STM JOURNALS

Journal of
Modern Chemistry &
Chemical Technology

https://journals.stmjournals.com/jomcct

ISSN: 2229-6999 (Online)
ISSN: 2321-5208 (Print)
Volume 17, Issue 1, 2026
January–April
DOI (Journal): 10.37591/JoMCCT

Review JoMCCT

Preparation and Characterization of Biopolymeric Film for Food Preservation and Packaging: A Review

M.B. Kumbhare[1],*, Yash Tambe[2]

Abstract

Petroleum-based polymers have been widely used for the production of various products for a long period due to their versatility and durability. However, the increasing demand of these petroleum-based plastic generates tremendous non-degradable plastic waste, leading to significant environmental concerns. Improper disposal practices lead to pollution, posing serious threats to the ecosystem and human health. In response to these challenges, biopolymers have emerged as a promising alternative source that have the potential to replace petroleum-based polymers because they are derived from renewable natural resources, such as polysaccharides, proteins, and lipids, making them eco-friendly and cost-effective. In this review paper, various natural sources of biopolymers, biopolymeric film preparation methods and film properties have been critically reviewed based on the most recent available research literature, with emphasized on the food preservation and packaging sector. The study systematically categorises biopolymers into natural, synthetic, and microbial origins and highlights how the incorporation of plasticizers and polymer blending can optimize film flexibility, processability, and biodegradability. Additionally, different film forming techniques such as solvent casting, extrusion and coating methods are reviewed to highlight their impact on film properties. The characterization of biopolymer films is also reviewed including mechanical, thermal, barrier essential for determining their suitability in food packaging applications. Overall, this study emphasises the growing potential of biopolymer films as sustainable packaging materials and highlights the need for further research to enhance their performance and commercial viability in the food industry. Furthermore, the comparative properties of Natural, Composite and Synthetic Biodegradable Polymeric Films are described in this study.

Keywords: Biopolymers, biodegradable films, food packaging, polymer blending, film characterization sustainable materials

***Author for Correspondence**
M.B. Kumbhare
E-mail: manojkumbhare@sgbau.ac.in

[1]Assistant Professor, Department of Chemical Technology, Sant Gadge Baba Amravati University, Amravati, Maharashtra, India
[2]Research Scholar, Department of Chemical Technology, Sant Gadge Baba Amravati University, Amravati, Maharashtra, India

Received Date: March 24, 2026
Accepted Date: March 27, 2026
Published Date: April 17, 2026

Citation: M.B. Kumbhare, Yash Tambe. Preparation and Characterization of Biopolymeric Film for Food Preservation and Packaging: A Review. Journal of Modern Chemistry & Chemical Technology. 2026; 17(1): 73–86p.

INTRODUCTION

Petroleum based polymer like polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polystyrene (PS) have been widely used for many applications and majorly contributed in plastic pollution *(Mori, 2023 [1])*. It also contributed to global warming and takes 100 of years for degradation *(Dutta & Sit, 2024 [2])* and releases toxic gases and microplastic in environment *(Lakshmiganthan et al., 2025 [3])*. Recently, many researchers have focused on biodegradable polymer/plastic called biopolymer. Generally, biopolymers/bioplastics are classified into three main categories Natural biopolymer, Synthetic biopolymer and microbial biopolymers as shown in Figure 1 *(Singh et al., 2021 [4])*.

