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Bio-sourced polymers as alternatives to conventional food packaging materials: A review

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ABSTRACT

Background: The role of plastic packaging in protecting food is quite appreciable, but the problems like non-biodegradable nature, recycling issues, and leaching of harmful chemicals to food and soil create serious concerns for human health and the environment. The global packaging protocols and awareness about plastic packaging also necessitate to develop new packaging material focusing on the environment, food quality and safety. Thus, urgent attention is required for alternatives of non-biodegradable food packaging materials from bio-sourced polymers.

Scope and approach: This paper highlights the different plastic packaging substitutes, opportunities, and challenges associated with biodegradable environment-friendly packaging. The paper also summarized different bio-sourced polymers with the application, biodegradability, and prospects for commercial applications in food packaging.

Key findings and conclusions: Bio-sourced packaging materials are an emerging alternative to conventional polymers. Natural feedstocks rooted biopolymers are economically competing with conventional ones due to their wide availability, easy processing, biodegradable, compostable nature, good mechanical and barrier properties. Bio-based polyesters produce diverse alternatives from stiff to soft material with properties ranging from partially to fully biodegradable. However, bio-based primitive drop-in plastics are yet the market leader because of their excellent physical properties, cost-effectiveness and durability.

1. Introduction

Food packaging performs different operations from packaging to consumption, i.e., products packing, maintaining, and improving food quality during transportation, distribution, and storage (Han et al., 2018). The purpose of packaging is also related to food wastages. Out of 1.3 billion tons of annual food wastage worldwide, post-harvest and processing losses contribute significantly, especially in low-income countries, about 40% of its total produce (Coll & Kleineidam, 2020; FAO, 2019). India is a leading food producer with approx. 40% wastages of the total produce (Kumar et al., 2020; Mor et al., 2018). However, about 20–25% of the residential food waste worldwide is due to conventional packaging design (Williams et al., 2012). Conventional materials like petrochemical plastic polymers, paper, metal, and glass are used in food packaging. Among petroleum-based plastics, polyethylene terephthalate, polyvinylchloride, polyamide, polystyrene, polypropylene, polyethylene, etc., are used in food packaging due to rigidity, flexibility, excellent barrier properties, low cost, and ease in production. Given such features, the legacy of World War II, plastic has achieved the production level of about 8 billion tons till now, 322 million tons only in 2015, and is supposed to be double by 2035 (Hahladakis et al., 2020, pp. 481–512).

Despite such advantages, plastic packaging material has a huge impact on human health and the environment. The non-biodegradable nature of the plastic materials and leaching of chemicals to food is the main concern with plastic packaging. Nowadays, consumers, regulatory bodies, and the food industry are very concerned about food quality and sustainable packaging, the risk of plastic packaging on human health, and the environment. Hence, the industries search for a suitable environment-friendly replacement of synthetic polymers, probably from the bio-sourced first and second-generation feedstocks (Licciardello & Piergiovanni, 2020, pp. 191–222). This paper reviews the problems of plastic packaging for the environment and consumer health and exploring suitable food packaging alternatives.

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2. Plastic packaging issues and approaches towards bio-sourced substitutes

Despite having so many benefits, plastic pollution results in the 2nd largest greenhouse gas (GHG) emission after incineration, with a cost of about 13 billion US dollars financial loss annually (Nielsen et al., 2020; Raynaud, 2014). Developed and developing countries contribute to accumulating plastic waste, and plastic contamination in the ocean is a global concern. About 8 million tons of plastics are credited into the sea annually, and most of it came from low-income developing countries due to lack of proper disposal of the technology. It is equal to the dumping of one truck of debris into the ocean per minute, and if appropriate steps are not taken, it will rise to two trucks per minute by 2030 and about four trucks per minute by 2050 (Jambeck et al., 2015). About 275 million tons of plastic wastes were produced in 2015 alone, and around 49% of single useable nature plastic wastes accounted for beach litter (Hahladakis et al., 2020, pp. 481–512; Singh & Devi, 2019). Dhall and Alam (2020, pp. 26–43) reported that around 31% of marine plastic-related debris comes only from the beverage and food packages sector and contributes to environmental pollution. Besides, China contributes the highest 28% share of mismanaged plastic waste globally, followed by Indonesia 10%, Philippines and Vietnam around 6%, Thailand 3.2%, Egypt 3%, Nigeria 2.7%, and South Africa 2% (Ritchie & Roser, 2018).

Despite the environmental pollution, plastic debris is also entering the food chains and is affecting human health because of the hazardous chemical processes allied with plastics production and recycling (Lithner et al., 2011). Plastics present in the sea start demolishing down into micro-plastics and are consumed by the marine species. When humans consume such species, many potentially toxic chemicals also enter the body (Engler, 2012). To some extent, chemicals used to improve the packaging material properties can also migrate into foods during processing and storage. Probable chemical migrants include plasticizers, antioxidants, light stabilizers, heat stabilizers, lubricants, slip compounds, antistatic agents, and monomers. This further causes taste, flavor loss, and noteworthy health harms once it crosses the specified limits (Bhunia et al., 2013; Guerreiro et al., 2018). Researchers reported leaching several chemicals of concern like antimony, bisphenol A, di-phthalates, etc., due to the reuse of improperly cleaned plastic materials. Exposure of PET bottles for about 30 days in the temperature range of 37–47 °C increases the concentration of ammonia, total dissolved salt, as well as nitrate, and sulphate ion (Abdullahi, 2014). Studies on the chemicals associated with plastic packaging show that at least 148 compounds have hazardous properties such as carcinogenic, endocrine-disrupting, persistent, bio accumulative and toxic, mutagenic, or reprotoxic. Out of these, a significant number of compounds are either unidentified or have only an unclear identification (Muncke, 2021).

Workers directly indulged in the plastic industries are severely affected. Different diseases, i.e., liver cancer, genotoxicity, and neurological dysfunction, were observed due to exposure to styrene monomer and vinyl chloride monomer (Azari et al., 2016; Christensen et al., 2017; Ruder et al., 2016). Recycling plastic packages and products is often suggested to decrease the hazardous effects of plastics on the environment. Out of the 78 million metric tons of synthetic packaging generated each year worldwide, rarely 14% can be recycled (Pennington, 2016). Unfortunately, it is also not safe due to exposure to several health hazard chemical compounds and breathing near burning plastic trashes. A study on the workers associated with recycling such conventional plastics generated waste shows unveiling volatile organic chemicals in recycling polystyrene, acrylonitrile-butadiene-styrene, polyamide 6, and polyvinyl chloride results in the development of cancer (Briassoulis et al., 2020).

All such issues related to human health, environmental hazard, and demerits associated with recycling, plastic packaging industries require urgent attention for an alternative environment-friendly sustainable solution for food packaging. This has opened the path to utilize the renewable bio-sourced feedstock in packaging that is more readily degradable in the environment (Fig. 1). In 2020, bio-sourced plastic used in food packaging was 0.99 million tons, equal to 47% of the total bio-sourced plastic produced. Asia is the largest bio-sourced plastic producer, with a share of 46% in total production worldwide (European Bio-plastics, 2020). Such bio-sourced plastics have further categorization, which is discussed in their subsequent part.

3. Bio-sourced plastics

The term bioplastic, a miscellaneous family of the material, was first coined by European Bioplastics, a European umbrella association working as bioplastic suppliers. It defined bioplastics as polymers that are biodegradable, bio-based, or can be both. It is mainly framed in three categories of bioplastics, i.e., Partially bio-based or bio-based and non-biodegradable plastics like bio-based Polypropylene (Bio-PP), bio-based Polyethylene (Bio-PE), bio-based Polyethylene terephthalate (Bio-PET); Bio-based biodegradable plastics, such as Polyhydroxyalkanoates (PHA), Polylactic acids (PLA), or Polybutylene succinate (PBS); and plastics that are conventional fossil resources grounded and are also biodegradable such as Polycaprolactone (PCL) or Polybutyrate adipate terephthalate (PBAT).

Bio-sourced plastics, a subgroup of bioplastic materials, are fabricated using biomass and biomass-derived chemicals that undergo chemical, physical, or biological therapy for conversion into bio-sourced plastics and are considered safe to cast off in food packing applications (Karan et al., 2019; Rujnić-Sokele & Pilipović, 2017). Bio-sourced plastics can be manufactured using a diverse variety of raw materials. Naturally occurring, first-generation renewable feedstock like corn, wheat, potato, sugarcane, etc., are the primary sources. Researchers also focus on utilizing agricultural, food industry residue, and lignocellulose biomass as second-generation raw materials for bio-sourced plastics production. All such agricultural products can be produced, refined, and transformed into bio-sourced plastics (FitzPatrick et al., 2010; Yaradoddi et al., 2019, pp. 2935–2954).

Bio-sourced plastics are manufactured either partially or entirely from renewable biomass resources like microorganisms, plants, animals, etc., and hence categorized as partial or fully bio-sourced plastics. Bio-based primitive polymers are chemically similar to their petroleum alternatives but partially derived from biomass, whereas natural rooted biopolymers and bio-based polyesters are biomass originated (Aeschelmann & Carus, 2015; Helanto et al., 2019). The key challenge in introducing bio-sourced packaging is to match its durability with product shelf-life. Temperature, relative humidity, spoilage microorganisms, ultraviolet exposure, etc., working individually or in combination are usually the modes of food quality degradation and spoilage. The factors that deteriorate the foods are the same, enhancing the degradation of the bio-sourced plastic material. Hence, special care should be taken during the development and generation of bio-sourced plastic materials.

Along with such aspects, a vital issue is to develop a system for transmitting the innovative features of bio-sourced plastics to the industrial scale so that safer material can be developed for food packaging purposes (Liu, 2006; Zhao et al., 2020). In 2020, bio-sourced plastics represented about 1% of the more than 368 million tons of plastics produced annually. Also, because of the ideal fit of bio-sourced plastics in the conventional plastic packaging market, this crafted number of global bio-sourced plastic production volumes is predicted to rise from about 2.11 million tons in 2020 to approximately 2.87 million tons by 2025 (European Bio-plastics, 2020).

Biomass for producing bio-sourced plastics can be directly extracted with the plant biomass (cellulose, starch) or generated by natural or improved microorganisms in the fermentation processes with the help of suitable carbon sources (PHA). Such biomasses can also be biocatalytically or chemically modified into building blocks to generate

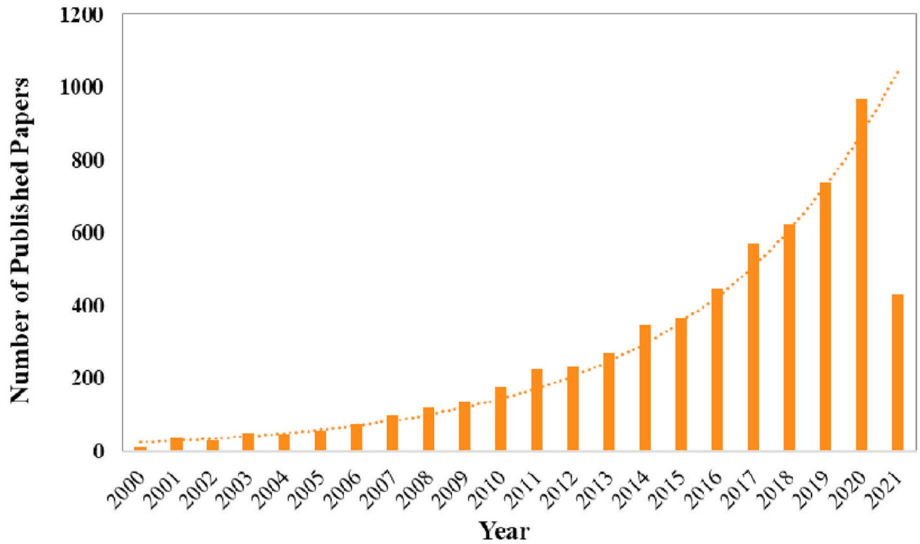


Fig. 1. Trends in the usage of renewable bio-sourced feedstock. Found in the Scopus database (Accessed April 13, 2021) with the keywords (bioplastic) OR (biopolymer) OR (biobased) OR (renewable) OR (biodegradable) OR (compostable) OR (oxodegradable) OR (inceneration) OR (recyclable) AND (food) AND (package) OR (packaging) OR (packet) OR (sustainable).

one more polymer (PLA). Again, the chemical conversion of bio-based monoethylene glycol (Bio-MEG) into building blocks followed by polymerization along with purified terephthalic acid (PTA) leads to the generation of a bio-based primitive plastic (Bio-PET) (FAO, 2016). Polyethylene furanoate (PEF), a 100% alternative of Bio-PET based on bio PTA, is also approved for food packaging, but it is still under development. The polymerization of bio-based ethylene forms one more conventional category of bio-based plastics (Bio-PE) from agricultural biomass-derived out of bioethanol after the dehydration process. Bio-PP is another bio-based plastic approved for food packaging, but like PEF, it is also under the development stage (Molenveld et al., 2015). These bio-based plastics have a specific production route approach and categorization (Storz & Vorlop, 2013). Fig. 2 summarizes the categorization of all the production routes of these bio-sourced plastics. Bio-sourced plastics in the food industry are used primarily to pack fruits, vegetables, confectionery chocolate and beverages in the form of cutlery, carrier bags, transparent and rigid containers, films, bottles, trays, dishes, and pouches, etc. Typical food packaging materials from the bio-sourced origin are shown in Fig. 3.

4. Plastics production from natural sources

Natural biopolymers are commonly used in plastics production industries due to their availability in large quantities and can be

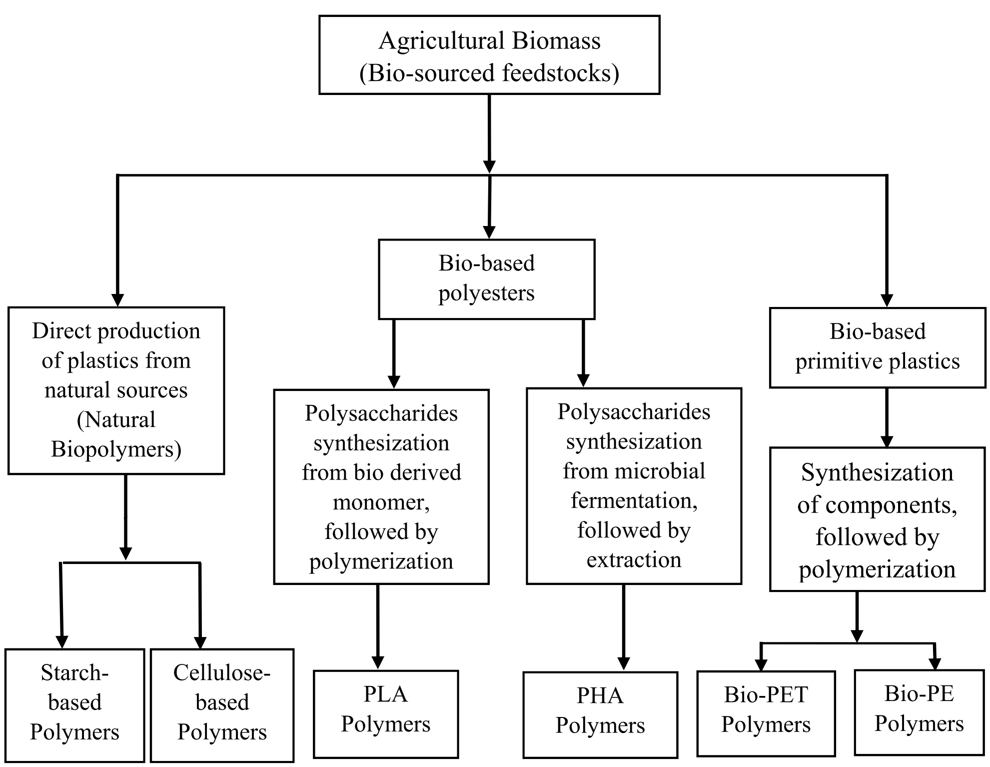


Fig. 2. Production route of bio-sourced plastics.

Fig. 3. Typical food Packaging materials from Bio-sourced origin (Grujić et al., 2017, pp. 139–160; Luzi et al., 2019).

synthesized easily through simple modification. Cellulose, starch, lignin, and chitin are the most abundant natural biopolymers in their worldwide productions (Avérous & Halley, 2009; Gadhave et al., 2018). However, chitin and lignin are used as pre-polymers and filler materials for thermoplastics and rubbers (Storz & Vorlop, 2013). Researchers have concentrated on starch and cellulose for generating alternatives to conventional plastics. The recent starch and cellulose study report that such materials can produce suitable alternatives with good mechanical and barrier properties (Khan et al., 2017; Mu et al., 2019). However, there is a necessity to further improve their properties and strength as per the utilization domain.

4.1. Starch-based polymers

The researchers in bio-sourced plastic development primarily focused on starch due to its widely available and renewable nature (Nagar et al., 2020). Starch is the polysaccharide having interlinked glucose molecules used to store energy in plants. It consists of two types of molecules: amylose, an unsystematic linear carbohydrate; and amylopectin, which has a higher molecular weight, systematic, and highly branched carbohydrate (Bello Perez & Agama-Acevedo, 2017, pp. 1–18; Singh & Sharanagat, 2020). The main feedstocks for such starch-based packaging products are starchy crops like potato, rice, corn/maize, cassava, etc. Maize is used primarily as a raw material for starch-based plastics around the world. More recent worldwide research focuses on extracting starch from wheat, barley, oats, and soy sources and evaluating its potential to be used to generate bio-sourced plastic (Jiménez et al., 2019). The primary concern associated with these sources is amylose and amylopectin variation with various varieties/species of different geographical locations, affecting the properties of packaging materials (Gadhave et al., 2018). The changing crystallinity and granular diameter level affect the processing grade and the outcome features (Dome et al., 2020).

Starch is an economic competitor of other polymers used in various methods to form biodegradable and compostable packaging to replace conventional plastics. There is a high demand for starch in the biodegradable film market, especially thermoplastic starch (TPS). However, starch grounded polymers have two serious shortcomings: weak mechanical strength and high moisture sensitivity. Hence, a little mechanical and thermal processing is required along with plasticizers (sorbitol, glycerol, and polyether) in native starch to form TPS (Ribba et al., 2017, pp. 37–76). It fractures the complicated crystalline structure of starch to obtain partial or complete gelatinization for further processing (Zhang et al., 2014, pp. 391–412). The material obtained resides in good thermal insulation and shock-absorbing properties. However, it further results in unnecessary homogenous molten material requiring an extra purification phase for obtaining TPS (Avérous & Halley, 2009). As discussed above, the fabrication of feedstock varies according to the plant biomass variety, geographical locations, and growing season, making it further complex to check the synthesized TPS characteristics (Shanks & Kong, 2012). TPS has been observed as demonstrating satisfactory oxygen-barrier properties, but hygroscopic nature limitation makes it inappropriate for liquid or high-water containing food products.

Starch is usually considered biodegradable (Moraes et al., 2017). It is also expected that starch-originated sheets are readily compostable in the surroundings subjected to the properties of specific forming materials. As a packaging material, starch-based plastic shows a brittleness nature (Marichelvam et al., 2019). The capacity of starch-originated bio-composites to substitute conventional plastics for packaging applications is very hopeful and satisfying. But, further work in improving its properties is required to increase penetration. Specifically, improvements are needed in mechanical properties and moisture sensitivity so that such polymers can replace plastics for more range of applications (Xie et al., 2013). Non-cellulosic polymer chitosan was reported to improve moisture sensitivity, oxygen barrier, and antimicrobial properties when manufacturing TPS composites (Dang & Yoksan, 2016). Such researchers also indicated that starch-based polymers could be cast-off as an edible film for pharmaceutical and food packaging applications.

This material is a perfect substitute for PS and is used mainly in disposable tableware, cutlery, bowls, plates, cups, egg trays, coffee machine capsules, bottles, films for food wrapping, and thermoplastics for food packaging. Many researchers aim to develop and form a biodegradable product that can satisfactorily substitute food packing (Ahmadzadeh et al., 2016). For this, scientists have focused on applying cassava starch, a vital staple crop, widely available in South America, Africa, and some parts of Asia. However, any starch can be used for this purpose without compromising food security. Starch-based packaging materials in their original form hardly qualify for food packaging applications; hence further modification is required to enhance material properties. Sugar palm starch has a potential application in food packaging bags and films. The modification in its properties concerning rigidity, brittleness, poor water sensitivity and low mechanical strength has been achieved by incorporating sugar palm fiber, sugar palm nanocellulose, clay, cellulose, lignin, etc. The development of such environment-friendly nanocomposites reduces the disposal issue and carbon footprint from conventional polymer packaging (Ilyas et al., 2018, pp. 189–220). Composite films produced by corn starch incorporated with untreated corn husk fiber enhance the tensile properties, crystallinity, and thermal stability and promote biodegradation (Ibrahim et al., 2019). Cheap and widely available cassava starch also requires modification in its structure for varying physical, chemical, and enzymatic properties. Films made up of plasticized cassava starch reinforced with clay nanoparticle is quite promising bio-sourced biodegradable packaging (Edhirej et al., 2017; Pandit et al., 2018, pp. 81–103). Flexible films made up of cassava starch and plasticizer mixture through extrusion technique have a potential application in dry food packaging.

Extrusion, injection-molding, compress-molding, solution casting and blowing are the most appropriate manufacturing methods for TPS output on a commercial scale (Shanks & Kong, 2012). Starch modification, blending with synthetic or biodegradable polymers, and compositing are the actual methods used to achieve changes in the mechanical and barrier properties of TPS material. Biocomposite packaging was developed by adding nanofillers, PCL, PVA, PLA, and PHB, with starch to improve material properties. For example, in the case of starch/PVA blends, films are usually formed in the presence of PVA by gelatinizing starch to improve the material's green character. (Ribba et al., 2017, pp. 37–76). A starch-based plastic film with 7–9 parts of nano montmorillonite has shown high strength and can be used as plastic bags and preservative films for food packaging applications (Gadhave et al., 2018).

In 2020, starch and its blend-based polymers increased to 18.7% of the worldwide production volumes of bio-sourced plastics from 10% as in 2014 (European Bio-plastics, 2020). Bio-sourced plastics production from starch is in a nascent stage with a minimal emerging level and even unregistered market players. However, BioEnvelop in Canada, Earthshell Corp. & Starch Tech, Inc. from the USA, National Starch Company active in the UK, Novamont working in Italy, EverCorn, Inc. operative in Japan, and VTT Chemical Technology functioning in Finland are the few well-established companies producing starch and starch blend bio-sourced plastic for food-related packaging applications (Table 1).

4.2. *Cellulose-based polymers*

4.2.1. *Pure cellulosic polymer*

Pure cellulose can be extracted from fiber crops such as agricultural waste, herbaceous crops, wood chips, etc. Cellulose in wood is around 40–50% by weight; hence wood pulp is the primary feedstock for cellulose retrieval (Dhall & Alam, 2020, pp. 26–43). Some other crops like moso-bamboo are specially grown as a raw product for cellulose. The

Table 1
Commercial applications of Starch-based packaging.

Category	Packaging applications	Suppliers	Properties	End of Life Techniques	References
Fruits and Vegetables	Translucent film	Novamont (Italy)	Sealable	Biodegradation & Composting	(Kabasci, 2020, pp. 67–96; Molenveld et al., 2015; Nakajima et al., 2017; Narancic et al., 2020; van den Oever et al., 2017; Zhao et al., 2020)
	Film	Albert Heijn (Zaandam, NL)			
	Net packaging	Bio4Pack (Haaksbergen, NL)	Durable, Fine finish		
	Bag	Willem Dijk A.G.F. (Enschede, NL)	Barrier for water		
Meat	Covering barrier film and Containers	Plantic (Jena, GER)	Barrier for water, Barrier for oxygen, Coatable with aluminum, Coatable with glass, Transparent,	Biodegradation & Composting	
Fish	Containers	Profish (Twello, NL)	Sealable		
Cheese	Covering film	Plantic (Jena, GER)			
Dry foods	Film laminate	Amcor (Zutphen, NL)	Approved for direct food contact	Biodegradation & Composting	
Egg	Egg boxes	Paperfoam (Barneveld, NL)	Smooth finish, Super lightweight	Biodegradation, Composting, & Recycling	
Bread	Sandwich bags	Biofutura (Rotterdam, NL)	Approved for direct food contact	Biodegradation & Composting	
Coffee	Capsules	Ethical Coffee Company (European countries)	Easy to use, Tastes great	Biodegradation, Recyclable & Composting	
Confectionery and Chocolate	Containers	Cadbury (Australia)	Approved for direct food contact	Biodegradation & Composting	
Others	Carrier bags	Marks and Spencer (UK) Bunzl (Almere, NL) Moonen Natural (Weert, NL) Novamont (Italy) Oerlemans (Genderen, NL)	Approved for direct food contact	Biodegradation & Composting	
	Drinking straws	Moonen Natural (Weert, NL)			
	Plates and Dishes	Novamont (Italy)			
	Cups for hot drinks	Biome Bioplastics (UK)	Hot fill		

GER: Germany, NL: Netherlands, UK: United Kingdom.

cellulosic biomass is used to produce semi-synthetic films and fibers for substituting the conventional polymer-based LDPE, HDPE, PS, and PP. Semi-synthetic word is used here because the raw material has to undergo different chemical processes to form the final product (FAO, 2016). Again such semi-synthetic fibers/films produce rayon fibers, vulcanized rubber, cellulose acetate films & fibers, and cellophane. Films and fibers are produced by extrusion through slits or spinnerets. All such materials need strong chemical processing to separate and extract cellulose (Guidotti, 2017, p. 309). Such cellulosic polymers qualify as compostable and biodegradable based on the coating and

Table 2
Commercial applications of Cellulosic polymer and its blend.

Category	Packaging applications	Suppliers	Properties	End of Life Techniques	References
Pure cellulosic Polymers					(Dhall & Alam, 2020, pp. 26–43; Ferreira et al., 2016; Gilbert, 2017, pp. 617–630; Helanto et al., 2019; Kabasci, 2020, pp. 67–96; Licciardello & Piergiovanni, 2020, pp. 191–222; Luzi et al., 2019; Molenveld et al., 2015; van den Oever et al., 2017; Zhao et al., 2020)
Butter	Packaging films	Innovia, (Merelbeke, B)	Sealable	Biodegradation & Composting	
Biscuits and Bakery products	Barrier films	Innovia, (Merelbeke, B)	Barrier for water, Transparent	Biodegradation & Composting	
Crisps	Films	Genpak (Canada) Innovia, (Merelbeke, B)	Barrier for water, Barrier for oxygen, Coatable with aluminum	Biodegradation & Composting	
Confectionery and Chocolate	Transparent film	Alce Nero (Italy) Innovia, (Merelbeke, B)	Transparent	Biodegradation & Composting	
	Barrier films	Alce Nero (Italy)	Barrier for oxygen, Coatable with aluminum		
		Innovia, (Merelbeke, B)			
Coffee	Barrier films	Innovia, (Merelbeke, B)	Barrier for oxygen, Coatable with aluminum	Biodegradation & Composting	
Tea	Films	Twinings (UK) Innovia, (Merelbeke, B)	Approved for direct food contact	Biodegradation & Composting	
Dry foods	Film laminate	Amcor (Zutphen, NL) Hain Celestial (Aalter, B) Innovia, (Merelbeke, B)	Approved for direct food contact	Biodegradation & Composting	
Others	Cups for cold drinks	Biome Bioplastics (UK) FKuR (Willich, GER)	Approved for direct food contact	Biodegradation, Composting, Recycling, & Incineration	
	Plates and dishes	Biome Bioplastics (UK) FKuR (Willich, GER)	Approved for direct food contact	Biodegradation & Composting	
Cellulose acetate					
Others	Cups for hot drinks	Biome Bioplastics (UK)	Hot fill	Biodegradation & Composting	
	Cutlery	Biome Bioplastics (UK) Bunzl (Almere, NL) FKuR (Willich, GER)	Approved for direct food contact	Biodegradation & Composting	
	Labels	Berkshire Labels (UK) Innovia, (Merelbeke, B)	Approved for direct food contact	Biodegradation & Composting	
Cellophane					
Fruits and Vegetables	Transparent film	Innovia (Merelbeke, B)	Transparent, Sealable	Biodegradation & Composting	
Meat and Fish	Top covering film	Bio4Pack (Haaksbergen, NL)	Barrier for water, Barrier for oxygen, Coatable with aluminum, Coatable with glass, Transparent, Sealable	Biodegradation & Composting	
Cheese		Innovia, (Merelbeke, B)			
Meat And Fish	Packaging film	Bio4Pack (Haaksbergen, NL)	Barrier for water, Barrier for oxygen, Coatable with aluminum, Coatable with glass, Transparent		
Cheese		Innovia, (Merelbeke, B)			
Bread	Packaging films	Innovia, (Merelbeke, B)	Approved for direct food contact	Biodegradation & Composting	
Egg	Egg boxes	Paperfoam (Barneveld, NL)	Smooth finish, Super lightweight	Biodegradation, Composting, & Recycling	

B: Belgium, GER: Germany, NL: Netherlands, UK: United Kingdom.

material properties. However, pure cellulosic polymers have limited market share in packaging applications due to their poor solubility characteristics, mechanical properties, moisture barrier properties, bad processing, brittleness, and a highly crystalline structure (Ferreira et al., 2016; Rastogi & Samyn, 2015). The alternating hydroxyl side chain along the cellulose backbone is accountable for the hydrophilic nature of pure cellulosic rooted packing materials. This chain is also responsible for the highly crystalline structure of cellulose, resulting in the brittleness of the packaging material and exhibits poor tensile strength and flexibility (Helanto et al., 2019; Liu, 2006). That is why researchers from different academic and industrial backgrounds focus on the evolution of different cellulose byproducts for food packing applications (Table 2).

Peptidopolysaccharide films composed of cellulose and peptide are four times effective than pure cellulose film as a promising antimicrobial application towards gram-positive and gram-negative bacteria (Wu et al., 2019). By minimizing moisture loss, emulsified cellulose-based biofilm consisting of maize starch, microcrystalline cellulose and soybean oil increased the shelf life of wrapped crackers processed at various RH values relative to unwrapped ones (Grujić et al., 2017, pp. 139–160). Cellulose in nano form as filler or coating allows the improvement of conventional packaging materials performance and helps to develop novel materials. However, nitrocellulose with or without polymer coating is used as a film when moisture barrier property is more desirable (Piergiovanni & Limbo, 2016; Siracusa & Rosa, 2018, pp. 275–307). Modified cellulose composite films with PVA reinforcement increase tensile strength and can be used as packaging materials. The nanocomposite of wheat gluten, titanium dioxide with cellulose nanocrystals shows good mechanical property with excellent antimicrobial activity. However, using carboxylated cellulose nanocrystals with wheat gluten in composite packaging films shows a promising mechanical, barrier and thermal property (Rydz et al., 2018, pp. 431–467).

4.2.2. Cellulose acetate

Cellulose acetate is manufactured from purified cellulose, which is generally extracted from cotton or wood pulp. It is then reacted with acetic anhydride and acetic acid, followed by dissolving in acetone. Then by extrusion as filaments through spinnerets, cellulose acetate fibers are formed (Kershaw, 2018; Liu et al., 2021). Cellulose acetate was first developed in the early 20th century and has been primitively used to manufacture film bases for photography and synthetic fibers (Gilbert, 2017, pp. 617–630). Its standing with the FDA as GRAS (Generally Recognized As Safe) has stimulated the food packaging industry to develop the alternative of conventional packaging with cellulose acetate. Cellulose acetate can sustain high temperature and is generally used to manufacture disposables cutlery and cups for hot drinks (Table 2) (Molenveld et al., 2015; van den Oever et al., 2017). Nowadays, cellulose acetate films are used for wrapping fresh produce and baked goods. The plasticizer is one of the main parts of cellulose acetate film, which enhances printability, clarity, gloss, dimensional stability, and rigidity. Such films show poor tearing strength but are tough and resistant enough to resist punctures. Cellulose acetate film demonstrates relatively poor water, gas barrier properties and undergoes hydrolysis to form acetic acid, commonly referred to as "vinegar syndrome" (El-Rehim et al., 2018). Such properties of cellulose acetate have restricted the widespread of cellulose acetate films in food packaging industries. However, sometimes it is mingled with other polymers to enhance the properties like durability, flexibility but this may affect the waste treatment and end life behavior.

Cellulose acetate blends are applicable for extrusion and injection molding and are food contact-approved biodegradable polymers. Cellulose acetate with graphene oxide or a double layer of hydroxide nano platelets shows high oxygen barrier properties (Helanto et al., 2019). Diethyl phthalate and triacetin are commonly used cellulose acetate plasticizers to produce plastic products with acceptable flow properties that simplify further processing (Gilbert, 2017, pp. 617–630). Nanocomposite cellulose acetate films with clay structures show a promising reduction of water vapor and oxygen transmission rate and could be cast-off in packaging uses (El-Rehim et al., 2018). Cellulose acetate, modified montmorillonite, thymol as a natural antimicrobial component, and triethyl citrate as plasticizers are promising nanocomposite blends for producing food packaging materials (Rydz et al., 2018, pp. 431–467). Nanocomposites produced by melt intercalation of cellulose acetate without plasticizers and montmorillonite nanoparticles show a superior mechanical property (Ramos et al., 2018, pp. 271–306). Cellulose acetate nanofiber incorporated with zinc oxide shows strong antimicrobial activity against *S. aureus*, *E. Coli* and Citrobacter, against *S. aureus*, *K. pneumoniae*, *E. coli* and *P. aeruginosa* with silver nitrate of 10–20 nm and Gram-positive *S. aureus* and Gram-negative *E. coli*, *K. pneumonia* and *P. aeruginosa* with silver nanoparticle of 21 nm (Khalil et al., 2016).

4.2.3. Cellophane

One more cellulose derivative which is utilized for the intention of food packing application is cellophane. Cellophane, the thin transparent film, is manufactured by cellulose with the help of the viscose method along with the addition of glycerin to improve flexibility (Helanto et al., 2019). In this method, carbon disulfide and aqueous sodium hydroxide dissolve wood pulp in a viscous solution, commonly known as viscose (Dhall & Alam, 2020, pp. 26–43; FAO, 2016). Cellophane is often sold as a breathable film used for bread and cheese packaging (Kershaw, 2018). It is used widely to packaging floral bouquets, confectionery, and ovenproof wrapping for cooking food (Table 2). Polymer coatings that are generally used to increase the shelf-life by enhancing the barrier properties can be used on cellophane to inhibit the rate of microbial degradation (Benyathiar et al., 2015). Unlike other films, it has a dead fold, i.e., once folded cannot be folded back. Also, cellophane cannot withstand melting, and hence a distinct sealing layer is needed for making the material sealable. Due to the broad availability of different barriers and sealing materials, many cellulose-based films exist in the market for an extensive range of utilization. One such example is that cellophane is often collaborated with a sealing layer of amorphous PLA or starch-based sealing layers to produce transparent sealable films (Muller et al., 2017). This film shows a highly compostability nature when combined with a thin layer of aluminum oxide barrier material. Cellophane behaves as biodegradable in suitable environments, but it falls under the label of compostable more correctly.

In order to enhance its moisture resistance properties, cellophane is often coated with nitrocellulose wax or polyvinylidene chloride and is used for baked goods, processed meat, cheese, fresh produce, and candy (Dhall & Alam, 2020, pp. 26–43). Unlike uncoated cellophane with high moisture sensitivity, coated cellophane with polyvinylidene chloride or nitrocellulose coating provides thermo sealability, high moisture resistance, and a range of applications in food packaging (Piergiovanni & Limbo, 2016). Like cellulose acetate and cellophane, other cellulose derivatives show nice film-forming characteristics, but such materials are not yet utilized at the industrial scale until now. This might be due to cellulose's crystalline structure, making the primary derivatization process costly and difficult (FAO, 2016). Continuous innovation and research are desirable in this zone to build up more cost-economic processing techniques and develop such cellulose derivatives for their diversified application in bio-sourced plastic packaging.

5. Bio-based polyesters

Bio-based polyesters are one of the most flexible groups of polymeric products structurally and functionally. Synthesization of such bio-based polyesters from biomass requires converting their abundant monomer units through numerous fermentation techniques. Such polymers are shaped by the polymerization reaction between dicarboxylic acids and hydroxyl acid or di-functional alcohols (Storz & Vorlop, 2013). Such polyesters can be manufactured with a larger variation in their properties as per the processing conditions, catalysts used, and the utilization of the different monomer units. It ranges from partly to fully bio-based plastics, stiff to soft products. Such polyesters fall under biodegradability because the ester linkage promotes degrades due to hydrolysis (Siracusa, 2019). Novel bio-based polyesters PLA and PHA are the utmost important biodegradable polyester of this category, originating from agricultural biomass and growing significantly, although not as much as drop-in plastics (Aeschelmann & Carus, 2015).

5.1. Polylactic acids (PLA) polymers

From the mid-20th century, the most innovative research for finding suitable alternatives to plastic packaging is going on in the field of bio-based polyesters synthesization through bacterial fermentation of polysaccharides. Such research had upshot the evolution of Polylactic acids (PLA) and Polyhydroxyalkanoates (PHA) (Nakajima et al., 2017). PLA, also called Polylactides, is an aliphatic (non-cyclic and non-aromatic) thermoplastic formed by polymerization of lactic acid/-lactide acquired through microbial fermentation of sugars derived from different agricultural biomass sources (Helanto et al., 2019). The raw agricultural material for producing PLA-based packaging material mainly consists of extraction of lactic acid from starch-rich and sugar crops like sugarcane, maize, wheat, cassava. Lactic acid undergoes a polymerization process, resulting in PLA formation with high variability in molecular weight. Current research exploits the second-generation feedstocks such as agricultural residue, bagasse, wheat straw, corn stover, wood chips, by-products, and industries wastage be used as a raw material for PLA production (Djukić-Vuković et al., 2019). Researchers are also showing their interest in the generation of lactic acid via methane fermentation. Since PLA is biodegradable, this interest has focused on making the whole PLA production a closed-loop process by utilizing the PLA waste to generate methane through anaerobic digestion (Kershaw, 2018). Extensive studies have been published on the impact of PLA production on the environment. Researchers reported that PLA manufacturing uses 50% less petroleum feedstock and releases 60% less CO_2 than conventional fossil-based plastics like PS and PET (Vink & Davies, 2015). It emits less greenhouse gas compared to hydrocarbon rooted polymers (Shen et al., 2012).

PLA can be readily manufactured with high molecular weight using a catalyst (stannous octoate) via lactide's ring-opening polymerization (Jiménez et al., 2019). The obtained thermoplastic film by this method has a good water vapor barrier property. It can also withstand the harshness of versatile manufacturing techniques like injection molding, blow molding, blow or vacuum thermoforming processes, and cast film extrusion for the production of packaging material (Jamshidian et al., 2010; Kabasci, 2020, pp. 67–96; Milovanovic et al., 2018; Peelman et al., 2013). However, PLA is too delicate and unsuitable for various packaging production techniques. It needs to be strengthened with additives like cellulose nanofibers and nanocellulose to make it compatible with other manufacturing techniques (Gan & Chow, 2018).

PLA can also be combined with nanocellulose fiber to enhance its properties. A blend of PLA and nanocellulose fibers applied on paper by the cast-coating process decreases the water vapor transmission rate of the paper. Inhibitors like ethylene-based copolymers minimize brittleness and retain sufficient degrees of stiffness when added to PLA up to 10%. Blending of PLA with PCL, PBS and PHB in 20–40% by weight has been reported for maintaining the acceptable level of toughness. PLA with organically modified montmorillonite enhances the gas barrier property of the material. Good mechanical properties with an increased elongation were reported for blending PLA, PBS and organically modified clay. Gypsum can also improve the mechanical property of PLA. Silane-treated halloysite nanotubes or organically modified clay blended with PLA decreases the water barrier property. However, PLA/nanoclay and PLA/PCL/nanoclay films improve both the water and oxygen barrier properties. Glycerol, polyethylene glycerol, silver, silver nanoparticles and chitosan with PLA were noticed to have a more hydrophilic and notable improvement in the antimicrobial properties. Blending the two forms of PLA poly (L-lactide acid) and poly (D-lactide acid) improves thermal stability compared to the individual form. (Helanto et al., 2019).

Kaolinite nanofillers addition to PLA films improves the thermal and mechanical properties. Also, chemically modified kaolinite improves the oxygen barrier property of amorphous PLA. Montmorillonite layered silicate combining with PLA improves the barrier property. The addition of cellulose nanowhiskers reduces the oxygen permeability of PLA. The addition of PLA to a chitosan film has a beneficial impact on the permeability of water vapor and moisture sensitivity but diminished the tensile strength and elasticity modulus. The mixture of PLA with starch, glycerol, or sorbitol plasticizers, along with other degradable polyesters, reduces the film's brittleness (Peelman et al., 2013). Soy protein isolate film coated with PLA improves the barrier and mechanical property; depending on the PLA concentration, it has strong adhesion between layers and high transparency (Dhall & Alam, 2020, pp. 26–43; Peelman et al., 2013). To eliminate brittleness, increase thermal stability, and strengthen mechanical properties such as impact strength, PLA has been blended and copolymerized with biodegradable PCL. PLA/PCL films impregnated with thymol or thyme extract also show antibacterial properties (Helanto et al., 2019; Narancic et al., 2020; Peelman et al., 2013).

PLA-Si/SiO_x, PCL-Si/SiO_x, or PEO-Si/SiO_x coating on PLA enhances the barrier property and these composites used in the MAP system to pack medium shelf-life products. Also, a thin 25 nm layer of AlO_x was reported for improving the barrier property of PLA films and PLA-coated board (Peelman et al., 2013; Zhao et al., 2020). For PLA/nanocellulose biocomposites, nanosilver packing of 0.5 wt % to 1 wt % can produce antimicrobial effects on *E. coli* and *S. aureus* along with either enhancement or maintenance of thermal, mechanical and barrier properties (Gan & Chow, 2018). The blending of PLA with PS can balance PS properties and cost-effectiveness of PLA-based film (Luzi et al., 2019). PLA coated cardboards with a 3% w/v PLA concentration in chloroform successfully improves the water barrier property and can be used as paper cups (Rastogi & Samyn, 2015).

PLA has a broad application due to its thermoplastic properties, which are the same as primitive synthetic polymers. It is a good replacement for PS, LDPE, PET, and HDPE, which is used primarily in the manufacturing of transparent & rigid containers, loose film packaging, disposable cups, and jar like items (Luzi et al., 2019; Narancic et al., 2020; Zhao et al., 2020). Regarding the utility of PLA in food packing, the PLA films are transformed into trays, notably for RTE meals, delicate products, and fresh organic produce like strawberries, bell peppers. PLA having good breathing properties makes it ideal for bread packaging, packaging of salads, and chopped lettuce. However, PLA has limited use in bottles as it is quite permeable to water vapor. Sometimes, PLA is also attached with the paper to form the coatings for biodegradable and compostable paper plates and paper cups (Rastogi & Samyn, 2015). These days, PLA is gaining more popularity as an alternative for traditional plastics in the catering business, as it is considered safe regarding direct contact with food items (Dhall & Alam, 2020, pp. 26–43; Gadhave et al., 2018). Generally, the wastes, utilized PLA cups, plates, and cutlery from the catering sector are accumulated in one place and are sent for either anaerobic digestion or industrial composting, which helps make PLA production a closed-loop process.

Apart from the starch-based packaging, Polystyrene foam (EPS) packaging can also be replaced by PLA-based foam-Biofoam (Molenveld et al., 2015). Recent advancement regarding PLA usage is in manufacturing PLA fibers, which can be used for non-woven products such as teabags. Recently, PLA-based material for cutlery and food packaging (PLA-LLDPE film) is developed by the Centre of Excellence-Sustainable Polymers (CoE-SusPol), IIT Guwahati (Katiyar, 2017). However, if we talk about the consumption volume of PLA in the world market, then in the year 2010, it stood at second position amongst all important bio-sourced plastics. In 2014, PLA production capacity was 0.2 million tons representing 10% of the global production capacity.

Also, in 2019 PLA polymer was 13.90% of the worldwide production volumes of bio-sourced plastics, which further increase to 18.70% in 2020 (European Bio-plastics, 2020). The commercial level manufacturing of PLA has a principal manufacturer in Japan, Europe, and the USA (Table 3).

5.2. Polyhydroxyalkanoates (PHA) polymers

Another bio-based polyester modernity resulting from the use of bacterial fermentation technique is Polyhydroxyalkanoates (PHA). PHA is a linear aliphatic polyester that shows elastomeric properties with physical cross-linking of crystals and can be transformed into thermoplastic polymers. Many microorganisms yield the PHA family via natural or polysaccharide bacterial fermentation process of lipids or sugars extracted from different agricultural by-products (Jha & Kumar, 2019; Luzi et al., 2019). More than 100 different monomers are well known, resulting in materials having many different features after interfusing within this family (Peelman et al., 2013). Based on the properties and applications, PHA polymer has three forms, i.e., pure PHA, poly-3-hydroxybutyrate (PHB), and Poly, 3-hydroxybutyrate-co-3-hydroxyvalerate (PHBV). The variation in properties and the high production cost are the two key restrictions for large-scale deployment of such bio-based polyesters in food packaging (Khosravi-Darani & Bucci, 2015).

5.2.1. Pure Polyhydroxyalkanoates (PHA)

Agricultural products like sunflower, olive, soy, rape seed oil and sugar crops like sugarcane are helpful for the generation of PHA (Bugnicourt et al., 2014; Helanto et al., 2019). Pure PHA can also be extracted from palm oil biomass residues, although not yet commercialized. PHA generally aggregates in the granular form inside the microbial cells making up around 90% of the cellular mass (Kabasci, 2020, pp. 67–96). That is why the generation of pure PHA is still confined and disseminated across different production facilities. Production of PHA is about 20–80% costlier than conventional plastics due to the higher cost of polymerization, fermentation techniques, and laboratory stage processing (Zhao et al., 2020). All such limitations necessitate materials like ecoflex and PLA combined with PHA for further use. However, regarding the impact of PHA production on the environment, no such data shows its effect on the environment due to the non-commercialization of PHA production globally (Aeschelmann & Carus, 2015).

PHA belongs to a broad group of biogenic polyesters that are purely bio-based. It shows biodegradability in various environments varying from seawater to cold soil (Dilkes-Hoffman et al., 2019; Rujnić-Sokele & Pilipović, 2017). Such materials have, in general, a lower degree of crystallinity, glass transition temperature, and melting point. The disadvantage of PHA polymers is non-transparency and low production volumes; hence, there is a need for further technical advancements to successfully replace the primitive petroleum polymers in food packaging applications (Wang et al., 2014). PHA was earlier used in the medical field (Bugnicourt et al., 2014), and it is compared with LDPE due to its low water vapor permeability. PHA blended with TPS had a beneficial effect on the barrier properties, starch-based film's hydrolytic and UV stability, and decreased processing temperature, allowing less breakdown of the starch (Peelman et al., 2013). The incorporation of inorganic nanofillers, including montmorillonite and layered double hydroxides, can improve the thermal stability of PHA (Khosravi-Darani & Bucci, 2015). Nano keratin film coated with electro-spun PHA fiber shows improved barrier properties and good adhesion (Luzi et al., 2019).

PHA shows good thermo-mechanical characteristics, like a conventional synthetic polymer like PP; hence it can be a perfect substitute for PE and PP. PHA, rooted in its medium chain length, is currently used in biodegradable cheese coatings and fast food service wares (Dhall & Alam, 2020, pp. 26–43; Khan et al., 2017). Containers made up of PHA are frequently used as a bio-based additive. The recent application consists of the film production used in carrier bags and utilities where biodegradability of the product is vital (e.g., mulch films) (Molenveld et al., 2015). In 2019, PHA polymers were only 0.025 million tons representing 1.20% of the worldwide production volumes of bio-sourced plastics. However, it has experienced the second most growing market share and touched about 1.70% production capacity by the end of 2020 (European Bio-plastics, 2020).

5.2.2. Poly-3-hydroxybutyrate (PHB)

The characteristics of PHA primarily depend on the temper of the carbon source utilized, types of bacteria used during the fermentation process, and the monomer unit's composition. It ensures the availability of numerous types of PHA, showing a varied range of different properties. PHA has more than 100 different well-known composites; out of that, the most common one is poly-3-hydroxybutyrate (PH3B or PHB) (Dhall & Alam, 2020, pp. 26–43). Like PHA, PHB is also generated with microorganism fermentation techniques with bacteria like *Cupriavidus necator*, *Bacillus megateriumal*, *Alcaligenes eutrophus*. It acts as an energy storage molecule inside the cellular structure of the microorganisms (Yaradoddi et al., 2019, pp. 2935–2954). For microbial extraction of PHB, at first two Acetyl-CoA molecules undergo condensation reaction results in acetoacetyl-CoA production, further condensed to hydroxybutyryl-CoA. This final reduced composite acts as the monomer unit for polymerization and PHB generation (Liu, 2006). It shows a high degree of crystallinity, higher glass transition temperature, and a higher melting point in contrast to PHA. Like PHA, PHB is also often combined with PLA to develop materials with better physical, mechanical and thermal properties compared to pure PLA-derived materials. Recent research on this combination shows that PHB infusion in PLA by 25% (w/w) improves the barrier properties of PLA; however, there is a somewhat reduction in its inherent transparency (Arrieta et al., 2017). A good barrier property of PHB is also due to its lamellar structure, making it biodegradable under different environments (Yeo et al., 2018).

PHB in combination with different reagents enhances the film properties. A thin 25 nm layer of AlO_x was reported for improving the barrier property of PHB, just like PLA-based packaging. PHB coating of more than 10% on cellulose paper and acetylated cellulose film improves the water barrier property along with better mechanical property. PVA embedded on poly-cis-1,4-isoprene and blended with PHB exhibits better tensile property. Improvements have been made to the mechanical and thermal properties with nanoclay and PHB (Helanto et al., 2019). PHB and PLA blend shows a better barrier and mechanical property. However, when this blend is reinforced with surfactant-modified cellulose nanocrystals shows enhancement in the adhesion between PLA and PHB. A blending of PHB with oxidized short-chain polyethylene has better mechanical properties. PVA blended with PHB have capable packaging application (Dhall & Alam, 2020, pp. 26–43). PHB incorporated with modified montmorillonite increases the biodegradability of PHB (Khosravi-Darani & Bucci, 2015). Starch and PHB have also been documented to be substantially compatible with each other and have the advantage of reducing the cost of PHB (Peelman et al., 2013). Polymeric matrices of PHB combined with poly (vinyl butyral), poly (ethylene oxide), poly (vinyl acetate), poly (vinyl phenol), cellulose acetate butyrate, chitin, and chitosan exhibits outstanding rigidity, thermal, and chemical performances (Luzi et al., 2019).

PHB, the most generic type of PHA, is also preferable concerning the food packaging application. Like PHA, PHB also resembles thermomechanical properties like PP having high melting temperatures (175–180 °C). However, it is more brittle and stiffer than PP. PHB possesses low density and has a slow crystallization rate (Ragaert et al., 2019). Due to such negative characteristics, PHB packaging shows low impact resistance and hence restricts its massive use in food packaging industries. Another critical factor restricting its wider use is relatively higher manufacturing costs than the conventional plastics production method. As PHB provides the advantages of biodegradability, researchers worldwide are continuously working to overcome its negative

Table 3
Commercial applications of PLA-based packaging.

Category	Packaging applications	Suppliers	Properties	End of Life Techniques	References
Milk and Dairy produce	Bottles	NatureWorks (USA)	Approved for direct food contact	Industrial composting & Recycling	(Dhall & Alam, 2020, pp. 26–43; Kabasci, 2020, pp. 67–96; Khan et al., 2017; Luzi et al., 2019; Molenveld et al., 2015; Narancic et al., 2020; van den Oever et al., 2017; Zhao et al., 2020)
	Cups	Danone (GER)		Industrial composting	
Fruit juice	Bottles	Noble Juice (USA) Polenghi (Italy)	Approved for direct food contact	Industrial composting	
Fruits and Vegetables	Transparent film	Albert Heijn (Zaandam, NL) Bio4Pack (Haaksbergen, NL) FKuR (Willich, GER) VDH Concept (Schoten, B)	Transparent, Sealable	Industrial composting	
	Trays/Dishes	Huhtamaki (Franeker, NL) Nedupack (Duiven, NL)	Approved for direct food contact	Industrial composting & Recycling	
	Containers	Huhtamaki (Franeker, NL) Nedupack (Duiven, NL) Biofutura (Rotterdam, NL)	Approved for direct food contact	Industrial composting	
	Fruit nets	FKuR (Willich, GER)	Durable, Fine finish	Industrial composting	
Meat And Fish	Top covering film and Packaging film	Bio4Pack (Haaksbergen, NL) Amcor (Culemborg, NL) Taghleef (Koblenz, GER)	Barrier for water, Barrier for oxygen, Coatable with aluminum, Coatable with glass, Transparent, Sealable (only for covering film)	Industrial composting	
Cheese	Top covering film and Packaging film	Bio4Pack (Haaksbergen, NL)	Barrier for water, Barrier for oxygen, Coatable with aluminum, Coatable with glass, Transparent, Sealable (only for covering film)		
	Trays	Clear Lam (USA)			
Meat		Coopbox (Italy) Depron (Weert, NL)	Approved for direct food contact, Sealable	Industrial composting	
Fish		Coopbox (Italy) Synbra (EttenLeur, NL)			
Cheese		Coopbox (Italy)			
Bread	Films	Biofutura (Rotterdam, NL) Sidaplax (B)	Approved for direct food contact, Sealable	Industrial composting	
Egg	Egg boxes	Biopla (China) ISAP (Italy)	Smooth finish, Super lightweight	Industrial composting & Recycling	
Water	Bottles	Cool Change (Australia) Sant'Anna (Italy)	Approved for direct food contact, Transparent	Industrial composting	
Coffee	Barrier films	Swiss Coffee Company (Switzerland)	Barrier for oxygen, Coatable with aluminum	Industrial composting	
	Cups	Beanarella (Switzerland)	Approved for direct food contact		
Tea	Teabags	Ahlstrom (Finland)	Approved for direct food contact	Industrial composting	
Dry food	Film	Bio4Pack (Haaksbergen, NL)	Approved for direct food contact	Industrial composting	
	Tray	Nedupack (Duiven, NL)			
Other (Freezer Section)	Ice cream cup	Biofutura (Rotterdam, NL	Approved for direct food contact, Cold storage	Industrial composting	
	Tray	Sandros (GER)			
Others	Carrier bags	BASF (GER) FKuR (Willich, GER) Oerlemans (Genderen, NL)	Approved for direct food contact	Industrial composting	
	Shrink film	BASF (GER) Chlondalkin (Wieringerwerf, NL)	Transparent	Industrial composting,	

(continued on next page)

Table 3 (*continued*)

Category	Packaging applications	Suppliers	Properties	End of Life Techniques	References
		Penn Packaging (UK)		Recycling & Incineration	
	Boxes	Bunzl (Almere, NL) Moonen Natural (Weert, NL)	Approved for direct food contact	Industrial composting	

B: Belgium, GER: Germany, NL: Netherlands, UK: United Kingdom, USA: United States of America.

characteristics for successfully replacing PP in packaging film applications, bags, and bottles.

5.2.3. Poly, 3-hydroxybutyrate-co-3-hydroxyvalerate (PHBV)

To overcome the demerits of PHB, researchers combined PHB with another hydroalkanoate unit poly-3-hydroxy valerate (PH3V or PHV), resulting in a co-polymer Poly, 3-hydroxybutyrate-co-3-hydroxyvalerate (PHBV) (Luzi et al., 2019). PHBV shows decreased stiffness, increased impact strength, lower crystallinity, and increased elongation at break (Ragaert et al., 2019). This incorporation was expected to result in a very low crystallinity because of the crystal lattice deformation. However, crystallinity decreases slightly due to isodimorphism, a co-crystallization phenomenon (Yeo et al., 2018). PHBV having a low percentage of valerate shows the same nature as that of PHB. At the same time, PHBV with high valerate content is flexible and generally used in film applications.

The incorporation of mica-based clay with PHBV films improves the water, oxygen, and UV barrier property. Carbon nanofiber incorporation with PHBV also results in lower oxygen permeability. However, cellulose fiber with PHBV film acts as a water barrier. Higher PLA concentrations with PHBV contribute to better elasticity modulus, flexural strength, and elongation at break but more difficult to handle (Peelman et al., 2013). Adding graphene nanoparticles into PHBV through the solution casting method increases its tensile strength. Titanium dioxide nanoparticle with PHBV improves thermal stability. However, poly N-vinylpyrrolidone groups grafted in PHBV improve thermal stability by restricting the crystallization process and flexibility of PHBV (Zhao et al., 2020). In a temperature range of 190 °C–230 °C, PHBV-coated paperboards have been documented to handle creasing and heat sealable to paperboard. The incorporation of lignin improved the stability of the PHBV films' thermo-oxidation stability as well as oxygen and carbon dioxide resistance. PHBV with organomodified clay or keratin fiber shows better water and oxygen barrier property (Helanto et al., 2019). Blending PBHV film with poly (butylene adipate-co-terephthalate) and poly (butylene sebacate-co-terephthalate) have better tear resistance, seal ability and water vapor barrier property. PHBV multilayered film with corn zein shows a promising barrier to oxygen (Dhall & Alam, 2020, pp. 26–43). Zinc oxide nanoparticle with PHBV films shows improvement in optical, anti-microbial and thermal properties of PHBV. PHBV consisting of more than 20 mol % of 3HV units can be used to manufacture films and fibers of varying elasticity and can be used in combination with paperboard (coating) for packaging of beverages, dairy and dry food products (Ragaert et al., 2019).

6. Bio-based primitive plastics

Scientists and manufacturers had primarily focused on developing biodegradable and compostable products from renewable biomass. However, the challenges associated with such bio-sourced plastics, like matching durability with the product shelf-life, cost factor, and restricted production volume. Consequently, the demand for cheaper bio-sourced commodities increased. It resulted in bio-based primitive plastic that may not degrade faster but are cheaper and have bio-based origin like Bio-PET and Bio-PE (Storz & Vorlop, 2013). The market data analysis shows that the plastic industries shift their production towards such primitive agro-originated plastics because of the growing market demand for Bio-PET and Bio-PE (Kabasci, 2020, pp. 67–96). Such agro-based polymers are formed by renewable agricultural resources and are identical to conventional petrochemical products (Aeschelmann & Carus, 2015). Since the monomers of such biodegradable plastics are agricultural products rooted and are the same as conventional ones, such plastics are also termed drop-in plastics (replacements) (Alaerts et al., 2018). One of the benefits of drop-in plastics is that such materials can be processed through the same primitive recycling routes (Prieto, 2016).

6.1. Bio-PET polymers

Packaging developed from PET plays an important role and is an inseparable part of our day-to-day life. This is primarily because of its durability and lightweight, which can execute several different functions and safety concerns for consumers. Generally, PET is manufactured by the combination of 70% purified terephthalic acid (PTA) and 30% mono ethylene glycol (MEG) (Bhunia et al., 2013; Volanti et al., 2019). However, the origin of PET from fossil sources had driven researchers from the entire globe to work for its development. Their constant effort in this development had evolved Bio-PET (Alaerts et al., 2018). Bio-based PET is a general term used for the PET polymer, which has a part of its constituent monomers derived from biological sources. MEG, the bio-based constituent of Bio-PET, can be derived through the sugar obtained by the sugar crops such as sugar beet and sugarcane (Siracusa & Blanco, 2020). This bio-originated sugar is converted into ethylene glycol via bioethanol. Bio-MEG is also generated by bagasse, molasses, and hay. Minimal studies report the life cycle assessment of Bio-PET and the effect of its uses on the environment. The study conducted by the Imperial College students shows that Bio-PET utilization led to a 10% decrease in fossil resource utilization and a 25% reduction in CO_2 emission (Robertson, 2012).

This 'drop-in' bio-based plastic is only 30% bio-based, as scientists can derive only one of its building materials, MEG, from renewable plant sources; PTA is still of petroleum origin (Beaucamp et al., 2019). Thus, Bio-PET is environment-friendly up to a mark, i.e., it is partially bio-based PET and is a good replacement of conventional petroleum-based PET. 70% of its building material is still fossil rooted plastics, so it has more dominant conventional PET properties (Collias et al., 2014). Products manufactured from this polymer have a similar weight, qualities, functions, and appearance as regular PET, and hence more precisely, it falls under the non-biodegradable category. It can also be recycled in the same manner and the same industrial plant as conventional petroleum-based PET products. Researchers worldwide are regularly working to develop Bio-PET further and constantly give their effort to make this partial renewable plastics a 100% bio-based PET (Volanti et al., 2019). Various research institutes and industries are evolving bio-based paraxylene, which acts as a base for PTA production (Smith, 2015, pp. 453–469).

Beaucamp et al. (2019) evaluated different lignin blending with Bio-PET and found that fractionated lignin displays higher glass transition temperature, higher hydroxyl groups, and higher ether linkage numbers, increasing Bio-PET miscibility. In comparison, hydroxypropyl modified lignin, where the phenolic groups replaced aliphatic hydroxyl groups, displays a lower degree of interaction with Bio-PET polymer chains, resulting in poor miscibility. Overall, to achieve adequate structural stability, the mechanical properties of these fibers require optimization in pilot facilities. The recycled cotton fiber incorporation with Bio-PET in 3–5 wt % improves the toughness as well as the mechanical and thermal resistance and is a promising rigid food packaging technique (Montava-Jordà et al., 2019). The individual usage of poly (ethylene-n-butylene-acrylate-co-glycidyl methacrylate) and poly (styrene-acrylic-co-glycidyl methacrylate) compatibilizer agent in the blend of PLA/Bio-PET improves the mechanical properties. However, using both compatibilizers jointly in blend decreases the mechanical properties (You et al., 2018).

Bio-PET is used to prepare various products that can be used in food industries. It includes drinking water bottles, soft drinks bottles, tomato ketchup bottles, and soda bottles. Apart from bottles, it is also used in films and containers. All such materials are good alternatives to plastic packaging and are environment-friendly. Since 2011, Bio-PET is gaining popularity at an extraordinary rate because of the growing consumption of bio-based bottles in place of conventional PET bottles. In 2020, Bio-PET production was around 7.80% of the total worldwide bio-based plastics production capacity (European Bio-plastics, 2020). This eco product is well trusted by Coca-Cola, one of the leading manufacturers in drink manufacturing (Sohn et al., 2020). Bio-PET is flourishing well, especially in the markets of American and European continents. Major countries in Bio-PET production are the US and Indonesia, while the largest supplier of Bio-PET is Indorama Ventures PCL, Bangkok (Table 4). 2,5-furan dicarboxylic acid (FDCA) is also biomass-derived chemicals that can substitute various petro-chemical products such as PTA of Bio-PET, PEF, polyesters, polyamides, and polyurethanes. FDCA is used as a bio-based plastic, which reduces greenhouse gas compared to fossil-based plastics. Wang et al. (2020) reported that it improves barrier ability due to the asymmetric rigid structure and the polarity of the furan rings. Its mechanical properties and thermal stability were better than PET. Due to its chemical structure and properties, FDCA has great potential to be used as bio-based plastic in food packaging (Wang et al., 2018).

6.2. Bio-PE polymers

Regarding production capacity per year and worldwide utilization, PE is the most crucial conventional petrochemical product. It has a wide area of use, especially in the construction and packaging industries. The data from plastic production industries can justify that PE production represents around 30% of the total plastic produced annually (Kabasci, 2020, pp. 67–96). Conventionally, these commercial PE polymers are formed by ethylene monomer through radical polymerization. The petrochemical base of this product had increased its production, and improper disposal and littering patterns adversely affected society and the environment. This promotes researches to focus on its bio-based version, i.e., Bio-PE (Hahladakis et al., 2020, pp. 481–512). Bio-PE, also referred to as renewable polyethylene, is the polyethylene that results from bio-based ethylene polymerization. This ethylene monomer is prepared out of bioethanol after a dehydration process (Bedia et al., 2011). Bio-based PE can be produced by the utilization of existing conventional polymerization reactors. The feedstock for the production of Bio-PE primarily includes sugarcane and sugar beet. However, sometimes wheat grains can also be utilized as raw stuff for Bio-PE production. Its carbon footprint can justify the aspects of its environmental benefits. Life cycle assessment data for this green PE shows that

Table 4
Commercial applications of Bio-based primitive plastics.

Category	Packaging applications	Suppliers	Properties	End of Life Techniques	References
Bio-PET Polymers					(Alaerts et al., 2018; Hahladakis et al., 2020, pp. 481–512; Molenveld et al., 2015; Narancic et al., 2020; van den Oever et al., 2017; Zhao et al., 2020)
Fruit and Vegetables	Trays	Toyota Tsusho Europe (Düsseldorf, GER)	Approved for direct food contact	Recycling	
Soft drinks	Bottles	Coca-Cola Toyota Tsusho Europe (Düsseldorf, GER)	Approved for direct food contact, Transparent	Recycling	
Water	Bottles	Dasani (USA) Toyota Tsusho Europe (Düsseldorf, GER)	Approved for direct food contact, Transparent	Recycling	
Sauces	Bottles	Heinz Toyota Tsusho Europe (Düsseldorf, GER)	Approved for direct food contact, Barrier for oxygen	Recycling	
Beer and Wine	Glass bottles	Biofutura (Rotterdam, NL)	Transparent, Barrier for oxygen, Coatable with glass.	Recycling	
Bio-PE Polymers					
Milk and Dairy produce	Bottles Caps	Danone (UK) Nestle (Brazil) Tetra Pak (Switzerland)	Approved for direct food contact	Recycling	
Fruit juice	Bottles	Odwalla (USA)	Approved for direct food contact	Recycling	
Bread	Bags	Amcor Flexibles (Australia) Hovis (UK) Oerlemans (Genderen, NL)	Approved for direct food contact	Recycling	
Sauces	Pouches	Gualapack (Italy)	Approved for direct food contact, Barrier for oxygen, Transparent	Incineration	
Others	Stretch film	FKuR (Willich, GER) Polythene (UK)	Approved for direct food contact	Recycling	
	Crates	FKuR (Willich, GER) Schoeller Allibert (GER)	Approved for direct food contact	Recycling	
	Carrier bags	Papier-Mettler (GER)	Approved for direct food contact	Recycling	

GER: Germany, NL: Netherlands, UK: United Kingdom, USA: United States of America.

on a net basis, there is roughly a sequestration of about 2.5 tons of CO_2 per unit ton of Bio-PE production instead of CO_2 emission; hence it helps in the reduction of the considerable amount of GHG emission (Kabasci, 2020, pp. 67–96).

Similar to Bio-PET, it is also a 'drop-in' bio-based polymer, but unlike that, it has 100% bio-based content. One of the facts concerning the fabrication of this bio-based plastics is that it is not a newer concept. Its production in Brazil and India was already in existence in the 1960s and 1970s (Storz & Vorlop, 2013). But, due to the low cost of petroleum products at that time, this technology remained unproductive. Despite awareness regarding the demerits of conventional petrochemical products, this bio-origin product faced difficulties regarding its penetration in society due to economic factors. In the first decade of the 21st century, this technology got attention again due to awareness regarding demerits of older non-renewable petroleum products (Morschbacker, 2009). Although having an origin from agricultural sources, this renewable Bio-PE is non-biodegradable, just like the traditional one (Licciardello & Piergiovanni, 2020, pp. 191–222). It can be recycled by the same methods and in the same waste streams due to identical chemical properties. Bio-PE has identical physicochemical properties with PE and has successfully made its way to packaging films and dairy packaging. However, more focused studies are required for biodegradation and improvement in the properties of the material.

A blend of Bio-PE and PLA was suggested to improve its properties. However, copolymers of ethylene-glycidyl methacrylate and ethylene-methyl acrylate-glycidyl methacrylate are used as compatibilizer agents in the blend of PLA/Bio-PE, which improves the mechanical properties along with morphology modification (Brito et al., 2016). Blend of Bio-poly (trimethylene terephthalate) and Bio-HDPE copolymer gives a decent balance between toughness and stiffness (Enriquez et al., 2016). Bio-PE blended with lignocellulosic curaua fibers, wood flour, kenaf chopper fibers, ultrafine cellulose powder and micro particles of mineral tuff filler upsurge mechanical strength. However, tuff micro particles and fine cellulose micro particles demonstrated greater break elongation and lower water absorption (Castro et al., 2012; Kuciel et al., 2014).

Due to the excellent moisture barrier properties of Bio-PE, it is successfully replacing the most widely used petrochemical packaging material made up of PE for the same purpose. Also, it has been utilized for the replacement of current PE films and PE bottles. Similarly, shrink films and bio-based stretch films can also be manufactured by Bio-PE. In 2020, Bio-PE production was around 10.50% of the global production volumes of bio-based plastics (European Bio-plastics, 2020). At present many companies are producing such green films. Danone Actimal bottles made up of Bio-PE are already in existence which can be recycled successfully in the same primitive petrochemical plant. The bottle cap made up of renewable PE replaces the conventional, and companies also produce drinks crates (Table 4). Carrier bags made up of Bio-PE are now available on various retail counters. Also, paper carrier bags are in practice as a pure bio-based alternative to polyethylene bags. Unfortunately, as stated earlier, such Bio-PE materials have an issue with their end-of-life phase. Such films and bags cannot be composted along with the vegetable residues. (Molenveld et al., 2015).

7. Biodegradability of bio-sourced plastics

The biodegradability of any material refers to material degradation by the action of naturally occurring microorganisms such as bacteria, fungi, and algae (ASTM- D883). Biodegradation of polymers depends on various factors like environmental conditions (temperature, moisture, pH, etc.), the chemical structure of the compound, chemical bonding, microbes, etc. It takes few days to a year or more. The packaging material produced by bio-sourced are not necessarily biodegradable in normal condition and most of the renewable biomass sources derived polymers are degradable in special conditions. Starch is biodegraded in the natural environment (soil and water) as well as in industrial composting (Karan et al., 2019). Whereas, in aerobic biodegradation medium, starch shows about 60% degradation rate in only 10 days. When cassava starch with yerba mate blend is subjected to the vegetal compost medium, degradation occurs in 6–12 days. The swelling capacity of this blend is 1.6 in acidic treatment conditions and about 1.9–2.2 in alkaline stability treatment (Chisenga et al., 2020). Pure cellulose and its derivative cellulose acetate generally show lower biodegradability in the natural environment (soil and water) and industrial composting, which can be improved through blending (Karan et al., 2019). However, cellophane biodegrades easily rather it falls under the compostable tag.

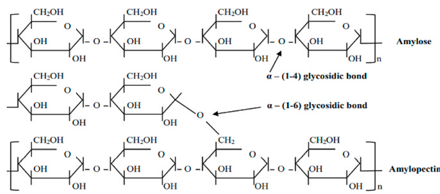
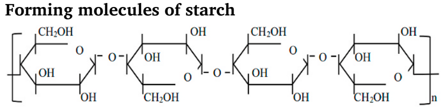
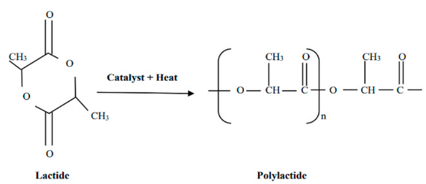
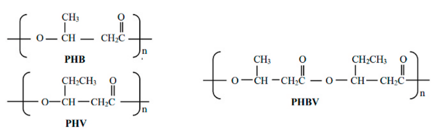
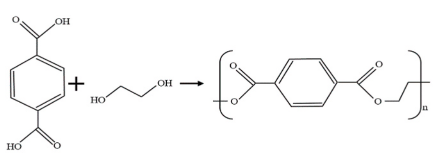
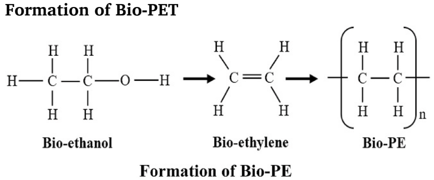
PLA is not biodegradable in a normal open environment and it shows a restricted degradation in domestic composting and at ambient temperatures in the soil. PLA requires incineration or industrial composting at 55–60 °C due to its high glass transition temperature and melting point for complete degradation (Nilsen-Nygaard et al., 2021). It is also not compatible with water (Karan et al., 2019). However, some natural fibers, like kenaf and abaca, enhance its degradation if added with PLA composites (Kershaw, 2018). PLA in hydrolytic degradation medium at pH 10 losses its mass as the function of immersion time and shows complete degradation in 288 h. However, PLA films with carvacrol essential oil demonstrate faster kinetics of hydrolytic reactions when compared to PLA in a hydrolytic degradation medium (Chisenga et al., 2020). PHA and its bio-composites are becoming popular as a substitute for conventional plastics because of their physicochemical similarities to traditional plastics and their biodegradability in soil, industrial composting, marine environment, aerobic and anaerobic conditions (Karan et al., 2019; Nilsen-Nygaard et al., 2021). PHAs can be used in composites matrix, where agro-byproducts and bio-based fillers are added to reduce the cost and improve the material's performance. Bio-based fillers like starch and protein enhance the soil and marine biodegradability rate as compared to other fillers. It often offers a carbon-neutral strategy and encourages creating a more environmentally friendly packaging system (Meereboer et al., 2020).

Bio-based primitive drop-in plastics have no difference from their petroleum-derived counterparts and are non-biodegradable in water, soil and not even in the industrial composting environment (Beaucamp et al., 2019; Karan et al., 2019). These can be returned to the circular economy through recycling in the same recycling stream as conventional one and decreasing the carbon footprint. Glycolysis can be used to recycle Bio-PET since it also produces a value-added component (Lambert et al., 2020). The products created by combining recycled cotton fiber and Bio-PET can be a sustainable and cost-effective alternative for the rigid packaging industry with a smaller carbon footprint and at affordable costs (Montava-Jordà et al., 2019). However, recent research by Salvador et al. (2019) recognized Bio-PET microbial degradation caused by the microbial polyester hydrolase effect, a critical alternative for recycling Bio-PET. Natural fillers like wood flour, kenaf chopped fibers, ultrafine cellulose powder and mineral tuff filler microparticles, when combined with Bio-PE, produce lightweight, environment-friendly materials at a relatively low cost (Kuciel et al., 2014). Since Bio-PE is highly resistant to solvents, it can only be recycled by pyrolysis. Both Bio-PET and Bio-PE lose their mechanical properties after certain recycling. Once the polymers have degraded to the point that these cannot be recycled, the monomers can be chemically recovered and re-polymerized, resulting in a circular manufacturing economy (Lambert et al., 2020). An overview of all such possible alternatives to petrochemical-based plastic packaging to be used in food industries with their general properties is shown in Table 5.

8. Challenges of bio-sourced plastics

One could believe that bio-sourced polymers are the new evolution, but the same has been used 3500 years ago in the earliest times of man. Olmec, the first major civilization of Mexico, uses naturally arising plastics fluid from gum trees to produce rubber balls for their children to

Table 5
Overview of bio-sourced plastics: Alternatives to conventional food packaging.

Bio-sourced Polymers		Chemical structures	Possible substitutes	Raw materials	General properties	Current status
Natural biopolymers	Starch-based polymers	 **Forming molecules of starch**	PS	Potato, rice, corn, cassava, tapioca, starch from potato, wheat, barley, oats and soy sources	• Good thermoplastic behaviour • Rigid in nature • Elastic in nature • Good gas barrier property • Biocompatible	• In 2020, starch and its blend based polymers were increased to 18.70% of the world-wide production volumes of bio-sourced plastics from 10% as in 2014.x'
	Cellulose-based polymers	 **Structure of cellulose**	LDPE, HDPE, PS, and PP	Fiber, herbaceous crops, cotton or wood pulp, and wood chips	• Good thermostable property • Biocompatible • Rigid	• Limited market share in packaging application due to its poor solubility characteristics, bad processing, poor moisture barrier properties, brittleness, poor mechanical properties, and high production costs.
Bio-based polyesters	PLA polymers	 **Conversion of PLA**	PS, LDPE, PET, and HDPE	Maize, wheat, cassava, corn starch, sugar crops like sugarcane, bagasse, wheat straw, corn stover, wood chips, as well as methane fermentation from PLA waste	• Good thermoplastic behaviour • UV resistant • Good gas barrier property • Biocompatible • Rigid in nature • Elastic in nature • Hydrophobic in nature	• Regarding consumption volume, PLA stood at second position amongst all important bio-sourced plastics in 2010. • In 2014, PLA production capacity was 0.2 million tons representing 10% of the global production capacities at that time. • Also, in 2019 PLA polymer was 13.90% of the world-wide production volume of bio-sourced plastics, which further increase to 18.70% in 2020.
	PHA polymers	 **Different form of PHA**	PE and PP	Sunflower, olive, soy, rapeseed, sugar cane, and palm oil residues	• Good thermoplastic behaviour • UV resistant • Good gas barrier property • Biocompatible • Rigid in nature • Elastic in nature • Hydrophobic in nature	• In 2019, PHAs polymers were only 0.025 million tons representing 1.20% of the world-wide production volumes of bio-sourced plastics. • However, it has experienced the second most emerging market share and touched about 1.70% production capacity by the end of 2020.
Bio-based primitive plastics	Bio-PET polymers	 **Formation of Bio-PET**	PET	Sugarcane, sugar beet, bagasse, molasses, and hay	•Durable • Transparent	• In 2020, Bio-PET production was around 7.80% of the total worldwide bio-sourced plastics production capacity.
	Bio-PE polymers	 **Formation of Bio-PE**	PE	Sugarcane and sugar beet	• Good thermoplastic behaviour • Good gas barrier property • Biocompatible • Rigid in nature • Elastic in nature • Hydrophobic in nature	• In 2020, Bio-PE production was around 10.50% of the global production volumes of bio-sourced plastics.

play (Kohjiya & Ikeda, 2014). Usage of latex ball by Mayan Pelote players is also an example (Rujnić-Sokele & Pilipović, 2017). From the ancient period, man has been utilizing renewable biomass to meet his needs. But, after introducing petroleum-based plastics, such bio-sourced plastics were neglected primarily due to the cost factor and not matching the level of durability as that of the conventional one. Again this modern bio-sourced plastic grew up somewhere 30 years ago and developed very dynamically only after society became aware of the ill effects of conventional plastics and increased petroleum prices (Storz & Vorlop, 2013). However, today, such modern plastics are too expensive due to the lower production yield and outdated technology. Most raw stuff for manufacturing such plastics is still the first-generation feedstock like corn, wheat, potato, sugarcane, etc. As the population grows daily and simultaneously, the demand for food increases, competition among the food and bio-sourced monomer production is also increasing. Researchers focused on utilizing agricultural, food industry residue, and lignocellulose biomass as raw materials for bio-sourced plastics production (Briassoulis et al., 2020; FitzPatrick et al., 2010). Second-generation feedstocks are an alternative, but some critical issues need to be addressed, such as producing successful lignocellulose pretreatment, hydrolysis, and advancement in the downstream technology (Djukić-Vuković et al., 2019; Klein-Marcuschamer et al., 2010).

With the shifting from petrochemical plastic, confusion regarding the word bio-sourced plastic is also arising. There is still an incorrect belief that all bio-sourced polymers are biodegradable (Mendes & Pedersen, 2021). It is important to understand the difference between bio-sourced plastics and biodegradable plastics. Biomass is utilized as the feedstock instead of the crude oil for bio-sourced plastics, whereas biodegradable plastics were produced from the biodegradability point of view (Iwata, 2015; Karan et al., 2019; Lambert & Wagner, 2017). The biodegradability of plastics does not depend on the feedstock used in its generation. Instead of that, it depends on the composition of the produced material and the environment required for its degradation. Additionally, some plastics may degrade in just a few hours, while others take months to degrade in the same atmosphere (Briassoulis et al., 2020; Dhall & Alam, 2020, pp. 26–43; Kabasci, 2020, pp. 67–96). The quality of biodegradable substances would mostly decide the correct end-of-life management method. From the environmental aspects, the most suitable final solution for biodegradable plastics is the process of composting. However, the process condition should be controlled strictly to get a desirable result (Briassoulis & Dejean, 2010; Gironi & Piemonte, 2011). Compostable plastics should be obtained via a separate recycling scheme and taken to a commercial composting plant; none is currently available in most countries.

Another solution for managing such modern plastics is recycling. However, the feedback from the recycling industries highlights that there is the presence of undesirable parts in reprocessed products, which affects the technological characteristics like durability, toughness, strength, etc., of the end product. Therefore, separation, sorting, and grading are crucial in producing quality end materials (Rujnić-Sokele & Pilipović, 2017). Since both the conventional and modern plastics have identical densities, mechanical separation does not work up to the mark. The waste separation optical systems cannot categorize such plastics. Although some tools and equipment like near-infrared spectroscopy are introduced to separate plastic waste automatically, but such devices pose major economic and technical obstacles at the moment (Havstad, 2020, pp. 97–129; Rani et al., 2019). Finally, multi-layer bio-sourced polymer laminates are needed for most food packaging applications to boost barrier properties, which further compromises the recyclability of the scrap (Kaiser et al., 2018). Thus, the most crucial challenge in the upcoming days is introducing new tools, processing methods, and marketing techniques for the overall benefits of society.

9. Future scope

Bio-sourced food packaging alternatives have significant demand in the market, but it is a challenge to make such materials commercially viable. Due to the unreliable nature of bio-sourced plastic, there is a need for developing a multilayer blend using additives. Further, there is a need for second-generation feedstock utilization or making third-generation feedstock (biomass from algae) effective for usage. On the other side, balancing is needed between biodegradation and recycling of these plastics. Also, modernizations, commercialization, technology transfer, etc., on bio-sourced plastic would revolutionize the packaging industry to tackle large-scale industrial production and its applications through academic partnerships.

10. Conclusions

When it comes to food packaging, plastic is the most desirable item due to its fabulous properties, which can fit every packaging aspect. But, the complexity in handling the plastics waste had forced to work in the area of its novel alternative bio-sourced plastics. Since the feedstocks and the production routes of such bio-sourced plastics vary greatly, their utilization in food packaging is also multiple. Bio-sourced plastic packaging material has an immense potential to be used in the food packaging industry. On the other hand, the second version of bio-sourced plastics, i.e., biodegradable plastic, is also satisfactorily dealing with human health and environmental problems caused by plastic waste generated from food packages. There is no question that both bio-sourced and biodegradable plastics will play a vital role in the future. However, there are still a few problems to be addressed, such as its high cost, land availability to produce raw materials, durability level, material performance compared to petrochemical-rooted plastics. Continuous research and developments are required to take complete advantage of biodegradable plastics for socio-economic benefits. It will be on the upcoming scientists to cope with such problems and mold a bright future for bio-source plastics by producing the necessary resources.

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Declaration of competing for interest

The authors declare no conflict of interest.

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