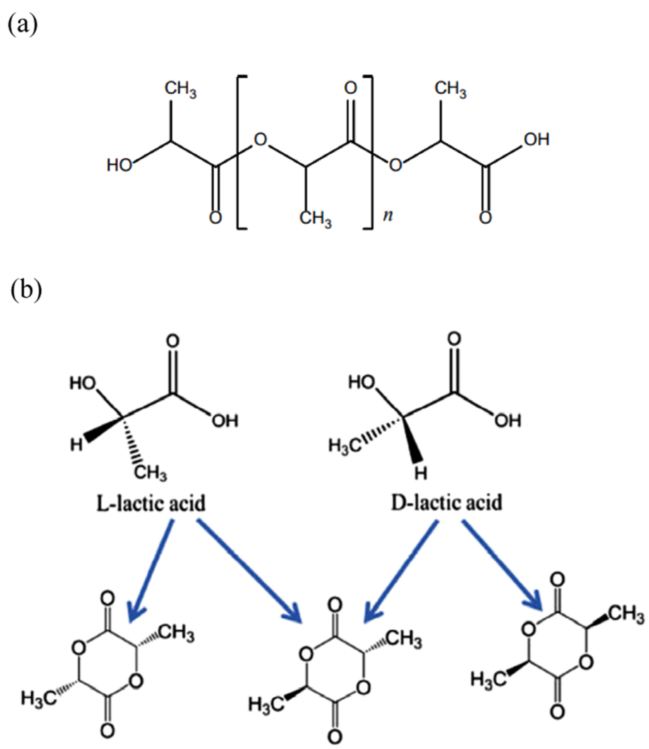

Fig. 5. (a) Chemical structure of poly (lactic) acid (PLA). Reproduced with permission from Pan et al., (2016). (b) Steoreoforms of lactides. Reproduced with permission from (Nesic et al., 2020).

may vary depending on the relationship and distribution of the two stereoisomers, as shown in Fig. 5b.

Since corn or other crops needed to produce PLA absorb a larger amount of CO_2, it can be associated with the emission of fewer greenhouse gasses (Zinoviadou et al., 2016). Jin and Zhang (2008) assessed the antimicrobial activity of films produced from PLA and niacin against some microorganisms (*Escherichia coli* O157:H7, *Salmonella Enteritidis*, and *Listeria monocytogenes*) in orange juice and liquid egg white. The results showed a reduction of 4.5-log Colony Forming Unit per milliliter (CFU/mL) in cell counts of L. *monocytogenes* at 24- h, a reduction of *E. coli* O157:H7 from 7.5 to 3.5log at 72 h in orange juice, and a 2-log reduction of *S. Enteritidis* in liquid egg white that was stored at 24 °C. The study thus proved that there is a great possibility of effectively using a combination of biopolymer and natural bacteriocin in antimicrobial food packaging.

3.3. Polymers produced by microorganisms or genetically modified bacteria

This category of bio-based polymers consists of microbial polyesters referred to as poly(hydroxyalkanoate)s (PHAs) and bacterial cellulose. PHA, poly-β-hydroxybutyrate (PHB), and their derivatives are the most widely produced microbial bioplastics. Certain bacteria process starch or glucose to yield the commonly used polyesters like PHAs and PHBs, which are extracted using solvents (Leungo *et al.*, 2003; Jabeen et al., 2015; Nesic et al., 2020).

3.3.1. Poly(hydroxyalkanoate)

This is an innovative, purely bio-based polyester from the bacterial fermentation technique. Pure PHA can also be extracted from palm oil biomass residues, although that is not yet on a commercial scale. It is a linear aliphatic polyester that shows elastomeric properties with physical cross-linking of crystals and can be altered into thermoplastic polymers (Steinbüchel, 2003; Braunegg et al., 2004). PHA is made up of a wide range of different hydroxy alkanoates (HAs), which occur as storage compounds for carbon, energy, and insoluble cytoplasmic inclusions in many bacteria, formed wholly in prokaryotes (Steinbüchel, 2003; Braunegg et al., 2004; Sid et al., 2021). PHA makes up about 90 % of the cellular mass of microbial cells (Sid *et al.*, 2021). The microbial storage polymers have properties that resemble the properties of main commodity plastics. The main property differentiating them from these conventional plastics is their complete biodegradability in the natural environment (Sudesh & Iwata, 2008).

The different forms of PHA depend on the carbon source and the microorganism(s) involved (Akinmulewo & Nwinyi, 2019). A molecule of PHA contains (*R*)-hydroxy fatty acid monomer units (Tan et al., 2014), which can vary from 600 to 35,000 (Nesic et al., 2020). Also, each monomer unit contains a side chain R group, usually a saturated alkyl group, but can also take the form of unsaturated alkyl groups, branch alkyl groups, and substituted alkyl groups. However, these forms are less common (Tan et al., 2014). Furthermore, PHAs are generally low crystalline thermoplastic elastomers with a high melting point. Their exhibited characteristics depend on the type of carbon source and microorganisms that caused the fermentation and composition of the monomer unit (Jabeen et al., 2015).

Many of the PHAs that are commercially important and have been studied extensively are the ones that have monomers ranging from 4 to 6 carbon atoms. Some of the derivatives of PHA include poly(3-hydroxybutyrate) [P(3HB)], poly(3-hydroxybutyrate-co-3-hydroxyvalerate) [P(3HB-co-3HV)], poly(3-hydroxybutyrate-co-4-hydroxybutrate) [P(3HB-co-4HB)] and poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) [P(3HB-co-3HHx)] (Sudesh & Itawa, 2008). Worldwide, production of PHA represented 1.20 % of production volumes of bio-sourced plastics in 2019 and increased to 1.70 % by the end of 2020 (Sid et al., 2021).

3.3.2. Polyhydroxybutyrate

The polyhydroxybutyrate (PHB) group of microbial bioplastics is considered the most used for industrial applications (Aramvash et al., 2015). Poly-D-(-)-3-hydroxybutyrate is an optically active aliphatic polyester that is produced by different types of microorganisms and accumulated by them as storage materials (Poirier et al., 1991; Maiti et al., 2007), and the most understood structure of PHB (Hassan, Bakhiet, Ali & Hussein, 2016).

This group of PHBs is generated with microorganism fermentation techniques with bacteria like *Bacillus megaterivmal, Cupriavidus necator*, etc. The microbial extraction of PHB follows the condensation of two (2) acetyl-CoA molecules to yield acetoacetyl-CoA, which is further condensed to produce hydroxybutyryl-CoA. This final reduced composite is the monomer unit for polymerization and PHB generation (Sid et al., 2021). Under controlled fermentation conditions of excess carbon and nitrogen limitation, some bacteria will yield about 70 % of the weight of PHB. With a solvent or enzyme extraction process, granules can be harvested (Doyle et al., 1991). Depending on the type of organism, growth conditions, and extraction method used, the molecular weight of PHB may differ, and it can vary from about 50,000 to well over a million (Dawes, 1988).

The ability of the PHB to degrade poses a high potential for exploitation. In addition to PHB being biocompatible, it exhibits high melting temperature and crystallinity. However, it has low mechanical and thermal properties that appear to narrow its applicability. Nonetheless, when blended with other materials such as poly (ethylene oxide), poly (vinyl butyral), etc., it produces a more enhanced composite that displays greater desirable characteristics (Maiti et al., 2007; Pan et al., 2016; Sid et al., 2021). An investigative study was conducted by Bucci, Tavares, and Sell (2005) to assess the effectiveness of PHB as a storage material for some foods (margarine, mayonnaise, and cream cheese), and it was shown that the material could indeed be potentially used for this purpose after dimensional and mechanical tests were conducted on it.

4. Methods used to process bio-based food packaging materials

Processing is an important step in engineering bio-based packaging materials or composites obtained from combining bio-based materials with other materials. Wet and dry processing techniques can be applied to produce packaging materials. In wet processing, polymers are solubilized or dispersed in solvents, and the homogenized mixture is evaporated to form films by casting. Melting is employed in the dry processing through blowing, moulding, extrusion, or injection (Ballesteros et al., 2018; Valencia & do Amaral Sobral, 2018).

4.1. Wet processing

The major wet process used to form films is the casting technique. The material's solubility is critical for producing biopolymers through casting (Suhag et al., 2020). During casting, the biopolymers (starch, plasticizer, and other additives) are solubilized in an appropriate solvent for the film-forming solution. The solution is cast on a mold or onto a well-leveled platform and allowed to dry by evaporating the solvent. The continuous dried film obtained is peeled off, as shown in Fig. 6 (Zhang et al., 2014; Valencia & do Amaral Sobral, 2018; Suhag et al., 2020). Casting is the most applied film-forming technique, especially in laboratories and pilot scales. This technique is easy to carry out and comes at a low cost (Suhag et al., 2020).

4.2. Dry processing technique

This technique is termed dry because there is no need for a solvent. In this technique, heat is used to melt the polymer mixtures, increasing the temperature of the glass transition (T_g) and/or melting (T_m) temperatures. The increase in temperature causes the melted polymers to flow and then be forced to form specified shapes (Ballesteros et al., 2018; Valencia & do Amaral Sobral, 2018). The process of forcing the biopolymer into a specified shape under high-temperature conditions is termed thermoforming (Valencia & do Amaral Sobral, 2018). Thermoforming, according to Ballesteros et al. (2018), can happen through blowing or extrusion to form bags or sheets or injected into a mold design to form trays, preforms, or bottles. Suhag et al. (2020) listed extrusion as one of the major processing techniques applied on an industrial scale for polymers, with single and twin-screw extruders used to form edible films. Fig. 7 gives a schematic view of film formation by extrusion.

5. Properties of bio-based packaging materials

For proper utilization of bio-based materials in the food packaging industry, they need to satisfy some physical and mechanical properties that enable them to maintain their optimum function without compromising the safety and durability of the food during storage until consumption or disposal. Properties important to food packaging are mechanical, thermal, gas, and moisture barrier properties, chemical reactivity, and optical properties (Ötles & Ötles, 2004; Ncube et al., 2020). These properties are crucial in ensuring the practical application of these biopolymers as food packages.

5.1. Thermal properties

The thermal properties of bio-based packaging materials are critical for their processing and usage in the food industry (Briassoulis & Giannoulis, 2018). These properties are important because they determine how biobased packaging materials react to temperature changes. Good thermal properties are needed to prevent the materials from deformation or degradation when products are stored under higher temperature conditions (Ncube et al., 2020). For crystalline polymers, melting is important and linked to the transition of the material from solid to liquid at a specified pressure (Ballesteros et al., 2018). Nesic *et al.* (2020) noted that the Tm and degree of crystallinity depend on the molar weight, thermal history of the material, and the purity of the polymer. Methods used to determine these thermal properties are differential scanning calorimetry (DSC) and thermo-gravimetric analysis (TGA), which analyze the degradation of the materials and resulting weight losses at very high-temperature conditions (Ballesteros et al., 2018; Nesic et al., 2020). Ahmed and Varshney (2011) measured a melting point of around 180 °C for crystalline polymers of pure lactide. Thermal properties are important for packaging materials that must be thermo-sealed and are necessary for the food products' safety and quality (Ballesteros et al., 2018).

5.2. Mechanical properties

Mechanical properties are necessary for packaging materials as they ensure that products are protected from external forces and stress and are strong enough to contain them (Ncube et al., 2020). Additionally, mechanical properties are needed to prevent tampering with the packaging materials, ensuring the food remains safe, and its quality is maintained during storage and transportation to meet consumer satisfaction (Briassoulis & Giannoulis, 2018). Some of the mechanical properties required of bio-based packaging materials include tensile properties, penetration resistance, seal strength, tear propagation, elongation at break, elastic modulus, yield strength, and Young's modulus (Roberton, 2008; Briassoulis & Giannouli, 2018). Martins et al. (2021) defined maximum tensile strength as the strength offered by the material at the point of failure and elongation as the percentage ratio between the elongation of the material in the test and its initial length. The tensile strength of these biobased polymers is important because it measures the material's resistance when pulled apart or stretched. Depending on their intended usage, bioplastics display different strength properties that may be appropriate, adequate, or inadequate (Ncube et al., 2020). Ötles and Ötles (2004) indicated that the modulus of biobased materials ranges from 2000 – 3000 MPa. The molecular weight of the polymer, chain construction, and extent of crystallinity can affect the mechanical properties of some biobased materials (Robertson, 2008). Nilsen-Nygaard et al. (2021) indicated that biobased materials generally exhibit poor mechanical properties, limiting their widespread applicability. However, PLA has good mechanical properties compared to other biopolymers and an elastic modulus ranging between 3000 – 4000 MPa with a tensile strength of 50 – 70 MPa (Robertson, 2008). Ncube et al. (2020) demonstrated that blending biobased materials with other materials can significantly improve the mechanical properties of the composites formed. In developing these biopolymers, the

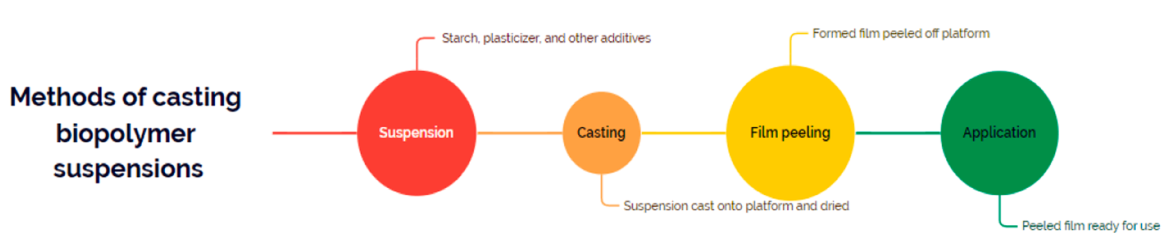

Fig. 6. Casting method for biopolymer suspensions, showing the casting, drying, and film peeling stages.

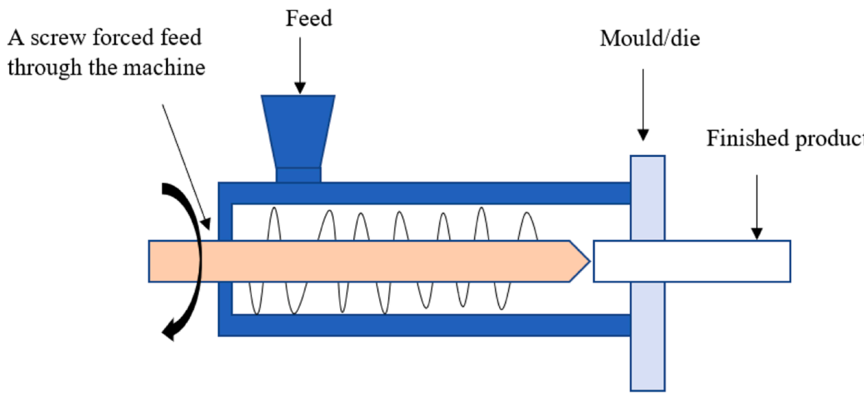

Fig. 7. Schematic view of the film formation using the extrusion technology. Reproduced with permission from (Suhag et al., 2020).

mechanical properties exhibited are closely connected to their chemical composition, molecular structure and processing conditions, making them important during their production.

5.3. Barrier properties

Barrier properties like permeability to O_2 and CO_2 are one of the main features of food packaging materials. Barrier properties are linked to the inherent ability of packaging materials to allow the exchange of low molecular weight substances through a mass transport process called permeation. Food packages should be able to offer a good barrier to gasses (O_2, nitrogen, and CO_2) and some other volatiles between the external environment and the food. The permeability of these molecular substances depends on factors such as the nature of the polymer material, its thickness, size, and shape of the penetrant, pressure, and temperature (Robertson, 2010). The ability of a food package to exhibit good barrier property is critical in ensuring that the quality and safety of the food is maintained through transport, storage, and disposal. For example, O_2 is a factor that contributes to the oxidation and spoilage of food (Kumar et al., 2011; Ballesteros et al., 2018; Ncube et al., 2020). Therefore, packages for storing oil-bearing foods are expected to be oxygen-proof to prevent rancidity.

Packaged food's product quality and shelf life can change when water vapor and O_2 transfer from the internal or external environment through the packaging material. This makes water vapor and O_2 the main permeants studied in barrier properties of bio-based packaging materials (Martins et al., 2021). Ballesteros et al. (2018) included CO_2 to transport the properties of packaging materials. Water vapor permeability (WVP) is the amount of water that permeates per unit area and the time through a packaging material. It is important for foods whose physicochemical and microbiological spoilage is closely linked to water activity. For example, low WVP is needed for baked foods (Ballesteros et al., 2018; Martins et al., 2021).

Oxidation reactions observed in packaged foods can be related to O_2 content. The O_2 barrier property of food packages, thus, plays a vital role in preserving the food. The O_2 permeability coefficient (OPC) indicates the amount of O_2 that permeates per unit area and time in packaging material. Typically, the shelf life of food can be extended when the O_2 pressure within a packaging material is reduced to a point where oxidation is delayed due to a low O_2 permeability coefficient (Ncube et al., 2020; Martins et al., 2021).

The CO_2 barrier of packaging material can similarly be measured by its permeability coefficient, which indicates the amount of CO_2 that permeates the material per unit of area and time. When modified atmosphere packaging is considered, CO_2 becomes an important factor in ensuring the extended shelf life of the food to be packed (Martins et al., 2021). The barrier properties of O_2 and CO_2 diffusion are vital in controlling the headspace conditions of agricultural products affected by the respiration and transpiration of this produce (Braissoulis & Giannolis, 2018). Diffusion and sorption are two main factors that influence the transport of molecules (gasses, volatiles, etc.) through a film. Diffusion measures the rate at which molecules infuse through the packaging material, and sorption is affected by the partition coefficient between the surface and the outer fluid and by the solubility of the molecules in the matrix (Ballesteros et al., 2018).

Bio-based polymers are generally hydrophilic; increasing humidity increases gas permeability. To manage or control the hydrophilic nature of bio-based materials, they can be coated externally with water-resistant materials, cross-linked with inorganic fillers, or blended with other water-resistant materials (Kumar et al., 2011; Ncube et al., 2020). Bio-based packaging materials generally exhibit good barriers to O_2 and CO_2, according to Ballesteros et al. (2018). Holm (2010) asserted that many bio-based packaging materials provide low water vapor barriers, and that moisture can affect their water vapor barrier properties.

5.4. Optical properties

The color of packaging materials produced from biobased and other food packaging materials is important because it indirectly translates into consumer acceptance of the packaged product. Transparency, opacity, gloss, etc., are some materials' optical properties. If a packaging material exhibits high opacity, less light will pass through it. For some fresh foods, consumers want to see through the packaging before making an informed decision, though the light is a catalyst for deterioration reaction in foods (Ballesteros et al., 2018; Ncube et al., 2020). According to Atta *et al.* (2022), optical properties are important in assessing the visual features of a primary packaging material. Characteristics such as the optical properties of packaging materials are usually made according to requirements, typically by adjusting processing conditions or adding compounds to the composites (Al-Tayyar *et al.*, 2020).

6. Applications and challenges associated with bio-based packaging

6.1. Applications and challenges

Bio-based materials can potentially be used for packaging fast foods like salad fresh or minimally processed fruits and vegetables, among other foods (Table 1). The high O_2 and CO_2 permeability of most of these materials can translate into using them as packaging materials for food that respires, for example, fruits and vegetables (Robertson, 2008). Tan et al. (2021) examined bio-based polymers as direct edible coatings for some food products. These bio-based polymers, including some polysaccharides, could be applied to the food by immersing the food into a bio-based solution, spraying it on the food, or brushing the solution on the food. The purpose of the edible coating is to provide a coating around the food and act as a barrier for mass transfer without adversely contaminating the food (Sorrentino et al., 2007). Grujić et al. (2017) also

Table 1
Summary of some biobased polymers used for food packaging.

Biopolymer used	Additive added	Synthesis method	Food packaged	Main characteristics	Limitations	References
Polylactic acid	Nano-zinc oxide (ZnONPs), pomegranate peel extract	Solvent-casting method	Cherry tomatoes	Increased UV barrier, WVP, elongation at break, good antibacterial and antioxidant activity	None stated	Dai et al. (2022)
Polylactic acid	Zein, polyethylene glycol (plasticizer)	Blended method	None used	Improved mechanical and water barrier properties	No specific food was used further to assess the blend's efficacy for food packaging.	Ge et al. (2022)
Polylactic acid	Cerium lactate (Ce-LA)	Precipitation method	None used	Increased crystallinity and enhanced antibacterial properties	No specific food was used further to assess the blend's efficacy for food packaging.	Wu et al. (2022)
Yam starch	Bentonite	Solvent-casting method	None used	Increased tensile strength, high degradability	No specific food was used further to assess the blend's efficacy for food packaging. Antimicrobial and antibacterial properties were not studied.	Behera et al. (2022)
Starch-based bioplastics	2,2,6,6-tetramethylpiperidine 1-oxy-oxidized cellulose nanofibers and zinc oxide nanoparticles	Not clearly defined (possibly gel-formation)	None used	Improved tensile strength (up to 24.54 MPa), water resistance, thermal resistance, biodegradability		Xie et al. (2023)
Yam starch	Glycerol (plasticizer), citric acid	Gel formation	Fish	High tensile strength (24.60 MPa), smart pH auto color detection		Poudel et al. (2023)
Pectin	Spent coffee grounds extracts, PHA (coating)	Dipping method	Mashed carrot	Improved water vapor permeability	Stiffness and opacity of film affected by PHA	Mirpoor et al. (2023)
Chitosan	Rice protein hydrolysate, glycerol (plasticizer)	Casting method (was not explicitly mentioned)	None used	Improved antimicrobial ability, improved tensile strength, enhanced gas barrier properties, enhanced UV–Vis light barrier	Low mechanical stability of film, specific synthesis method not mentioned.	Zhao et al. (2023)
Chitosan/ gelatine	Vanillin	One-pot method	None used by proposed for pre-mature fruits and vegetables	Improved mechanical strength, improved water resistance, improved antioxidant activity, and UV-shielding efficacy		Yu et al. (2023)
Alginate	Nitrogen carbon dots (NCDs), layered clay	Casting method	Banana	Improved mechanical property and reduced surface wettability		Mao et al. (2023)
Protein and pectin (yellow passion fruit peel)	None mentioned	Casting method	None used	Improved strength and elasticity, improved thermal stability, low water permeability		Florentino et al. (2022)
Alginate	Citrus lemon extract	In-situ method	None used	Good antibiofilm effect	Mechanical strength and thermal stability were not assessed	Velgosová et al. (2021)

highlighted that a genetically modified organism (GMO)-free starch-based plastic was used to produce food service items like plates and cutlery. Besides, cellophane, a natural biopolymer, is a packaging film for wrapping bakery and confectionery products. Matching the durability of the biobased primary packaging with product shelf life has been one of the biggest challenges in the food packaging industry. Furthermore, most biobased materials have limited application in food packaging because they demonstrate poor properties (Ncube et al., 2020). Robertson (2008); Grujić et al. (2017), and Muthuraj et al. (2018) highlighted the fact that performance, processing, and cost are some of the factors that limit the application of most bio-based materials in the food packaging industry. Analyses of the physical and mechanical properties of some bio-based materials (PLA, starch, and PHB) indicated that WVP, a crucial parameter for starch, needs to be improved before it can be used for food packaging (Petersen, Nielsen, & Olsen, 2001).

Blending bio-based materials with other materials produces composites that drastically improve the overall performance relative to the non-blended materials (Table 1). Nanoparticles were fused into biopolymers to yield good characteristics such as heat and cold-stable composite impermeable to gasses with strong, firm, and antimicrobial properties (Grujić et al., 2017). A study by Braissoulis and Giannoulis (2018) showed high water vapor permeability for the bio-based composite material compared to the pristine material it was tested against. Furthermore, Aliotta *et al.* (2019) emphasized the enhanced mechanical and physical properties of composite material obtained from PLA and cellulose during their study. Imam et al. (2008) also specified that though agriculturally derived polymers, i.e., cellulose, starch, and proteins, displayed poor physical-mechanical properties and performed poorly under extreme environmental conditions, blending them with polymers like PLA, PHAs, PHA, and other additives showed promising results for food packaging. However, blending bio-based polymers with other materials could sometimes lead to non-degradability, as Chen et al. (2021) noted.

It must be noted that though bio-based materials often exhibit poor performance under extreme environmental conditions, they are susceptible to biodegradation compared to conventional petroleum-based packages. Moreover, most bio-based polymers, including starch, cellulose, and proteins, are renewable and abundant agriculture-derived materials (Imam et al., 2008). Owing to their biodegradability, bio-based materials are appropriate for producing compost, which carries nutrients and organic materials to the soil (Grujić et al., 2017). Besides, they are adaptable to many plastic processing methods, requiring little or no adjustments (Imam et al., 2008). However, despite their bio-degradable nature, one major challenge likely to be encountered is accepting society to embrace the concept of disposal for proper decomposition (Kale, et al., 2007). Many studies have been carried out recently to develop bio-based materials for food packaging, and a summary of some of these studies has been presented in Table 1 for more emphasis.

6.2. Prospects

Bio-based materials are expected to stay as relevant sources of food packaging materials, and research on possible methods to improve their functionality and subsequent future applications will continue (Kumar et al., 2011). Using plant fibres as reinforcement will lead to the production of composites that have high performance and are renewable and sustainable. These composites are envisioned to bridge the property-performance gap between renewable and petroleum-based polymers (Ncube et al., 2020).

There is increased research on blends from polymers and nanoclays (nanocomposites). These nanocomposites are expected to result in better barrier and mechanical properties, hence the possibility of producing these composite materials to be commercialized as substitutes for conventional packaging materials (Sorrentino et al., 2007; Robertson, 2008). Ahmed and Varshney (2011) mentioned the development of innovative materials from nanocomposite materials, which include such techniques as nanocomposite formation.

Furthermore, modifying microbial biomass and its derivatives to obtain materials with more desired characteristics and enhanced functional properties for food packaging is an emerging area being explored for future potential (Cottet et al., 2020).

Conclusion

The need for more sustainable and environmentally friendly food packages has risen, mainly due to concerns from all stakeholders regarding the use of conventional petroleum-based food packages. In fact, the emergence of bio-based polymers has been considered a possible alternative to conventional petroleum-based plastics, and their application in food packaging systems is expected to keep growing with increasing consumer expectations. The bio-based materials can be obtained from biomass, agricultural raw materials, and microorganisms. These materials broadly include polysaccharides, proteins, and polyhydroxyalkanoates (PHAs). Some bio-based materials are used as edible coatings and food service materials (spoons and plates).

Though regarded as renewable compared to conventional materials, bio-based materials have limited applications due to their poor performances, difficulty in processing, and high permeability. In addition, the high cost involved in scaling up the production of these materials is another limitation that remains a crucial hurdle to be overcome in order to ensure ease in their applications. A breakthrough in research has come in the identification of blending these materials with other materials to improve the functionality of the resulting composite materials, thereby increasing their applicability for food packaging. Therefore, bio-based materials remain a sustainable and environmentally friendly option for food packaging. There is, however, a need for continued research and collaboration between all stakeholders for a brighter future for the industry. Several factors will have to be considered for their actual application in the food industry, including their degradability, even though they are considered as environmentally friendly.

Ethical statement

The research presented does not involve any animal or human study.

CRediT authorship contribution statement

Leticia Donkor: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Gladys Kontoh:** Data curation, Writing – review & editing. **Abu Yaya:** Funding acquisition, Validation, Writing – review & editing. **John Kwame Bediako:** Funding acquisition, Supervision, Software, Writing – review & editing. **Vitus Apalangya:** Funding acquisition, Conceptualization, Supervision, Investigation, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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