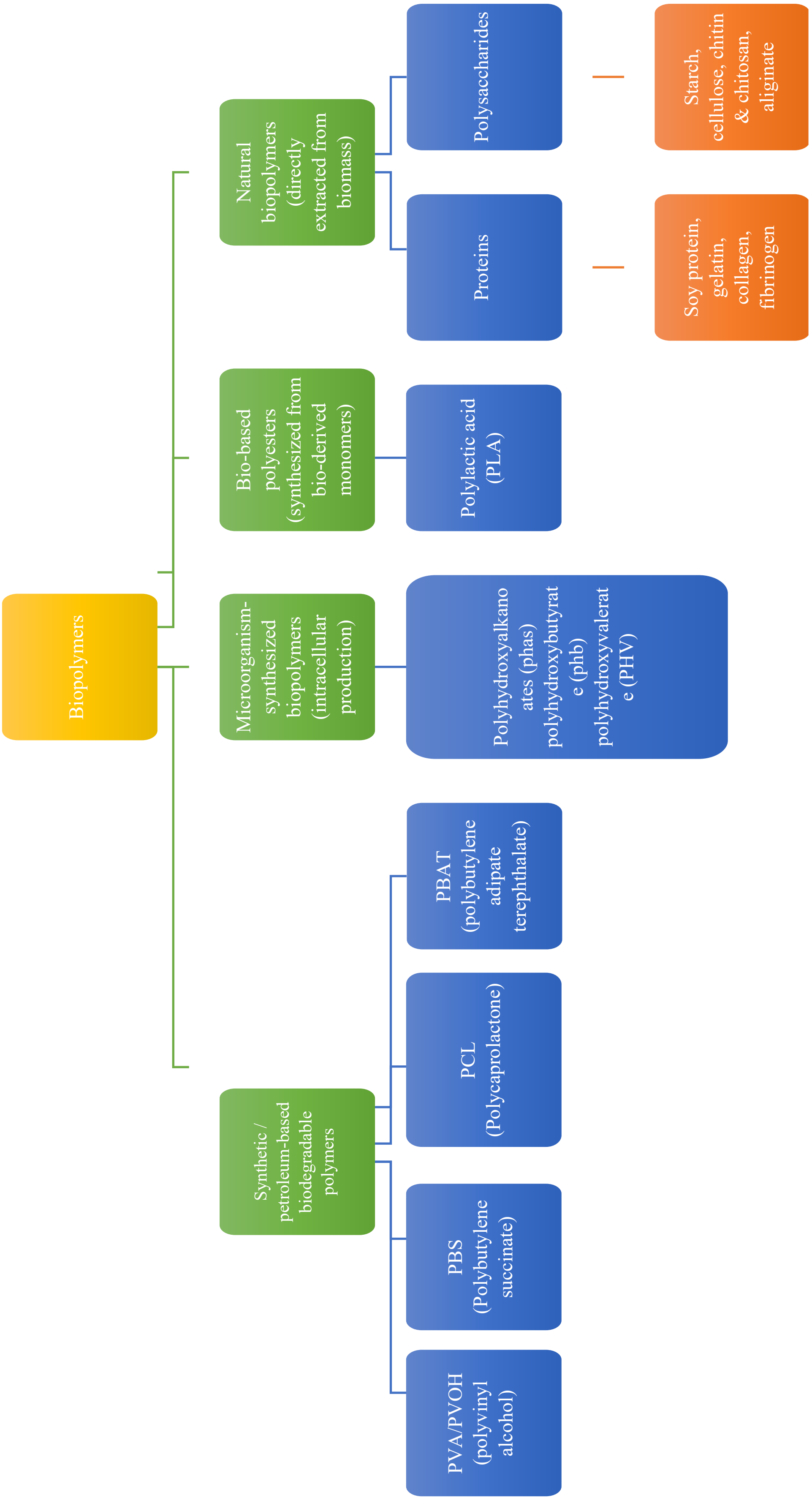

Figure 1. Classification of biodegradable polymers.

Natural biopolymer: Natural biopolymers are polymers that naturally occur in plants, animals, bacteria, fungi, yeast, and other organisms [5]. Some examples are starch, cellulose and chitin & chitosan, are the polysaccharide biopolymer and collagen, fibrinogen, soy protein and gelatin are the protein-based biopolymer, these polymers are biodegradable, eco-friendly and able to replace petroleum-based polymer *(Reddy et al., 2013 [6]; Caillol et al., 2020 [7]; Liu et al., 2023 [8]; Othman et al., 2025 [9])*.

Starch: It is a natural biopolymer that contains amylose and amylopectin, which are the two main polysaccharides generally made of glucose monomers *(Vardhan et al., 2025 [10])*. Starch is biodegradable, abundant, renewable, easily available, a low-cost biopolymer, and can be processed with conventional plastic processing equipment. Main source of starches are grains like corn, rice & wheat and tubers like potato and cassava (tapioca). Starch extraction and isolation are easy and affordable techniques. Washing, grinding, extraction, decantation and drying are the primary steps of wet extraction *(Jiang et al., 2020 [11])*. It is used in many industries primarily as a thickener, binder and stabilizer in foods, providing texture and consistency, for tablets in pharmaceuticals, paper manufacturing, cosmetics and because of its eco-friendly and biodegradable nature, researchers are focusing on preparing biodegradable polymer which is applicable for packaging *(Puri et al., 2025 [12])*.

Cellulose: Cellulose is the most abundant organic polymer homo-polysaccharide on earth, available in plant cell walls, made of glucose units, having the formula $(C_6H_{10}O_5)_n$ *(Etale et al., 2023 [13])*. Cellulose is a nontoxic, biocompatible, biodegradable organic polymer produced by many organisms and available in a wide range of plant and agricultural wastes and is compatible for generating biopolymer *(Kour et al., 2025 [14])*. Cellulose can be extracted from various sources such as wood pulp, rice husk, corn waste, wheat waste, coffee waste, banana peel, sisal fibers, sugarcane bagasse (SCB) and many other sources by applying chemical and mechanical techniques; pre-hydrolysis, pulping and bleaching are the three major steps of cellulose extraction *(Chopra et al., 2022 [15])*. Cellulose is used in many industries like medical and pharmaceutical, paper and pulp industry, biofuels and bioplastics. Cellulose can be combined with other material to produce a compatible eco-friendly biopolymer *(Marinho, 2025 [16])*.

Chitin & Chitosan: Chitin is a polysaccharide found in a variety of biomass, crustacean exoskeletons, insects and fish scales. Chemical treatment, biotechnological techniques and microwave irradiation are the common extraction methods used to extract chitin. Chitosan is produced by deacetylation of chitin. It is the second most abundant natural biopolymer offering biodegradability, biocompatibility, nontoxicity and antimicrobial activity, applicable in various fields like piezoelectric materials, biomedical applications, sensing layers for sensors and food packaging *(Hisham et al., 2024 [17])*.

Alginate: Alginate is a polysaccharide-based hydrophilic biopolymer mainly extracted from marine brown algae, having good film-forming properties, low permeability to O_2 and vapors, flexibility and water solubility *(Kontominas, 2020 [18])*. Commercial alginate extraction techniques include acid treatment, alkaline treatment, clarification, precipitation followed by drying; modern techniques such as ultrasound-assisted extraction and microwave techniques are also used *(Bojorges et al., 2023 [19])*.

Collagen: Collagen is a biodegradable natural polymer consisting of repeated protein units (amino acids), mostly extracted from skin and bones of bovine and porcine vertebrates and is commercially applicable in various industrial sectors like medical, pharmaceutical, nutraceutical, and cosmetic *(Fatiroi et al., 2023 [20]; Dey et al., 2025 [21])*. It is a widely used biopolymer to create biodegradable polymeric films for packaging because of its excellent film-forming, oxygen barrier, and antioxidant properties. However, lower mechanical strength, poor water resistance, and low thermal stability are major disadvantages that limit its application; proper combination with other materials can improve performance in food preservation *(Meenu et al., 2025 [22])*.

Fibrinogen: Fibrinogen is a biodegradable glycoprotein synthesised by the liver forming fibrin; it is a natural polymer used for wound sealing, drug delivery, and tissue engineering *(Sanz-Horta et al., 2023 [23])*.

Soy protein: Soy protein is a renewable and biodegradable biopolymer extracted from soybean plants and widely used in biochemical applications because of its biodegradability, abundance, and easy availability at low cost *(Sabouri & Khakyzadeh, 2024 [24])*. Soy protein properties can be improved by proper combination with other materials to make it applicable in the food packaging sector *(Ly et al., 1998 [25])*.

Gelatin: Gelatin is a protein-based natural polymer; skin and bones of pigs and cattle are the most common sources, however fish and insects are also good sources *(Lu et al., 2022 [26])*. Acid extraction, ultrasound-assisted extraction, enzymatic extraction, high-pressure extraction, and ohmic heating are commonly used methods *(Xu et al., 2025 [27])*. Gelatin is a non-toxic, biocompatible, and biodegradable polymer containing proline, glycine, and hydroxyproline; it has excellent film-forming ability, which helps to form flexible films. Blending with other biopolymers makes it suitable for food preservation applications *(Ye et al., 2022 [28])*.

Synthetic biopolymer: Synthetic biopolymers are synthesized from natural or synthetic monomers, offering biodegradability, biocompatibility, renewability, and non-toxicity. These properties make them promising alternatives to petroleum-based polymers, which are non-degradable and harmful to the environment *(Rahman & Hasan, 2019 [29]; Perera et al., 2023 [30])*. Synthetic polymers like PLA, PBAT, polyhydroxyalkanoate (PHA), polybutylene succinate (PBS), polyhydroxybutyrate (PHB), and polycaprolactone (PCL) are commonly used in the food preservation and packaging sector *(Perera et al., 2023 [30]; Trivedi et al., 2023 [31])*.

PLA: PLA is a thermoplastic biodegradable aliphatic polyester synthesized from lactic acid monomers via bacterial fermentation of natural agricultural sources like potatoes, corn, and sugar beet; *Lactobacillus* bacteria are mostly used in fermentation to produce lactic acid *(De Luca et al., 2023 [32])*. Good transparency, high tensile strength, and moderate gas barrier properties make it a strong competitor to conventional polymers. However, low thermal stability, poor water vapor barrier properties, and high production costs limit its applications in packaging. Material modification through plasticizers, blending, compounding with other polymers, and reinforcement with nanoparticles can improve its properties and make it suitable for food preservation and packaging *(Lyn et al., 2024 [33])*.

PBAT: PBAT (polybutylene adipate terephthalate) is a petroleum-based, fully biodegradable, eco-friendly, and highly flexible polymer *(Roy et al., 2024 [34])*. PBAT is synthesized by a two-stage melt polycondensation technique involving esterification/transesterification followed by polycondensation of adipic acid (AA), 1,4-butanediol (BDO), and terephthalic acid (PTA) *(Jian et al., 2020 [35])*. Its exceptional film-forming ability, high elongation at break, and good processing ability make it a promising alternative to low-density polyethylene *(Itabana et al., 2024 [36])*.

PHA: Polyhydroxyalkanoates (PHA) are polyesters produced naturally by microorganisms (*Alcaligenes latus, Azotobacter vinelandii, Bacillus megaterium, Cupriavidus necator, Escherichia coli,* and *Pseudomonas oleovorans*) as energy storage materials *(Bolla et al., 2025 [37])*. Properties like biodegradability, biocompatibility, and renewability make them suitable alternatives to petroleum-based polymers; however, high processing cost and limited mechanical strength restrict their widespread use. Good processability, flexibility, rigidity, and impact resistance increase their application in the packaging sector *(Kusuma et al., 2024 [38])*.

PBS: Polybutylene succinate (PBS) is an aliphatic polyester that can be synthesized from succinic acid and 1,4-butanediol. Its biodegradability, compostability, good mechanical endurance, ductility, toughness, and remarkable thermal resistance (above 90°C) make it suitable for packaging applications *(Barletta et al., 2022 [39])*. This polymer is produced by polymerization of monomers obtained either from renewable resources (sugarcane, cassava, and corn) or fossil fuels *(Aliotta et al., 2022 [40])*.

PHB: Polyhydroxybutyrate (PHB) is the most commercially used bio-based biodegradable polyester preferred for food packaging *(Briassoulis et al., 2022 [41])*. Polyhydroxyalkanoates (PHAs) are produced via microbial fermentation of natural, renewable carbon sources, including plant/animal oils, carbohydrates, fatty acids, sugars, and alkanes *(Stublić et al., 2024 [42])*. The most extensively used bacterial strains for fermentation include *Bacillus megaterium, Ralstonia eutropha (Cupriavidus necator), Haloferax mediterranei, Pseudomonas putida, Azotobacter, Syntrophomonas, Aeromonas,* and *Clostridium (Chouhan & Tiwari, 2025 [43])*. PHB offers an excellent barrier against moisture due to its hydrophobic nature and also provides a barrier against O_2 and CO_2. It is a promising alternative to polypropylene because of its excellent properties such as high melting point (~175°C), high crystallinity, and strong tensile strength *(Li et al., 2025 [44])*. PHB is used to prepare containers, trays, and films. Proper blending with other polymers like PCL or PLA can improve flexibility and reduce brittleness.

PCL: Polycaprolactone (PCL) is a petroleum-based biodegradable, flexible, and biocompatible thermoplastic polyester widely used for sustainable packaging, particularly in food, medical, and agricultural industries. Its low melting point (~60°C) and high compatibility with other polymers make it ideal for producing films, coatings, and blended compostable materials. It is easily processed at temperatures around 59–64°C *(Richert et al., 2023 [45])*. There are two methods for synthesizing PCL: ring-opening polymerization (caprolactone) and polycondensation (hydroxycarboxylic acid) *(Ntrivala et al., 2025 [46])*.

Film Preparation Technique

Solution casting: The solution casting method is generally used to prepare polymeric films at laboratory or small-scale production. In this method, a solution is prepared by dissolving the polymer in water or a suitable solvent and continuously agitated to obtain a homogeneous solution; the film is then cast on glass by solvent evaporation *(Kumbhare et al., 2018 [47])*. Properties of the film can be affected by solution concentration, evaporation rate, and the addition of plasticizers, fillers, or other materials *(Dhalsamant et al., 2025 [48])*. Pooja et al. prepared more flexible potato starch and corn starch films with uniform distribution of plasticizer (glycerol) using the solution casting method *(Pooja et al., 2024 [49])*. In another study, various corn-based starch films were produced by varying the concentration of starch and glycerol using solution casting, with an average thickness between 0.25 to 0.45 mm *(Nasir & Othman, 2021 [50])*.

Extrusion method: This method is mostly used in industries to prepare films. In this process, polymer enters a screw extruder where it is melted, mixed, and forced through a die to form a film. Combining with blowing and calendaring techniques can help modify film properties *(Dhalsamant et al., 2025 [48])*.

Electrospinning: This is a newer technique successfully applied for preparing films for food packaging. It uses high-voltage electricity to produce ultrathin fibers (nano- to micro-scale). After thermal post-treatment (annealing) above the glass transition and below the melting temperature, polymers reduce porosity and form continuous and homogeneous films with excellent barrier properties. This technique is mainly used for carbohydrate-based materials *(Akinalan et al., 2019 [51]; Dhalsamant et al., 2025 [48])*.

Layer-by-layer assembly, three-dimensional printing, and spray coating are also recent methods used in food preservation packaging *(Dhalsamant et al., 2025 [48])*.

Important Properties of Biopolymers for Food Packaging

Various properties play an important role in food packaging. Properties like barrier, mechanical, chemical, and thermal properties are crucial. Barrier properties help isolate food from the external environment. Mechanical properties indicate the strength of the packaging film, while chemical resistance prevents absorption and interaction with food chemicals and external gases. Thermal properties make packaging suitable for high temperatures. Proper crosslinking is necessary to improve tensile strength, water resistance, and gas barrier properties as shown in Table 1.

Barrier: Barrier properties play an important role in the food packaging and preservation sector, as they separate the food product from the immediate environment. Gas, water vapour, organic vapours, and liquid barrier properties are essential for maintaining product quality and shelf life *(Perera et al., 2023 [30])*. Most biopolymers are hydrophilic in nature, resulting in high water solubility and poor barrier properties. Gas and oxygen permeability can affect odour, colour, taste, and lead to food deterioration *(Pires et al., 2021 [52])*. Barrier properties are mainly affected by glass transition temperature and film formation method *(Kumbhare & Sapkal, 2022 [53])*. Additionally, branching level, polymer chain flexibility, and degree of crystallinity also influence barrier performance *(Öhman, 2018 [54])*. ASTM standard methods are generally used to measure Water Vapor Permeability (WVP), Oxygen Transmission Rate (OTR), and Carbon Dioxide Transmission Rate (CO_2TR) *(Pires et al., 2021 [52])*.

Mechanical Properties: Desired mechanical properties are essential to protect packaging material during handling, storage, and processing of food. Mechanical properties of packaging films are determined by tensile strength, elongation at break, and Young's modulus *(Perera et al., 2023 [52])*. These properties are influenced by factors such as the nature of the polymer, preparation method, film composition, crystallinity, barrier properties, and thermal stability *(Shah et al., 2023 [55])*. A high value of Young's modulus indicates higher rigidity of the material *(Lakshmiganthan et al., 2025 [3])*.

Thermal Properties: Food packaging films prepared from biopolymers such as starch, cellulose, and proteins generally have lower thermal stability compared to PE and PP, but this can be improved through structural modification and blending with other materials *(Shah et al., 2024 [56])*. Thermal properties such as glass transition temperature (Tg), melting temperature (T_m), and decomposition temperature (T_e) can be determined using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) *(Chirayil et al., 2024 [57])*.

Various Biodegradable Polymeric/Composite Films for Food Preservation and Packaging

Various plasticizers are used in biodegradable polymers to alter or improve properties like flexibility, processability, and degradability. Glycerol and fructose are widely used plasticizers. The addition of plasticizers increases hydrophilicity, enhances water absorption, and promotes microbial attack, resulting in faster biodegradability *(Lakshmiganthan et al., 2025 [3])*. Various corn starch films were prepared by adding glycerol, fructose, and glycerol/fructose; results showed that plasticizer addition increases water solubility and decreases tensile strength and Young's modulus. Mohammed et al. prepared wheat starch biofilms using different plasticizers such as glycerol (G), fructose (F), sorbitol (S), and urea (U), and studied their effects on morphological, mechanical, thermal, and physical properties; results showed improved water resistance *(Mohammed et al., 2022 [58])*.

In another study, cellulose–glycerol bioplastic films were prepared by the solution casting method, showing that glycerol increases water and oxygen permeability while maintaining transparency *(Benitez et al., 2024 [59])*. Cellulose bioplastics with antimicrobial and antioxidant properties were developed by adding beeswax; this increased the crystallinity of the film *(Florido-Moreno et al., 2025 [60])*.

Soiklom et al. prepared carboxymethyl cellulose (CMC) films blended with glycerol, PEG, and sorbitol, where sorbitol improved mechanical strength and solubility *(Soiklom et al., 2025 [61])*.

Table 1. Comparative properties of natural, composite and synthetic biodegradable polymeric films

Biopolymer Film	**Plasticizer/ polymers**	**Tensile strength (MPa)**	**Elongation at break (%)**	**Young's modulus (MPa)**	**Water Contact angle (WAC)<90° >**	**Water solubility (%)**	**Ref.**
Natural biodegradable polymer							
Corn Starch	–	21	Apx 25	Apx 110	–	10	Lakshmiganthan et al., 2025 [3]
Corn Starch	Glycerol	–	–	–	32.11°–35.50	–	Pooja et al., 2024 [49]
Corn Starch	Glycerol	0.15-1.28	12.69-20.09	1.31-14.68	–	–	Nasir & Othman, 2021
Corn Starch	Glycerol	5.09-2.75	37.13-35.24	Apx 25	–	37.4-51.2	Lakshmiganthan et al., 2025 [3]
Corn Starch	fructose	22.55-8.67	Apx 90	Apx 105	–	33.98-52.78	Lakshmiganthan et al., 2025 [3]
Corn Starch	Glycerol/ fructose	16.65-4.52	Apx 80	Apx 90	–	33.98-52.78	Lakshmiganthan et al., 2025 [3]
Potato Starch	Glycerol	–	–	–	44.12°–48.73°	–	Pooja et al., 2024 [49]
Wheat Starch	–-	37.81	1.94	1629.8	–	2.54	Mohammed et al., 2022 [58]
Wheat Starch	Glycerol	22.8-6.35	4.4-47.2	1119-68.76	–	12.92-20.00	Mohammed et al., 2022 [58]
Wheat Starch	fructose	18.99-7.6	9.41-47.5	822.22-152.54	–	14.92-29.02	Mohammed et al., 2022 [58]
Wheat Starch	Sorbitol	25.3-6.35	3.3-60.7	1230.3-121	–	15.19-28.00	Mohammed et al., 2022 [58]
Wheat Starch	Urea	5.64-1.12	32.3-54.1	224.14 -6.56	–	13.29-20.42	Mohammed et al., 2022 [58]
Cellulose	–	65	4	3384	–	–	Benitez et al.,2024 [59]
Cellulose	Glycerol	18	49	1218- 358	–	–	Benitez et al.,2024 [59]
Chitosan	Acetic acid	16.43	189	2.143	–	–	Bhuvaneshwari et al., 2011 [62]
Chitosan	Acetic acid/coconut fiber	52.34	60.2	0.468	–	–	Bhuvaneshwari et al., 2011 [62]
Natural/composite film							
Cellulose+ Glycerol	Beeswax	20-8	12%-4%	673- 481	–	–	Florido-Moreno et al., 2025 [60]
CMCss (Carboxymethyl Cellulose)	PEG	0.058 to 0.02	–	–	–	–	Soiklom et al., 2025 [61]
CMCss	Glycerol	0.075-0.001	–	–	–	–	Soiklom et al., 2025 [61]

CMCss	Sorbitol	0.42 to 0.22	–	–	–	–	Soiklom et al., 2025 [61]
Sodium Alginate (SA)	---	83.01± 2.9	9.64 ± 1.10	–	50°	–	Zhou et al.,2024 [63]
Sodium Alginate (SA)	Cinnamaldehyde (CA)	87.07- 43.37	24.49- 11.89	–	50°-86°	–	Zhou et al.,2024 [63]
Collagen-based	Starch, Sodium Carboxymethyl Cellulose, and Sodium Alginate (glutaraldehyde as cross-linking agent and glycerol as humectant	24- 287	76%	–	–	–	Yang et al., 2014 [64]
Gelatin	Chitosan 1%	12.32±0.37	16.84±1.04	–	–	–	Momtaz et al., 2024 [65]
Gelatin	Chitosan 2%	23.83±1.09	22.53±0.72	–	–	23.68±0.34	Momtaz et al., 2024 [65]
Gelatin/Chitosan	Nickel oxide nanoparticles (NiONPs) 0.5-2%	26.45-26.61	26.43- 20.00	–	–	22.46-21.02	Momtaz et al., 2024 [65]
Synthetic biodegradable polymers							
PLA	–	58.4	11.7	2430	–	–	Di Maio et al., 2014 [66]
PLA	Microparticles a-tocopherol	34.2	22.8	2170	–	–	Di Maio et al., 2014 [66]
PBAT	–	15 – 34	508 – 670	74	–	–	Dutta & Sit., 2024 and Singh et al., 2021 [2]
PBAT	–	20.1± 2.4	689.5± 110.3	81.0± 2.5	–	–	(de Matos Costa et al, 2020) [67]
Poly (butylene adipate-co-terephthalate) (PBAT)	–	30.04 ± 2.50	353 ± 6.00	80.00 ± 5.00	72.2°	–	Niksefat et al., 2025 [68]
PBAT	PBS 25%	22.7±1.1	393.1± 13.0	134.9± 1.1	–	–	de Matos Costa et al, 2020[67]
PBAT	PBS 50%	15.2	16.4±0.3	299.8±4.0	–	–	de Matos Costa et al, 2020 [67]
PBAT	PBS 75%	10.2 ± 0.2	10.2±0.3	488.8 ± 7.2	–	–	de Matos Costa et al, 2020 [67]
PBAT	Tannic Acid (TA)	23.97 ± 2.99	284.67 ± 5.77	73.33 ± 15.28	78.2°	–	Niksefat et al., 2025 [68]
PBAT	Zinc Sulfide (ZnS)	25.94 ± 3.87	290.00 ± 9.17	86.67 ± 15.28	65.0°	–	Niksefat et al., 2025 [68]
PBAT	Tannic Acid (TA)/Zinc Sulfide (ZnS)	20.85 ± 1.30	274.33 ± 20.22	70.00 ± 17.32	81.6°	–	Niksefat et al., 2025 [68]
PBS	–	29.6 ± 1.5	7.1 ± 0.3	725.6 ± 15.6	–	–	de Matos Costa et al, 2020 [67]

PHA (peanut oil)	–	2.7 ± 0.2	25.7 ± 1.5	75.8 ± 6.3	–	–	Pérez-Arauz et.al., 2019 [69]
PHB	–	20±0.7	5.8±0.2	820±39.7	–-	–	Pérez-Arauz et.al., 2019 [69]
PHB	–	9.7 ± 0.15	2.5 ± 0.5	–	–	–	Mittal et al., 2023 [70]
PHB	PEG/CEO	7.1 ± 0.14	6.5 ± 1.00	–	–	–	Mittal et al., 2023 [70]
PHB	PEG/CEO/Si 1%	17.3	10.0 ± 4.00	–	–	–	Mittal et al., 2023 [70]
PCL	–	29.59±1.22	302.96±46.54	–	–	–	Lyu et al., 2019 [71]
PCL	GSE 1%	28.31±1.08	334.87±20.71	–	–	–	Lyu et al., 2019 [72]
PCL	GSE 3%	27.99±1.73	360.96±25.62	–	–	–	Lyu et al., 2019 [72]
PCL	GSE 5%	27.31±2.27	360.53±15.13	–	–	–	Lyu et al., 2019 [72]
Polyethylene (PE)	–	10–30	100–1000%	–	–	–	Moraczewski et al., 2025 [73]
polypropylene (PP)	–	25–40	100–600%	–	–	–	Moraczewski et al., 2025 [73]
Polyethylene terephthalate (PET)	–	50–80	50–150%	–	–	–	Moraczewski et al., 2025 [73]
Poly (vinyl chloride) (rigid)	–	40–80	20–40%	–	–	–	Moraczewski et al., 2025 [73]

Priyadarshi and Rhim concluded that chitosan is a promising biopolymer compared to other biopolymers and petroleum-based polymers due to its antimicrobial activity, chelation ability, film-forming properties, and decent mechanical strength; further modification and blending can enhance its applications *(Priyadarshi & Rhim, 2020 [74])*. Bhuvaneshwari et al. developed and characterized chitosan films and observed that reinforcement with cellulose from coconut improved thermal stability, reduced swelling ratio and water vapor permeability, and increased contact angle *(Bhuvaneshwari et al., 2011 [62])*.

Zhou et al. developed alginate-based films incorporated with cinnamaldehyde (CA) for fruit preservation, showing excellent mechanical, antimicrobial, and antioxidant properties; CA reduced film hydrophilicity and enhanced its potential as a petroleum-based packaging alternative *(Zhou et al., 2024 [63])*. Yang et al. prepared composite films of collagen blended with sodium alginate, starch, and sodium carboxymethyl cellulose; increasing alginate concentration improved elongation at break, tensile strength, and intermolecular interactions *(Yang et al., 2014 [64])*.

Momtaz et al. developed gelatin/chitosan nanocomposite films incorporating NiO nanoparticles via casting, showing good antibacterial behavior and improved barrier, thermal, and mechanical properties *(Momtaz et al., 2024 [65])*.

PLA is a biodegradable, transparent thermoplastic with good mechanical durability and processability; however, its high glass transition temperature ($T_g \approx 60°C$), rigidity, and brittleness limit its applications where flexibility is required. These properties can be improved by compounding with plasticizers, additives, fillers, and other polymers *(Hasanoglu et al., 2024 [75])*. Di Maio et al. developed biodegradable active PLA films incorporating α-tocopherol microparticles; results showed improved ductility without affecting optical and oxygen barrier properties *(Di Maio et al., 2014 [66])*.

Niksefat et al. developed PBAT-based nanocomposite films incorporating tannic acid (TA)/ZnS hybrids; results showed that TA improved hydrophobicity while ZnS reduced it *(Niksefat et al., 2025 [68])*.

Polyhydroxyalkanoates (PHA) are biodegradable polymers produced from renewable sources and may exist as homo-, co-, or heteropolymers depending on monomer composition. Short-chain-length (PHAscl) and medium-chain-length (PHAmcl) PHAs are the main types. *Cupriavidus necator* produces PHAscl such as PHB *(Pérez-Arauz et al., 2019 [69])*. PHB is a crystalline thermoplastic with excellent barrier properties and biodegradability, but its hardness and brittleness limit its applications *(Mittal et al., 2023 [70])*. A novel PHA film synthesized from peanut oil showed lower elastic modulus and increased elongation at break (up to 70%) along with higher permeability *(Pérez-Arauz et al., 2019 [69])*. Mittal et al. prepared PHB films incorporating PEG (plasticizer), nano-silica (reinforcement), and clove essential oil (antimicrobial); PEG reduced mechanical strength while nano-silica improved it *(Mittal et al., 2023 [70])*.

PBS is a biodegradable hydrophilic polymer suitable for film casting, with mechanical properties similar to low-density polyethylene (LDPE). Its barrier properties are comparable to PLA and can be improved by blending with polyvinyl alcohol (PVOH), which reduces oxygen permeability *(Barbato et al., 2023 [71])*. De Matos Costa et al. prepared PBAT, PBS, and PBAT/PBS blend films and reported that gas permeability decreases with increasing PBS content, while elongation at break increases with higher PBAT content *(de Matos Costa et al., 2020 [67])*.

PCL is a semi-crystalline hydrophobic biodegradable polyester with a low melting point (~60°C) and glass transition temperature (~−60°C), making it easy to process but limiting its application in food packaging *(Lyu et al., 2019 [72])*. Lyu et al. developed PCL and PCL/GSE composite films incorporating grapefruit seed extract (GSE) as an antimicrobial agent; results showed reduced tensile strength and increased elongation at break *(Lyu et al., 2019 [72])*.

CONCLUSION

Biopolymers are produced from natural organisms like plants, animals, and microorganism are mostly hydrophilic in nature. Films developed by natural polymers allow water to penetrate in film and initiate enzymatic activities, break biopolymer into smaller polymer chains or monomer and further converted in biomass, water and CO_2. Addition of plasticizer like glycerol, fructose and sorbitol in a biopolymer like corn-starch increases water and oxygen permeability, which increases the flexibility, processability and biodegradability; on the other hand, it reduces mechanical strength. But in some starch (wheat starch) plasticizer increases water resistance. Film prepared by cellulose is a quite transparent film; the addition of plasticizers improves water and oxygen permeability. Beeswax in cellulose film increases the crystallinity. Glycerol, PEG, and sorbitol improve mechanical strength and solubility. Chitosan has an antimicrobial property with adequate mechanical strength; the incorporation of other polymers/plasticizers in a proper composition can improve thermal stability and contact angle. Alginate and gelatine applications in the food packaging area are limited, but blending with other biopolymer or nanoparticles can improve their thermal, mechanical, antibacterial and barrier properties. Synthetic biopolymers like PLA is a most suitable comparators to petroleum-based polymers because of their hydrophobicity, biodegradability and good optical & processability properties, high glass transition temperature restricts their application in packaging sector. Compared to PLA, polybutylene adipate terephthalate (PBAT) is a flexible, soft, having low glass transition temperature and biodegradable petroleum-based polymer that can be used as an alternative to PE, but has quite lower strength and higher costs as compared to PE. PHA/PHB film is biodegradable offering excellent barrier properties, but still struggling in the packaging sector due to their hardness and brittleness. PCL is a semicrystalline easy processable biodegradable polymer but their low melting point restrict their applications in packaging sector. Some synthetic biopolymers having potential to compete with the petroleum-based nondegradable polymer their properties are quite similar. However, surface modification or modification in structure by incorporation of other plasticizers, polymer or nano particles can enhance their application in food packaging and preservation sector.

REFERENCES

1. Mori, R. (2023). Replacing all petroleum-based chemical products with natural biomass-based chemical products: a tutorial review. RSC Sustainability, 1(2), 179–212.
2. Dutta, D., & Sit, N. (2024). A comprehensive review on types and properties of biopolymers as sustainable bio-based alternatives for packaging. Food Biomacromolecules, 1(2), 58–87.
3. Lakshmiganthan, S. M., Rao, V. S., Rengarajan, S., & Srividhya, S. (2025). Environmental assessment of corn starch based biodegradable plastic with glycerol and fructose. GLOBAL NEST JOURNAL, 27(4).
4. Singh, R., Gautam, S., Sharma, B., Jain, P., & Chauhan, K. D. (2021). Biopolymers and their classifications. In Biopolymers and their industrial applications (pp. 21–44). Elsevier.
5. Singh, R. S., Saini, G. K., & Kennedy, J. F. (2008). Pullulan: microbial sources, production and applications. Carbohydrate polymers, 73(4), 515–531.
6. Reddy, M. M., Vivekanandhan, S., Misra, M., Bhatia, S. K., & Mohanty, A. K. (2013). Biobased plastics and bionanocomposites: Current status and future opportunities. Progress in polymer science, 38(10–11), 1653–1689.
7. Caillol, S. (2020). Special issue “natural polymers and biopolymers II”. Molecules, 26(1), 112.
8. Liu, L., Liang, W., Zhang, Y., & Fu, Q. (2023). Nanoencapsulation in polymeric materials: weaving magical coats for microorganisms. Nano Today, 52, 101973.
9. Othman, S. H., Zaid, N. S., Shapi'i, R. A., Nordin, N., Talib, R. A., & Tawakkal, I. S. M. A. (2025). Starch biopolymer films containing carbon black nanoparticles: Properties and active food packaging application. Journal of Science: Advanced Materials and Devices, 10(4), 100995.
10. Vardhan, H., Singhal, N., Vashistha, P., Jain, R., Bist, Y., Gaur, A., & Wagri, N. K. (2025). Starch–biomacromolecule complexes: A comprehensive review of interactions, functional materials, and applications in food, pharma, and packaging. Carbohydrate Polymer Technologies and Applications, 101001.
11. Jiang, T., Duan, Q., Zhu, J., Liu, H., & Yu, L. (2020). Starch-based biodegradable materials: Challenges and opportunities. Advanced Industrial and Engineering Polymer Research, 3(1), 8–18.
12. Puri, A., Mohite, P., Ramole, A., Verma, S., Kamble, M., Ranch, K., & Singh, S. (2025). Starch Science Advancement: Isolation Techniques, Modification Strategies, and Multifaceted Applications. Macromol, 5(3), 40.
13. Etale, A., Onyianta, A. J., Turner, S. R., & Eichhorn, S. J. (2023). Cellulose: a review of water interactions, applications in composites, and water treatment. Chemical reviews, 123(5), 2016–2048.
14. Kour, M., Chaudhary, S., & Kumar, R. (2025). Cellulose based bioplastics: A sustainable approach toward environmental safety-A review. Sustainable Materials and Technologies, e01694.
15. Chopra, L. (2022). Extraction of cellulosic fibers from the natural resources: A short review. Materials Today: Proceedings, 48, 1265–1270.
16. Marinho, E. (2025). Cellulose: A comprehensive review of its properties and applications. Sustainable Chemistry for the Environment, 100283.
17. