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Beyond Plastics: Exploring Eco-Friendly Alternatives in Food Packaging - A Review of Both Biodegradable and Bio-based Bioplastic Materials.

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Abstract— Due to the increased levels of environmental degradation arising from conventional plastics, rise of appropriate interventions, especially in the food packaging industry. Covering the basics of conventional plastics, their usage, and potential harm, one must turn their attention to bioplastics. Bioplastics made from renewable sources like starch, cellulose, polylactic acid (PLA), and proteins. This review provides detailed coverage of the bio-based polymers and bioplastics such as synthetic bioplastics, polybutylene adipate terephthalate (PBAT), PLA, polyhydroxyalkanoate (PHA), polyvinyl alcohol (PVOH), polycaprolactone (PCL), and starch-based bioplastics, cellulose-based bioplastics, and protein-based bioplastics. This allows one understand the various characteristics they possess and how effective they could be when used in food packaging. Effects on the environment, effectiveness on the economy, biodegradable ability of the product, and its effects on the environment at different stages of life, regulatory boundaries, and safety measures are assessed. However; the bioplastics are present some difficulties in attaining the required mechanical and barrier properties, degradation of the biodegradable polymers, and limitations in processing. Moreover, correlates that affect the acceptance of the products by consumers and the position of the role of regulatory frameworks in the use of bioplastics are presented. According to the review made, it is found out that bioplastics if promoted in the right way have a high potential to be used as sustainable food packaging material; however, more research needs to be done, the policies should be more supportive and the consumers need to be sensitized in order to bring more improvement in the use of bioplastics.

Keywords— biodegradable; bioplastic; biopolymer; food packaging; mechanical properties; Polymer; sustainability

1 INTRODUCTION

Plastic waste is becoming a major environmental threat globally [1]. Carbon emissions from plastics disposed in landfills are estimated at 253 g CO_2 per kg of plastics [2], [3], while emissions from plastic waste when burned range between 673 g to 4605 g CO_2 per kg [4]. Another reason is that those cremations use greenhouses gases and therefore, lead to global warming. It is indicated that even after a century, the amount of degradation of polythene is as low as half a percent. The long periods of degradation and detrimental impacts on terrestrial and marine ecosystems of conventional plastic materials, which are mostly generated from non-renewable fossil fuels, make them a chronic source of pollution in the environment [5]. The plastics-heavy food packaging sector is under growing pressure to switch to more environmentally friendly and sustainable options [4], [6], [7].

Bioplastics are plastic products that are made from renewable biomass feedstocks like starch, cellulose or polylactic acid and are therefore, being studied as a potential to reduce the problems associated with conventional plastics [8]. These materials hold several benefits, including low levels of carbon emission when used compared to conventional materials [9], degradability, and capability to reduce reliance on fossil resources. Therefore, increased awareness regarding bioplastics is likely to make it a suitable solution for applications in food packaging [10].

However, in light of recent developments in the issue of bioplastic materials with regards to food packaging, this review seeks to offer an extensive update on the topic. The different categories of bioplastics that we will examine include synthetic bioplastics (PBS, PLA, PHA, PVOH, PCL), starch base bioplastics, cellulose base bioplastics, and protein base bioplastics, which will cover the methods of making bioplastics [8], [11], the properties and the capability of using these kinds of plastics as food packaging materials. Furthermore, the review will consider the courses and behaviors of the mentioned materials such as the barrier properties, mechanical strengths, and how they tend to behave with food items [12].

Other factors such as environmental and economic impacts will be investigated to determine the sustainability of food packaging that employs bioplastics. Bio-degradability and comparative assessments with conventional plastics, as well as life cycle assessments of the product, will be evaluated [13]. Moreover, the review will focus on some aspects such as the regulation and safety, and concern the frameworks that control the bioplastics in direct relationship with food contact applications.

Although bioplastics have vast potentiality and actuality, there exist some issues that need to be solved including technical problems related to bioplastic production (limited resources, high cost, material properties, etc.) [14] the performance of bioplastics under various conditions, and accepting the idea of bioplastic usage among the consumers [15]. This review shall describe these challenges and in the subsequent sections discuss future developments to improve the life cycle of bioplastic food packaging and make the options more popular.

Bioplastics are divided into three groups such as Bio-based, Biodegradable, and both of Bio-based and Biodegradable as shown in Fig. 01. Bio-based plastic does not necessarily show biodegradability and biodegradable plastic does not show necessarily show bio-based origin. Therefore bio-based and biodegradable bioplastics are not the same. Because some bioplastics are bio-based but not biodegradable (bio-PE: monomers are produced from corn but it not biodegraded) [16].

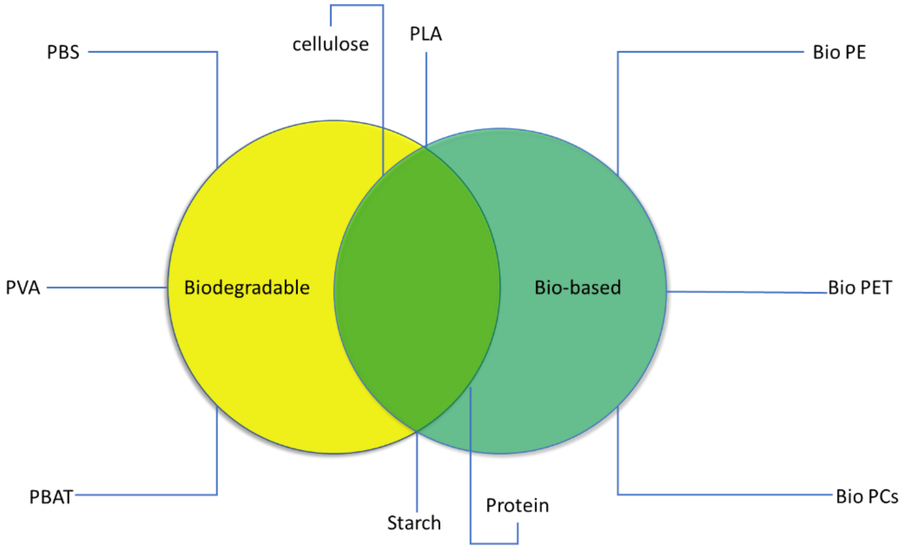

Fig. 01: The classification of Bioplastics, bio-based plastics, biodegradable plastics and, both bio-based and biodegradable plastic.

In order to achieve this goal, this review discusses the development of both bio-based and biodegradable bioplastic materials (Starch, Protein, PLA, Cellulose) used in food packaging, their applications in food industries in current society, as well as the future developments of this research field. Thus, we envision ourselves being able to contribute to the ongoing continuation of the discussion related to more sustainable forms of packaging for the food industry in particular and to the improvement of the current situation in this sphere in general.

2.TYPES OF BOTH BIO-BASED AND BIODEGRADABLE BIOPLASTIC MATERIALS

These are divided by their source and most importantly their biodegradation characteristic. Bio based bioplastics are obtained from renewable sources of biological origin similarly biodegradable bioplastics dissolve naturally in the environmental surroundings. What’s more, some bioplastics are categorized both as bio-based and biodegradable bioplastics. However, bioplastics that satisfy all these conditions are of different types as further discussed below with regards to their production process, properties and uses, strengths, and weaknesses.

2.1 Cellulous

Cellulose is a polydisperse linear homopolymer composed of D-glucopyranose units linked with a β-1,4-glycosidic bond, including free hydroxyl groups (-OH) at the C-2, C-3, and C-6 atoms. Based on the -OH groups and the oxygen atoms of both the pyranose ring and the glycosidic bond, ordered hydrogen bond networks can be formed (Fig. 02) [12].

Cellulose, a natural polymer found in all plants, is one of the most abundant materials on the Earth and has a great potential to be used in developing new materials. Available in large quantities, cellulose is renewable and biodegradable as well as cheap[17]. And also, harmless, green, non-toxic, non-neocarcinogenic, nonbioaccumulative, and thermally[18]. Thus, it becomes chemically stable and derivable. This is very rich in fruit and vegetable waste and indeed it contains a higher yield of Carbon Dioxide than compost prepared from other materials[19]. The valuable biopolymer among the two primary categories of cellulose derivatives, it is the cellulose ester and cellulose ether that has the most demand in industrial application in the production of pure cellulose bioplastics which is still rather challenging as far as melting and overall structural complexity of metals are concerned. It can be dissolved in accordance with standard practices. Mechanical properties, thermal stability, that is, biopolymers' flexible characteristics such as tensile strength, elongation at break, and water absorption are some of the properties that could be enhanced with the addition of cellulose[12].

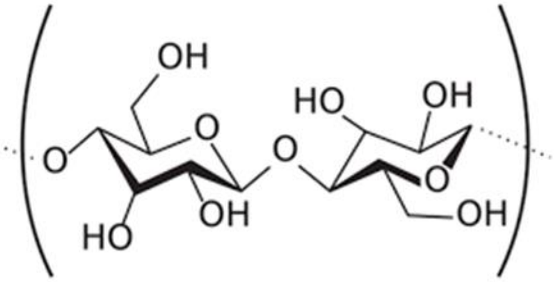

Fig. 02: Chemical structure of cellulose [20]

2.1.1 Characteristics and performance in packaging

Cellulose and its derivatives have been tested for packaging applications[21]. Cellulose composites showed excellent mechanical properties, reinforcing capabilities, biodegradability, and availability[22]. For instance, Carrillo et al. prepared the cellulose lyocell fiber/cellulose acetate butyrate composite[23]. They displayed increased tensile properties, dimensional stability, fiber and matrix compatibility, and biodegradability[6], [23]. Carboxymethyl cellulose (CMC) based films fabricated by incorporating bioactive Chinese chives root extract (CRE) showed higher oil resistance properties in addition to the improved physical and barrier properties, antioxidant and antimicrobial activity (against B. cereus, S. aureus, E. coli, and S. Typhimurium), which is desirable for packaging of oil products[21]. Peptidopolysaccharide developed using 2,3-dialdehyde cellulose and antimicrobial nisin peptide showed improved mechanical properties, lower water-holding capacity, and excellent antimicrobial activity against S. aureus and E. coli. This active film also showed an extended shelf life of fresh pork meat stored at 4°C for 6 days. In another study, antimicrobial packaging film was prepared using cellulose acetate butyrate/organically modified montmorillonite (OMMT) incorporated with carvacrol and cinnamaldehyde[24]. The properties and applications of the films are presented in Table 1.

Table 1. Mechanical properties and applications of cellulose-based bioplastics

Types of cellulose	properties	Packaging applications	Ref.
Carboxymethyl cellulose (CMC)/Chinese chives root extract (CRE)	Higher oil resistance properties, improved physical and barrier properties, antioxidant and antimicrobial activity against both Gram-positive (*B. cereus* and *S. aureus*) and Gram-negative (*E. coli* and *S. typhimurium*)	Active packaging for sunflower oil	[25]
A 2,2,6,6-tetramethyl piperidine-1- oxy radical (TEMPO)-oxidized	Flexible and highly transparent, higher YM[1] (about 10 GPa) and lower elongation (about 5.1%) than those of the TOCN-COONa, lower	Biodegradable packaging	[26]

cellulose nanofibrils with free carboxyl groups (TOCN-COOH) prepared from the softwood celluloses	oxygen permeability (0.049mL μmm−2 day−1kPa−1) than poly (ethylene terephthalate) films.		
2,3-dialdehyde cellulose/nicin	Improved mechanical property, lower water holding capacity, WVP[2], and oxygen permeability, Excellent antimicrobial activity against *S. aureus* and *E. coli.*	Antimicrobial packaging for fresh pork meat at 4°C.	[27]
TEMPO-oxidized cellulose nanofibers (TOCN) prepared from the softwood and hardwood celluloses	Higher TS (about 200%) and YM (about 100%) than cellophane film. PLA film surface-coated with TOCN showed reduced oxygen permeability.	High-tech food and Medicinal packaging material	[28]
Hydroxyethyl cellulose, carboxymethyl chitosan and zinc oxide NPs	Exhibited lower water solubility and improved elasticity, thermal stability, UV shielding ability, antibacterial ability against Listeria monocytogenes and Pseudomonas aeruginosa, and improved crystallinity.	Composite film for food packaging	[29]
Chitosan/bacterial cellulose composite with curcumin	Excellent barrier properties, hydrophobicity, mechanical, and antioxidant properties.	Biodegradable food packaging for strawberry and edible oil.	[30]
Cellulose acetate films with geranyl acetate (0.5% v/v and 1.0% v/v)	Antimicrobial activity against bacteria, *Staphylococcus aureus* and *Escherichia coli* and against fungi *Aspergillus flavus*.	Food packaging	

[1] Young's modulus – YM; [2] Water Vapour Permeability-WVP

2.1.2 Environmental impact and biodegradability

Cellulose is derived from plants, making it a renewable source. Unlike fossil-based plastics. Therefore cellulose-based plastic does not deplete non-renewable resources[12]. Bioplastic generally has a lower carbon footprint than fossil-based plastics, because the use of renewable resources[7]. And also, cellulose base bioplastics are free from toxic additives and plasticizers. Therefore, it safer both human health and the environment[31].

In controlled conditions, cellulose-based bioplastics can biodegrade within a few weeks to months[32]. Biodegradation of cellulose-based bioplastics takes place mainly through the action of microbial which includes bacteria, fungi and other microbes that secrete enzymes that break down cellulose into water, carbon dioxide biomasses[32], [33]. This phase needs to take place under conditions such as the right temperature, correct moisture levels, or right microbial activity in the substrates[33]. The optimal conditions are regulated by industrial composting facilities to ensure that biodegradation takes place at a fast pace but not past the required time. However, in natural conditions of their existence, for example, in loamy ground or in sea conditions their maintenance can be different considerably, and, therefore, degradation processes occur at different rates and, as a rule, slower. Hence, even though cellulose-based bioplastics yield several benefits of the environment in which they are discarded controls their biodegradation effectiveness[34].

2.2 Starch

Starch is one of the least expensive biomaterials. Cereals and legumes, such as wheat, rice, barley, oat, corn, beans, and soy, are also significant sources[35]. It is also abundant, biodegradable, and renewable, and its possibility of blending with conventional polymers has garnered wide interest in the bioplastic market[36]. Starch-based bioplastics are mixtures of amylose/amylopectin ratios[36], depending on their botanic origin Starch may have many weaknesses, and plasticizers help maintain their chemical and physical robustness. Since bioplastic's biodegradability is faster than petroleum-based plastics, their life long has been questioned many times. They can be an excellent choice for degradation, but wearing them for a long time is not recommended[37].

The general chemical formula for starch (representing both amylose and amylopectin) is $(C_6H_{10}O_5)n$, where 'n' is the number of repeating glucose units (Fig. 03). The ratio of amylose to amylopectin varies depending on the source of the starch, affecting its physical and chemical properties.

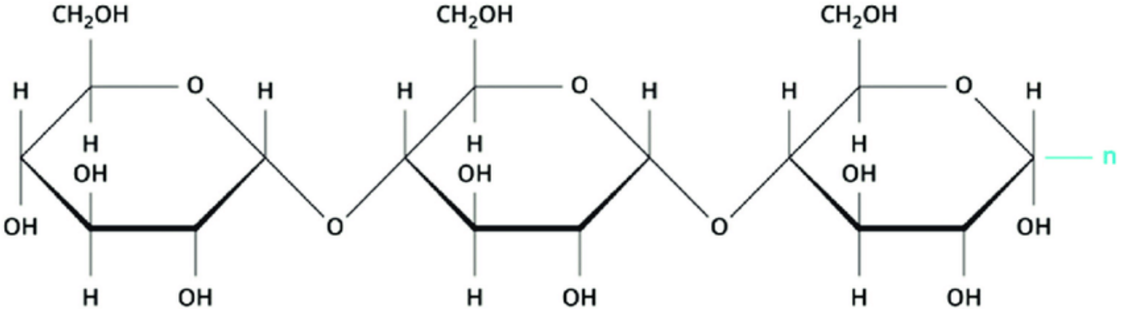

Fig. 03: Chemical structure of starch [38]

2.2.1 functional properties

The fundamental starch structure is amorphous, consisting of amylose and an inter-crystalline zone of dense cross-branched amylopectin. Such morphology is responsible for the thermal, plasticization, and rheological properties of the starch[39]. In native starch, amylopectin chain length and chain ramification determine the granule crystallinity[39]. Starch components along with lipids (amylopectin, amylose) are radially oriented towards the surface of starch. The native structure of starch is not suitable for industrial applications, because of its brittle nature and poor mechanical and rheological properties[13], [40].

Plasticizers are substrates with low molecular weight which when introduced into the starch matrices, can enhance the flexibility and processability of polymeric compounds by decreasing the hydrogen bonding of the starch-starch molecules[41]. Plasticizers on the other hand can influence the physical properties of the processed starch by controlling its collapsing rate and depolymerization[39]. The properties and applications of the films are presented in Table 2.

Table 2. Mechanical properties and applications of starch-based bioplastics

Types of starch	properties	Packaging application	Ref
Starch/PBS	Excellent elongation at brake, Outstanding bending capability	Food wrap and food containers, grocery bags	[42]

	(flexural modulus 378.69- 3188.48 MPa), good tensile properties (tensile strength 11.32 - 18.13 MPa, Young's/tensile modulus 534.77- 2655.27 MPa)		
thermoplastic starch (TPS)	Adding starch at 15% yielded good mechanical properties, (ultimate Tensile strength = 12.1 MPa, Elongation @brake % = 250%), starch decreased the gloss%	Food packaging	[43]
Thermoplastic PVA/starch blend (TPPS)	glycerol and urea as a complex plasticizer for TPPS increased Tensile strength (7.83 MPa) and Elongation @brake (203%).	Biodegradable polymer to replace starch polymers.	[44]
Cassava starch/glycerol/clay nanoparticles (NPs)	lower glycerol content presented better tensile and barrier properties, and clay NPs diminished the film permeability	Biodegradable and cheaper food packaging	[45]
Starch/clay (montmorillonite) NPs	Increase of mechanical parameters (stress at peak = 6-22 MPa and Youngs modulus = 450 -1135 MPa)	Edible packaging	[46]
Carboxymethyl potato starch and citric acid (CA) (as a crosslinker and plasticizer)	The highest tensile strength (160 kPa), Young modulus (650 kPa), and improved thermal stability (increased Tg[1] 58 °C) were reported with CA[2] at 30 wt%.	Edible packaging	[47]

[1] glass transition temperature – Tg; [2] starch and citric acid – CA;

2.2.2 Suitability for food packaging

Starch is derived from renewable resources like corn, potatoes, and other crops, making it a sustainable option[48]. Starch-based bioplastics are compostable and degrade naturally therefore reducing the environmental impact compared to conventional plastics[31].

However, starch-based plastics are brittle and therefore hydrophilic, limiting their processing and application and leading to problems such as lack of water barrier, and poor mechanism properties[49]. Therefore, it cannot be used directly as packaging material[13], [50]. Despite the limitations, starch-based bioplastic is the best option for food packaging because of its unique characteristics[51].

2.3 protein

Based on the raw materials, the protein bioplastics can be classified in two groups: plant protein biopolymers and animal-derived protein biopolymers[52]. Food plant proteins include wheat gluten and proteins derived from soy, pea, corn zein, and cotton seed[53], [54]. Sometimes they include whey, casein, collagen, gelatin and keratin and others are of animal origin[55], [56]. Since proteins are made from different types of amino acids, these strong intermolecular forces of proteins come up with positive functional changes in protein-based bioplastics in as far as their performance is better than that of carbohydrates and lipids[4], [57]. Despite the fact that they are not very robust, they are thousands of times cheaper than synthetic films and possess an extraordinary number of advantages, such as richness in proteins, non-ecotoxicity, biodegradability, and high film-forming ability[55].The bond formed between the carboxyl group of one amino acid and the amino group of another (Fig. 04).

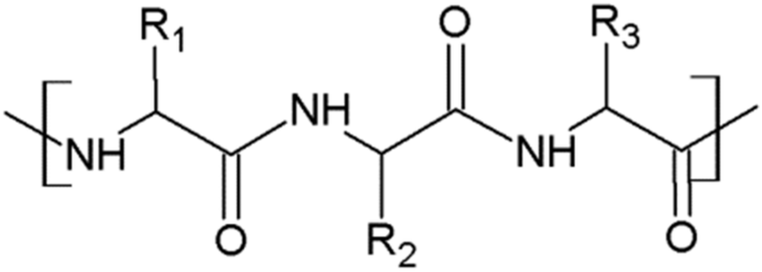

Fig. 04: Chemical structure of protein [58]

2.3.1 Characterization of Protein-Based Bioplastics

For any material to be used in an end-product, it has to fulfill certain requirements, depending on the intended application. Among these requirements, specific values for the mechanical, thermal and/or optical properties may desired and this suggests the onset of the characterization of these aspects through various experimental methods. The analytical methods are based on the physical characteristics and for made measurements there are use physical quantities of macroscopic parameters analysis can be comparable with microscopic or molecular structure of the evaluated materials[59], [60], [61]. The properties and applications of the films are presented in Table 3.

Table 3. Mechanical properties and applications of protein-based bioplastics

Types of proteins	properties	Packaging application	ref
Canola protein	plasticized by glycerol had TS[1] between 1.19 to 4.31 MPa and E of 41.9% to 287.4%, plasticized by sorbitol had TS of 1.60 to 3.30 MPa and E[2] of 12% to 21%, Tg of CPI-based film containing 30% glycerol (wt %) -52.7°C.		[62], [63], [64]
Soy protein	low water resistance, good optical transmittance of the SPI film (98.90±0.58%), SPI film showed the lowest water solubility (27.37±0.73), SPI film[3] TS is (4.093±0.531)		[65]
Wheat gluten protein	present good barrier properties for oxygen and carbon dioxide, generally not water-soluble, s adhesiveness and cohesiveness	non-food applications, such as films, plastics, and adhesives	[61]
Corn/ zein Protein	better barrier to moisture compared to other proteins and a very good barrier to oxygen, tensile strength (32–42 MPa)	standalone films in food packaging	[66], [67]
Barley proteins (hordein)	200 μm thick; resistant to degradation in a gastric juice environment, but broken down completely in an intestinal juice environment; low cytotoxicity to Caco-2 cells	Delivery of drugs to the colon	[56]
Keratin	transparent materials, with proper UV barrier properties, thermal stability from 50 to 200 C, and water sensitivity, an additive for synthetic	Sponges, films	[68]

	elastomers, giving rise to materials with good thermal, mechanical, flame resistant, and thermo-oxidative properties, Tensile strengths of keratin-based plastics films generally have a lower tensile strength value as compared to other biodegradable plastics such as starch-based and citric acid cross-linked plastics film.	

1) Tensile Strength – TS; 2) Modulus – E; [3]Soy protein isolate film - SPI film

2.3.2 Environmental impact

Protein-based bioplastics are produced from renewable sources like corn, sugarcane, and other biopolymers hence avoiding the many natural resources from the fossil chain[60], [69]. Nonetheless, their production and use affect the conversion of lands to production, deforestation, and competition with other crops that may influence the population densities and food supply. Further, biopolymer production can also turn out costly where the biomass feedstock needs a lot of processing in order to produce the desired material[70]. Dramatic increase cost of energy and demand for it can be offset by the improvement of production technologies and utilization of renewable energy[14], [71]. Nonetheless, the production of protein-based bioplastics creates, in general, fewer greenhouse gas emissions compared to traditional plastics, mainly on factors of carbon mitigation in biomass growth[59]. To assess the environmental emissions, it means that lifecycle assessments (LCAs) are need since other indirect parameters may include agricultural practices, transportation and manufacturing processes[72].

2.4 Poly (lactic acid) (PLA)

“Cargill Dow’s polylactide (PLA) is a versatile new compostable polymer that is made from 100% renewable resources like corn, sugar beets or rice”[73]. PLA is formed from a monomer called lactic acid, which has a molecular formula of 2-hydoxypropionic acid, and basically exists in two types, namely L-lactic acid and D-lactic acid. PLA is a thermoplastic aliphatic polyester made through the polyesterification of bio-based feedstocks such as starch and can be assigned a ‘biodegradable’ label due to the presence of hydrolyzable linkages in its backbone structure[74]. The PLA advantage relies on its mechanical properties that compensate for its flawed versatility by being akin to petroleum-based plastics such as polystyrene (PS) and polyethylene terephthalate (PET). Lactic acid is an organic water-soluble acid that is inherent and is synthesized by chemical synthesis from petrochemical compounds or through fermentation[75]. Lactic acid generation by fermentation is essentially more sustainable compared to chemical synthesis since it can be derived from renewable material and uses lesser energy as well as costs less to produce[76]. In the global scenario of PLA production, it was approximately 180,000 tons in 2012 and it is projected that PLA production should cross a minimum of 800,000 tons per annum by 2020[75]. The plant-derived starch or sugar is converted into lactic acid through fermentation. Microorganisms such as Lactobacillus species are used to ferment the sugar into lactic acid. Glucose ($C_6H_{12}O_6$) is broken down into two molecules of lactic acid ($C_3H_6O_3$). The lactide undergoes ring-opening polymerization in the presence of a catalyst to form high molecular weight PLA (Fig. 05).

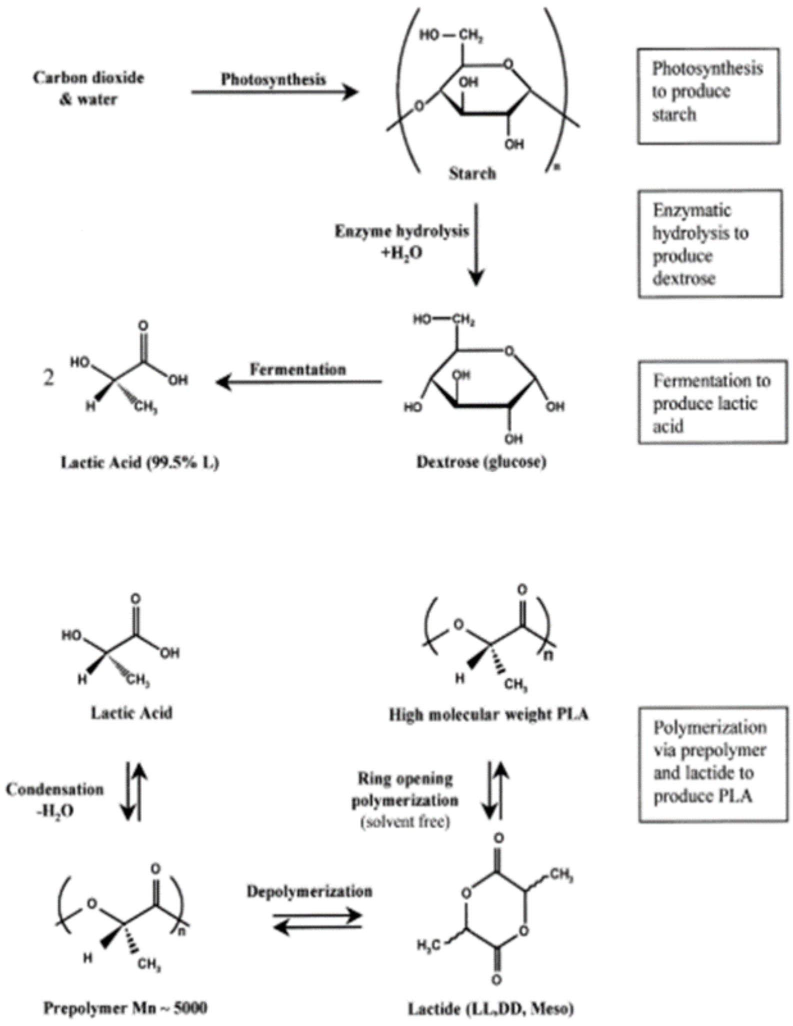

Fig. 05: PLA manufacturing overview [73]

2.4.1 functional properties

The crystallinity of PLA has benefits including improved heat setting, chemical resistance, higher strength in fibers/non-wovens, heat resistance and stiffness in cutlery, permeability and chemical resistance in films[74][77]. High molecular weight (MW) PLA (Mw > 100,000 D) is generally characterized by high mechanical strength with a tensile strength in the region of 50-70 MPa which is comparable to nonbiodegradable conventional plastics[78]. And also, high molecular weight Poly (L-lactide) has a melting point of 180 ^{o}C, while the introduction of meso-lactide depresses the crystalline melting point to 130 ^{o}C[79].

2.4.2 Applications

PLA has been commercialized in commodity production for short-life cycle compostable products like semi-rigid Films, food packaging bags, and containers; most of which are currently in use as containers[75]. Originally the market for PLA was confined to food and packaging applications but often now it is also used in Electronics, Baseballs, Synthetic fibers, Wrapping films & Tapes, etc. Ingeo™ fibers introduced by Cargill Dow in 2003 are the first synthetic fibers that are 100% annually renewable and mainly in application on pillows, mattresses, and or duvet, apparels, floor, wall, and or furniture textiles. PLA also finds its uses in the cosmetic products industry and is currently being utilized in 3-D printers[80].

2.4.3 Environmental impact and biodegradability

According to Cargill Dow in 2003, the PLA production system uses 25-55% less fossil energy than petroleum-based polymers[80]. While disposal of PLA products (combustion, composting, etc.) causes carbon dioxide release to the atmosphere, it can be considered a low-impact greenhouse gas polymer compared to petrochemical-based polymers[80]. This is because the CO_2 generated during PLA biodegradation is balanced by an equal amount removed from the atmosphere during the growth of the plant feedstocks[73]. PLA greenhouse gas emission rate is about 1600 kg CO_2 per metric ton, while polypropylene (PP), polyethylene terephthalate (PET), and nylon have greenhouse gas values of 1850, 2740, 4140, and 7150 kg CO_2 per metric ton respectively[81].

In nature, biotic and abiotic factors exist together; therefore, the whole degradation mechanism of a certain material can be referred to as environmental degradation[82]. The environmental degradation process of PLA is affected by its material properties such as molecular first-order structure (molecular weight, optical purity) and higher-order structures (crystallinity, Tg, and Tm), and by environmental factors such as humidity, temperature, and catalytic species (pH and the presence of enzymes or microorganisms)[83].

When the molecular weight is low (Mw < 100,000 D), PLA is brittle, cloudy, and opaque, while at higher molecular weights, PLA is stronger, more transparent, and less susceptible to degradation[84]. Crystalline regions within PLA hydrolyze much more slowly than the amorphous regions as water diffuses more readily into the less organized amorphous regions compared to the more ordered crystalline regions, causing greater rates of hydrolysis and increased susceptibility to biodegradation[85], [86], [87]. In semi-crystalline PLA, degradation occurs first in the amorphous regions and more slowly in the crystalline regions. Therefore, with time, the proportion of the crystalline regions within the PLA increases and the rate of degradation decreases[88], [89].

The rate of PLA degradation is much greater above the glass transition temperature (Tg, 55-62°C) as polymer chains become more flexible and water absorption increases, accelerating both hydrolysis and microbial attachment[90], [91].

3.Regulatory and Safety Considerations

The use of bioplastic materials for food packaging therefore, strict legal and safety measures are taken to check on the outcomes on the health of the consumers and the environmental impacts. Different countries and self-governing authorities like the USA's FDA and the EFSA of the European Union have laid down code of practices and norms for the interaction of bioplastics with food products or articles intended for food contact. The following are aspects that these regulations cover, material safety, migration limits and food safety standards.

3.1 **FDA (U.S. Food and Drug Administration)**

In the United States, the FDA monitors the materials interacting with food through Title 21 of CFR on Food and Drugs. Firstly, with the usage of bioplastics for food packaging requires that bioplastics must also adhere to the FDA food contact substances that requires that bioplastics should undergo a series of tests to ensure they do not leach into the food[92].

3.2 EFSA (European Food Safety Authority)

In Europe, the EFSA assesses the safety of food contact materials The European Food Safety Authority is responsible for assessing the safety of the Food Contact Material under EU no. 10/2011 on Plastic Material and article intended to come into contact with food substances. This regulation provides a definition to set up maximum levels of migration to food substances from the bioplastic to avoid harm to the consumer[93].

3.3 Other International Frameworks

Different other countries have their respective standard and regulatory authorities like Health Canada and from China's National Food Safety Standards (GB standards), and the Food Sanitation Law of Japan. All of these frameworks ensure food safety compliance for bioplastics meant for food contact purposes[94], [95].

3.4 Biodegradability and Compostability Standards

Currently, specification about labeling bioplastics as compostable includes ASTM D6400, which is available in the USA, and EN 13432 which is from Europe. These standards make sure that when the bioplastics are disposed, they will biodegrade under Industrial composting conditions and do not have a negative impact when discarded into the environment[96].

4.GLOBAL TRENDS AND ANALYSIS FOR THE INTERNATIONAL BIOPLASTIC PACKAGING MARKET

In the year 2020, the market was affected due to COVID-19 arising from the outbreak affecting nations worldwide, which led to the implementation of nationwide lockdowns that disrupted manufacturing processes and supply chain and production halts. However, the conditions began improving in 2021 to again make the market grow during the forecast period.

4.1 Current market dynamics

The global bioplastic market in 2023 was valued at 11.33 billion[97]. There are several reasons for that, such as including increasing environmental awareness, stringent government regulations aimed at reducing plastic pollution, and advancements in bioplastic technologies[97]. Therefore, with projection estimating a substantial increase to around US $ 15.30 billion by the end of 2024[98].

4.2 Future forecast

The global biodegradable bioplastic market in 2021 was valued at US $ 7.7 billion. The market is further estimated to grow at (CAGR) of 16.4% in the forecast period of 2021-2030 to reach a value of around US $ 23.3 billion by 2030 (Fig. 06)[99].

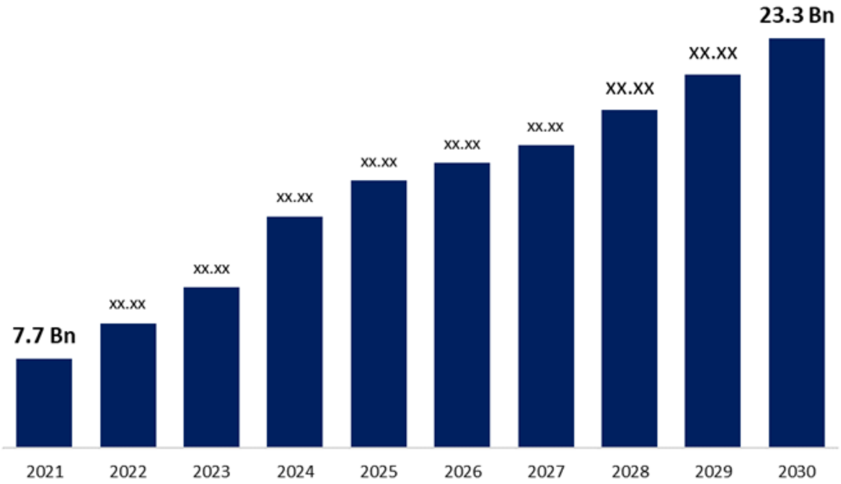

Fig. 06: Estimated global market size of biodegradable plastics in the forecast period of 2021-2030 [99]

Sustainability focus, food and beverage sector demand, technological advancement, and regulatory initiatives are the main factors in the growth of the global bioplastic market. As an example, Bioplastics are mainly used in food and beverage sector for food packaging application[99]. Bottles and food containers made out from bioplastics. Bottles made of PLA plastic are strong, single-use, and have qualities like gloss and transparency. And also, PLA based bioplastics do not release hazardous fumes when it is burned like petroleum-based plastics. Therefore, it is anticipated that throughout the forecast period, the demand for the bioplastics industry trends will continue to be very high[100].

5.FUTURE TRENDS

Investors in Sea6 Energy Pvt. Ltd. include Aqua-Spark, a Dutch investment firm, and BASF Venture Capital GmbH, the corporate venture business of BASF SE, Germany. In terms of growing and preparing tropical red seaweed, Sea6 Energy is a pioneer. Additionally, Red Seaweed-based biofuels and bioplastics are being developed by Sea6 Energy[101].

MAGNUM BIO ABS was introduced by Trinseo for use in automotive settings. With the introduction of MAGNUM BIO ABS, the business is able to provide a wider range of sustainably-advantaged products and services to its clientele, assisting them in realising their sustainability objectives[101].

ABB technology to automate NatureWorks' new bioplastics plant in Thailand, helping to meet the increasing global demand for sustainable materials. The new site is set to produce 75,000 tons of Ingeo PLA biopolymer per year - an integrated process from fermentation to polymerization enhances supply chain reliability. ABB technology will help improve the energy and production efficiency of bioplastic manufacturing, expected to grow over 260% by 2026[101].

6. CONCLUSION

Bio-based plastics are well favored to replace the ordinary plastics used in the food packaging industry owing to their biodegradability hence a reduced shelf life of 500 years thus addressing environmental concerns. Still, there are challenges that mean that mechanical strength cannot be effectively controlled, barriers may be irregular, and biodegradability might be inconsistent, which must be solved with better material science. Another disadvantage is the relatively high production cost of bioplastics and the issues in conformity to the FDA regulations required for food packaging application. It is important for most consumers and can be improved on through education and clear labeling. However, with further research, advocacy, and policy support, and an enhanced consumer campaign, bioplastics are set to assume a critical role in shaping a greener and environmentally friendly food packaging system.

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REFERENCES

[1] L. Bartolucci, “Sustainable Valorization of Bioplastic Waste: A Review on Effective Recycling Routes for the Most Widely Used Biopolymers,” *International Journal of Molecular Sciences*, vol. 24, no. 9. Multidisciplinary Digital Publishing Institute (MDPI), May 01, 2023. doi: 10.3390/ijms24097696.

[2] L. Behera, M. Mohanta, and A. Thirugnanam, “Intensification of Yam-Starch Based Biodegradable Bioplastic Film with Bentonite for Food Packaging Application,” *Environ Technol Innov*, vol. 25, Feb. 2022, doi: 10.1016/j.eti.2021.102180.

[3] F. Nur Arici, E. Ebrar YÜCESOY, F. Nur ARICI, C. Demirci, and G. Baysal, “Bioplastics Used in Renewable Packaging in the Food Industry 1*,” *Gülay BAYSAL International Journal of Food Engineering Research (IJFER) Year*, vol. 5, pp. 7–16, 2019, doi: 10.17932/IAU.IJFER.2015.003/ijfer_v05i1002.

[4] M. Zubair and A. Ullah, “Recent Advances in Protein Derived Bionanocomposites for Food Packaging Applications,” *Critical Reviews in Food Science and Nutrition*, vol. 60, no. 3. Taylor and Francis Inc., pp. 406–434, Feb. 04, 2020. doi: 10.1080/10408398.2018.1534800.

[5] S. Nuurul Huda Mohammad Azmin and A. Chandra Iwansyah, “Processing and Characterization of Bioplastic Film Fabricated from a Hybrid of Cocoa Pod Husk and Kenaf for the Application in Food Industries Palsan Sannasi.” [Online]. Available: https://www.researchgate.net/publication/366634320

[6] S. Wang, A. Lu, and L. Zhang, “Recent Advances in Regenerated Cellulose Materials,” *Progress in Polymer Science*, vol. 53. Elsevier Ltd, pp. 169–206, Feb. 01, 2016. doi: 10.1016/j.progpolymsci.2015.07.003.

[7] U. Qasim *et al.*, “Renewable Cellulosic Nanocomposites for Food Packaging to Avoid Fossil Fuel Plastic Pollution: A Review,” *Environmental Chemistry Letters*, vol. 19, no. 1. Springer Science and Business Media Deutschland GmbH, pp. 613–641, Feb. 01, 2021. doi: 10.1007/s10311-020-01090-x.

[8] L. G. Hong, N. Y. Yuhana, and E. Z. E. Zawawi, “Review of Bioplastics as Food Packaging Materials,” *AIMS Mater Sci*, vol. 8, no. 2, pp. 166–184, 2021, doi: 10.3934/matersci.2021012.

[9] E. G. Shershneva, “Biodegradable Food Packaging: Benefits and Adverse Effects,” in *IOP Conference*

Series: Earth and Environmental Science, IOP Publishing Ltd, Feb. 2022. doi: 10.1088/1755-1315/988/2/022006.

[10] T. D. Moshood, G. Nawanir, F. Mahmud, F. Mohamad, M. H. Ahmad, and A. AbdulGhani, “Biodegradable Plastic Applications Towards Sustainability: A Recent Innovations in the Green Product,” *Clean Eng Technol*, vol. 6, p. 100404, Feb. 2022, doi: 10.1016/J.CLET.2022.100404.

[11] V.-B. J, “Polylactic Acid (Pla) As a Bioplastic and its Possible Applications in the Food Industry,” *Food Sci Nutr*, vol. 5, no. 2, pp. 1–6, Dec. 2019, doi: 10.24966/FSN-1076/100048.

[12] F. Vilarinho, A. Sanches Silva, M. F. Vaz, and J. P. Farinha, “Nanocellulose in Green Food Packaging,” *Crit Rev Food Sci Nutr*, vol. 58, no. 9, pp. 1526–1537, Jun. 2018, doi: 10.1080/10408398.2016.1270254.

[13] N. Nur Nadia and O. Siti Amira, “Feasibility of Irradiated Corn-Based Bioplastics as Packaging Material,” in *Solid State Phenomena*, Trans Tech Publications Ltd, 2021, pp. 241–250. doi: 10.4028/www.scientific.net/SSP.317.241.

[14] A. Karpušenkaitė and V. Varžinskas, “Bioplastics: Development, Possibilities and Difficulties,” *Environmental Research, Engineering and Management*, vol. 68, no. 2, Jul. 2014, doi: 10.5755/j01.erem.68.2.6777.

[15] P. Morone, V. E. Tartiu, and P. Falcone, “Assessing The Potential of Biowaste for Bioplastics Production Through Social Network Analysis,” *J Clean Prod*, vol. 90, pp. 43–54, Mar. 2015, doi: 10.1016/J.JCLEPRO.2014.11.069.

[16] M. H. Rahman and P. R. Bhoi, “An Overview of Non-Biodegradable Bioplastics,” *Journal of Cleaner Production*, vol. 294. Elsevier Ltd, Apr. 20, 2021. doi: 10.1016/j.jclepro.2021.126218.

[17] K. S. Jeenusha and P. Amritkumar, “Production of Biodegradable Food Packaging Material from Musa (Banana Plant) Leaves Byecofriendly Methods,” *IOSR Journal of Environmental Science*, vol. 14, pp. 1–05, 2020, doi: 10.9790/2402-1404020105.

[18] S. N. H. M. Azmin, N. A. B. M. Hayat, and M. S. M. Nor, “Development and Characterization of Food Packaging Bioplastic Film from Cocoa Pod Husk Cellulose Incorporated with Sugarcane Bagasse Fibre,” *Journal of Bioresources and Bioproducts*, vol. 5, no. 4, pp. 248–255, 2020, doi: 10.1016/j.jobab.2020.10.003.

[19] A. W. Mwangi, “Synthesis of Silver Nanoparticles Based Antimicrobial Bioplastic from Musa Acuminata (Banana) Peelings.” [Online]. Available: https://www.researchgate.net/publication/333429773

[20] M. Visanko, “Functionalized Nanocelluloses and Their Use in Barrier and Membrane Thin Films,” 2015, doi: 10.13140/RG.2.1.4859.9769.

[21] J. S. Yaradoddi, “Biodegradable Carboxymethyl Cellulose Based Material for Sustainable Packaging Application,” *Sci Rep*, vol. 10, no. 1, Dec. 2020, doi: 10.1038/s41598-020-78912-z.

[22] A. R. Norafah Izzati, A. M. Hanis Madihah, N. M. Nurazzi, and M. K. M. Haaz, “The Effect of Cellulose Loadings on the Properties of Tapioca/Banana Peels Starch Bioplastics”, doi: 10.21203/rs.3.rs-4210538/v1.

[23] F. Carrillo, G. Martín, M. López-Mesas, X. Colom, and J. Cañavate, “High Modulus Regenerated Cellulose Fiber-Reinforced Cellulose Acetate Butyrate Biocomposites,” *J Compos Mater*, vol. 45, no. 17, pp. 1733–1740, Aug. 2011, doi: 10.1177/0021998310386261.

[24] L. S. Zárate-Ramírez, A. Romero, C. Bengoechea, P. Partal, and A. Guerrero, “Thermo-Mechanical and Hydrophilic Properties of Polysaccharide/Gluten-Based Bioplastics,” *Carbohydr Polym*, vol. 112, pp. 24–31, Nov. 2014, doi: 10.1016/J.CARBPOL.2014.05.055.

[25] A. Riaz, “Effect Of Chinese Chives (Allium Tuberosum) Addition to Carboxymethyl Cellulose Based Food Packaging Films,” *Carbohydr Polym*, vol. 235, May 2020, doi: 10.1016/j.carbpol.2020.115944.

[26] S. Fujisawa, Y. Okita, H. Fukuzumi, T. Saito, and A. Isogai, "Preparation and Characterization of TEMPO-Oxidized Cellulose Nanofibril Films with Free Carboxyl Groups," *Carbohydr Polym*, vol. 84, no. 1, pp. 579–583, Feb. 2011, doi: 10.1016/j.carbpol.2010.12.029.

[27] Y. Wu, Q. Li, X. Zhang, Y. Li, B. Li, and S. Liu, "Cellulose-Based Peptidopolysaccharides as Cationic Antimicrobial Package Films," *Int J Biol Macromol*, vol. 128, pp. 673–680, May 2019, doi: 10.1016/j.ijbiomac.2019.01.172.

[28] H. Fukuzumi, T. Saito, T. Iwata, Y. Kumamoto, and A. Isogai, "Transparent and High Gas Barrier Films of Cellulose Nanofibers Prepared By TEMPO-Mediated Oxidation," *Biomacromolecules*, vol. 10, no. 1, pp. 162–165, Jan. 2009, doi: 10.1021/bm801065u.

[29] C. Cen, "Design and Characterization of an Antibacterial Film Composited by Hydroxyethyl Cellulose (HEC), Carboxymethyl Chitosan (CMCS), and Nano Zno for Food Packaging," *Int J Biol Macromol*, vol. 231, p. 123203, Mar. 2023, doi: 10.1016/J.IJBIOMAC.2023.123203.

[30] L. C. M. Celuppi, "Microbiological, Thermal and Mechanical Performance of Cellulose Acetate Films with Geranyl Acetate," *Int J Biol Macromol*, vol. 228, pp. 517–527, Feb. 2023, doi: 10.1016/J.IJBIOMAC.2022.12.170.

[31] G. Atiwesh, A. Mikhael, C. C. Parrish, J. Banoub, and T. A. T. Le, "Environmental Impact of Bioplastic Use: A Review," *Heliyon*, vol. 7, no. 9, Sep. 2021, doi: 10.1016/j.heliyon.2021.e07918.

[32] A. Alahakoon, D. Maneth, T. Sulaksha, and M. Gamage, "Bioplastics for Sustainable Future," 2023. [Online]. Available: https://www.researchgate.net/publication/370057039

[33] L. Singh and D. Kumar, "A Study on Biodegradable Plastics-Bioplastics." [Online]. Available: https://www.researchgate.net/publication/363405559

[34] Vaishnavi A. Harkal and Swati P. Deshmukh, "A Review on Biodegradable Polymers: Used as Packaging Materials," *GSC Biological and Pharmaceutical Sciences*, vol. 25, pp. 107–115, Nov. 2023, doi: 10.30574/gscbps.2023.25.2.0423.

[35] S. Amira Othman and N. Nadia Nasir, "Starch Bio-Plastics For Packaging Application," *Sciences and Technology*, vol. 3, no. 1, pp. 294–297, 2023, doi: 10.30880/ekst.2023.03.01.033.

[36] N. N. Rohidi and S. A. Othman, "Investigate the Properties of Different Irradiated Starch Bioplastic for Packaging Application," *Malaysian Journal of Science*, vol. 43, no. 1, pp. 59–71, 2024, doi: 10.22452/mjs.vol43no1.6.

[37] G. Genecya, D. R. Adhika, Widayani, and T. D. K. Wungu, "Optimization Of Mechanical Properties of Carrageenan-Based Bioplastic as Food Packaging," in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics, 2023. doi: 10.1088/1755-1315/1201/1/012079.

[38] N. K. Othman, E. M. Salleh, Z. Dasuki, and A. M. Lazim, "Dimethyl Sulfoxide-Treated Starch of Dioescorea Hispida as a Green Corrosion Inhibitor for Low Carbon Steel in Sodium Chloride Medium," in *Corrosion Inhibitors, Principles and Recent Applications*, InTech, 2018. doi: 10.5772/intechopen.73552.

[39] A. Ashok, "Effect of Softening Agents in the Thermal and Morphological Properties of Starch Based Bioplastics Journal of Polymer & Composites Effect of Softening Agents in the Thermal and Morphological Properties of Starch Based Bioplastics," *Article in Journal of Polymer & Composites*, vol. 5, no. 1, pp. 15–24, 2017, [Online]. Available: www.stmjournals.com

[40] R. V. Gadhave, A. Das, P. A. Mahanwar, and P. T. Gadekar, "Starch Based Bio-Plastics: The Future of Sustainable Packaging," *Open Journal of Polymer Chemistry*, vol. 08, no. 02, pp. 21–33, 2018, doi: 10.4236/ojpchem.2018.82003.

[41] N. Akter, "Thermomechanical, Barrier, And Morphological Properties Of Chitosan-Reinforced Starch-

Based Biodegradable Composite Films," *Journal of Thermoplastic Composite Materials*, vol. 27, no. 7, pp. 933–948, 2014, doi: 10.1177/0892705712461512.

[42] A. Gamage, "Polysaccharide-Based Bioplastics as Green and Sustainable Packaging Materials," 2023, doi: 10.20944/preprints202310.1491.v1.

[43] S. Amira Othman and U. Tun Hussein Onn Malaysia, "Corn Bio-Plastic for Packaging Application Nurul Fathihah Abu Bakar." [Online]. Available: https://www.researchgate.net/publication/334957903

[44] Z. W. Abdullah, Y. Dong, I. J. Davies, and S. Barbhuiya, "PVA, PVA Blends, and Their Nanocomposites for Biodegradable Packaging Application," *Polymer - Plastics Technology and Engineering*, vol. 56, no. 12, pp. 1307–1344, Aug. 2017, doi: 10.1080/03602559.2016.1275684.

[45] Y. A. Septiati and M. Karmini, "Effect of Using Cassava and Glycerol as Food Storage on the Quality of Bioplastic Packaged Food," *Healthc Low Resour Settings*, vol. 11, no. 2, Dec. 2023, doi: 10.4081/hls.2023.11778.

[46] F. A. Syamani, W. B. Kusumaningrum, F. Akbar, Ismadi, B. A. Widyaningrum, and D. A. Pramasari, "Characteristics of Bioplastic Made from Modified Cassava Starch with Addition of Polyvinyl Alcohol," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Nov. 2020. doi: 10.1088/1755-1315/591/1/012016.

[47] V. B. Carmona, A. C. Corrêa, J. M. Marconcini, and L. H. C. Mattoso, "Properties of a Biodegradable Ternary Blend of Thermoplastic Starch (TPS), Poly(E-Caprolactone) (PCL) and Poly(Lactic Acid) (PLA)," *J Polym Environ*, vol. 23, no. 1, pp. 83–89, Mar. 2015, doi: 10.1007/S10924-014-0666-7.

[48] M. Ates and P. Kuz, "Journal of Sustainable Construction Materials and Technologies Starch-Based Bioplastic Materials for Packaging Industry," *J Sustain. Construct. Mater. Technol*, vol. 5, no. 1, pp. 399–406, 2020, doi: 10.29187/jscmt.2019.44.

[49] W. C. R. Mandala, E. Saepudin, and N. M. Nizardo, "Effect of Addition of Antibacterial Compound from Kelor Leaves Extract (*Moringa oleifera* Lam) to Foodborne Pathogen Bacteria Activity on Crosslinked Bioplastic Poly(Vinyl Alcohol)/Starch," in *AIP Conference Proceedings*, American Institute of Physics Inc., Jun. 2020. doi: 10.1063/5.0010360.

[50] S. A. Afolalu, O. M. Ikumapayi, A. T. Ogundipe, O. R. Oloyede, and O. O. Yusuf, "Development of Biodegradable Plastic Sheet from Blends of Low-Density Polyethylene (LDPE) and Banana Peel Starch," in *Key Engineering Materials*, Trans Tech Publications Ltd, 2022, pp. 22–31. doi: 10.4028/p-kof718.

[51] K. Tarangini *et al.*, "Eco-Friendly Bioplastic Material Development Via Sustainable Seaweed Biocomposite," *Ecological Chemistry and Engineering S*, vol. 30, no. 3, pp. 333–341, Sep. 2023, doi: 10.2478/eces-2023-0036.

[52] M. Kuddus and R. Roohi, *Bioplastics for Sustainable Development*. Springer Singapore, 2021. doi: 10.1007/978-981-16-1823-9.

[53] M. Alonso-González, M. Felix, and A. Romero, "Influence of the Plasticizer on Rice Bran-Based Eco-Friendly Bioplastics Obtained by Injection Moulding," *Ind Crops Prod*, vol. 180, Jun. 2022, doi: 10.1016/j.indcrop.2022.114767.

[54] "Ecofriendly Bioplastics from Tamarind Seed Powder", doi: 10.37896/JBSV23.1/1647.

[55] M. Jiménez-Rosado, E. Bouroudian, V. Perez-Puyana, A. Guerrero, and A. Romero, "Evaluation of Different Strengthening Methods in the Mechanical and Functional Properties of Soy Protein-Based Bioplastics," *J Clean Prod*, vol. 262, Jul. 2020, doi: 10.1016/j.jclepro.2020.121517.

[56] J. Taylor, J. O. Anyango, and J. R. N. Taylor, "Developments in the Science of Zein, Kafirin, and Gluten Protein Bioplastic Materials," *Cereal Chem*, vol. 90, no. 4, pp. 344–357, 2013, doi: 10.1094/CCHEM-12-

12-0165-IA.

[57] M. Alonso-González, M. Felix, and A. Romero, “Development of Rice Bran-Based Bioplastics Via Injection Molding: Influence of Particle Size and Glycerol Ratio,” *Resour Conserv Recycl*, vol. 208, Sep. 2024, doi: 10.1016/j.resconrec.2024.107713.

[58] R. Sonnier, A. Taguet, L. Ferry, and J.-M. Lopez-Cuesta, “Flame Retardant Biobased Polymers,” 2018, pp. 1–32. doi: 10.1007/978-3-319-67083-6_1.

[59] R. J. H. Navasingh, M. K. Gurunathan, M. P. Nikolova, and J. B. Królczyk, “Sustainable Bioplastics for Food Packaging Produced from Renewable Natural Sources,” *Polymers (Basel)*, vol. 15, no. 18, Sep. 2023, doi: 10.3390/polym15183760.

[60] L. Di Gioia and S. Guilbert, “Corn Protein-Based Thermoplastic Resins: Effect of Some Polar and Amphiphilic Plasticizers,” *J Agric Food Chem*, vol. 47, no. 3, pp. 1254–1261, Mar. 1999, doi: 10.1021/jf980976j.

[61] S. Sun, Y. Song, and Q. Zheng, “Morphologies and Properties of Thermo-Molded Biodegradable Plastics Based on Glycerol-Plasticized Wheat Gluten,” *Food Hydrocoll*, vol. 21, no. 7, pp. 1005–1013, Oct. 2007, doi: 10.1016/J.FOODHYD.2006.03.004.

[62] W. A. R. Manamperi and S. W. Pryor, “Properties of Canola Protein-Based Plastics and Protein Isolates Modified Using SDS and SDBS,” *JAOCS, Journal of the American Oil Chemists’ Society*, vol. 89, no. 3, pp. 541–549, Mar. 2012, doi: 10.1007/s11746-011-1935-4.

[63] W. A. R. Manamperi, S. K. C. Chang, C. A. Ulven, and S. W. Pryor, “Plastics from an Improved Canola Protein Isolate: Preparation and Properties,” *JAOCS, Journal of the American Oil Chemists’ Society*, vol. 87, no. 8, pp. 909–915, Aug. 2010, doi: 10.1007/s11746-010-1616-8.

[64] Y. Zhang, Q. Liu, and C. Rempel, “Processing and Characteristics of Canola Protein-Based Biodegradable Packaging: A Review,” *Crit Rev Food Sci Nutr*, vol. 58, no. 3, pp. 475–485, Feb. 2018, doi: 10.1080/10408398.2016.1193463.

[65] J. Han, S. H. Shin, K. M. Park, and K. M. Kim, “Characterization of Physical, Mechanical, and Antioxidant Properties of Soy Protein-Based Bioplastic Films Containing Carboxymethylcellulose and Catechin,” *Food Sci Biotechnol*, vol. 24, no. 3, pp. 939–945, Jun. 2015, doi: 10.1007/s10068-015-0121-0.

[66] I. S. Bayer, “7 Zein in Food Packaging,” 2021.

[67] W. Shi and M. J. Dumont, “Review: Bio-Based Films from Zein, Keratin, Pea, and Rapeseed Protein Feedstocks,” *Journal of Materials Science*, vol. 49, no. 5. pp. 1915–1930, Mar. 2014. doi: 10.1007/s10853-013-7933-1.

[68] N. Ramakrishnan, S. Sharma, A. Gupta, and B. Y. Alashwal, “Keratin Based Bioplastic Film from Chicken Feathers and Its Characterization,” *Int J Biol Macromol*, vol. 111, pp. 352–358, May 2018, doi: 10.1016/j.ijbiomac.2018.01.037.

[69] A. Jones, A. Mandal, and S. Sharma, “Protein-Based Bioplastics and Their Antibacterial Potential,” *J Appl Polym Sci*, vol. 132, no. 18, May 2015, doi: 10.1002/app.41931.

[70] S. Nanda, B. R. Patra, R. Patel, J. Bakos, and A. K. Dalai, “Innovations in Applications and Prospects of Bioplastics and Biopolymers: A Review,” *Environmental Chemistry Letters*, vol. 20, no. 1. Springer Science and Business Media Deutschland GmbH, pp. 379–395, Feb. 01, 2022. doi: 10.1007/s10311-021-01334-4.

[71] R. R, “Advanced Biomaterials for Sustainable Applications in the Food Industry: Updates and Challenges,” *Environmental Pollution*, vol. 283, p. 117071, Aug. 2021, doi: 10.1016/J.ENVPOL.2021.117071.

[72] B. Chalermthai, A. Giwa, J. E. Schmidt, and H. A. B. Taher, “Life Cycle Assessment of Bioplastic

Production from Whey Protein Obtained from Dairy Residues," *Bioresour Technol Rep*, vol. 15, p. 100695, Sep. 2021, doi: 10.1016/J.BITEB.2021.100695.

[73] E. T. H. Vink, K. R. Rábago, D. A. Glassner, and P. R. Gruber, "Applications of Life Cycle Assessment to Natureworks^{tm} Polylactide (PLA) Production," *Polym Degrad Stab*, vol. 80, no. 3, pp. 403–419, Jan. 2003, doi: 10.1016/S0141-3910(02)00372-5.

[74] S. Domenek, C. Courgneau, and V. Ducruet, "Characteristics and Applications of Poly(Lactide)."

[75] D. Garlotta, "A Literature Review of Poly(Lactic Acid)," 2001.

[76] S. Li and M. Vert, "Biodegradation of Aliphatic Polyesters," 2002.

[77] N. Burgos, "Functional Properties of Plasticized Bio-Based Poly(Lactic Acid)_Poly(Hydroxybutyrate) (PLA_PHB) Films for Active Food Packaging," *Food Bioproc Tech*, vol. 10, no. 4, pp. 770–780, Apr. 2017, doi: 10.1007/S11947-016-1846-3.

[78] B. Freeland, "A Review of Polylactic Acid as a Replacement Material for Single-Use Laboratory Components," *Materials*, vol. 15, no. 9. MDPI, May 01, 2022. doi: 10.3390/ma15092989.

[79] M. Harada, T. Ohya, K. Iida, H. Hayashi, K. Hirano, and H. Fukuda, "Increased Impact Strength of Biodegradable Poly(Lactic Acid)/Poly(Butylene Succinate) Blend Composites by Using Isocyanate as a Reactive Processing Agent," *J Appl Polym Sci*, vol. 106, no. 3, pp. 1813–1820, Nov. 2007, doi: 10.1002/APP.26717.

[80] E. T. H. Vink, K. R. Rábago, D. A. Glassner, and P. R. Gruber, "Applications of Life Cycle Assessment to Natureworks^{tm} Polylactide (PLA) Production," *Polym Degrad Stab*, vol. 80, no. 3, pp. 403–419, Jan. 2003, doi: 10.1016/S0141-3910(02)00372-5.

[81] J. H. Song, R. J. Murphy, R. Narayan, and G. B. H. Davies, "Biodegradable and Compostable Alternatives to Conventional Plastics," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 364, no. 1526, pp. 2127–2139, Jul. 2009, doi: 10.1098/rstb.2008.0289.

[82] K. Madhavan Nampoothiri, N. R. Nair, and R. P. John, "An Overview of the Recent Developments in Polylactide (PLA) Research," *Bioresource Technology*, vol. 101, no. 22. pp. 8493–8501, Nov. 2010. doi: 10.1016/j.biortech.2010.05.092.

[83] K.-L. G. Ho, A. L. Pometto, and P. N. Hinz, "Effects of Temperature and Relative Humidity on Polylactic Acid Plastic Degradation 1," 1999.

[84] K.-L. G. Ho, A. L. Pometto, A. Gadea-Rivas, J. A. Briceno, and A. Rojas, "Degradation of Polylactic Acid (PLA) Plastic in Costa Rican Soil and Iowa State University Compost Rows 1," 1999.

[85] M. Hakkarainen, "Aliphatic Polyesters: Abiotic and Biotic Degradation and Degradation Products."

[86] M. S. Reeve, S. P. Mccarthyj, M. J. Downey, and R. A. Gross, "Polylactide Stereochemistry: Effect on Enzymatic Degradability," 1994.

[87] H. Tsuji and Y. Ikada, "Properties and Morphology of Poly(L-Lactide). II. Hydrolysis in Alkaline Solution," John Wiley & Sons, Inc, 1998.

[88] G. Kale, R. Auras, and S. P. Singh, "Comparison of the Degradability of Poly(Lactide) Packages in Composting and Ambient Exposure Conditions," *Packaging Technology and Science*, vol. 20, no. 1, pp. 49–70, Jan. 2007, doi: 10.1002/pts.742.

[89] H. Nishida and Y. Tokiwa, "Effects of Higher-Order Structure of Poly(3-Hydroxybutyrate) on Its Biodegradation. II. Effects of Crystal Structure on Microbial Degradation," 1993.

[90] M. Agarwal, K. W. Koelling, and J. J. Chalmers, "Characterization of the Degradation of Polylactic Acid Polymer in A Solid Substrate Environment," 1998.

[91] Z. Paul Lorenc, "Techniques for the Optimization of Facial and Nonfacial Volumization with Injectable

Poly-L-Lactic Acid," *Aesthetic Plastic Surgery*, vol. 36, no. 5. pp. 1222–1229, Oct. 2012. doi: 10.1007/s00266-012-9920-3.

[92] J. M. Dages, "Regulatory Affairs What Clearances Currently Exist for Bioplastics Under the Plastics Regulation?" [Online]. Available: https://www.efsa.europa.eu/en/efsajournal/pub/rn-21.

[93] E. Bioplastics, "Fact Sheet." [Online]. Available: www.european-bioplastics.org

[94] "The_Status_of_Biodegradable_Plastic_in_China-Yunxuan_Weng".

[95] O. Wang, "Sustainable Food Contact Material in China."

[96] S. Hann, "Relevance of Biodegradable and Compostable Consumer Plastic Products and Packaging in a Circular Economy", doi: 10.2779/497376.

[97] "Bioplastics Market Size, Share & Growth Statistics | 2032." Accessed: Jun. 08, 2024. [Online]. Available: https://www.expertmarketresearch.com/reports/bioplastics-market

[98] "Bioplastics & Biopolymers Market Size, Industry Share Growth Forecast, Global Trends Report, [Latest]." Accessed: Jun. 08, 2024. [Online]. Available: https://www.marketsandmarkets.com/Market-Reports/biopolymers-bioplastics-market-88795240.html

[99] "Global Biodegradable Plastics Market Size, Forecast 2021-30." Accessed: Jun. 08, 2024. [Online]. Available: https://www.sphericalinsights.com/reports/biodegradable-plastics-market

[100] N. Farmer, "The Future: Global Trends and Analysis for the International Packaging Market in Relation to the Speed of Impact of Packaging Innovation and Likely Material Changes," in *Trends in Packaging of Food, Beverages and Other Fast-Moving Consumer Goods (FMCG)*, Elsevier Inc., 2013, pp. 288–312. doi: 10.1533/9780857098979.288.

[101] "Bioplastics Market Size - Industry Share & Research." Accessed: Jun. 08, 2024. [Online]. Available: https://www.mordorintelligence.com/industry-reports/bioplastics-market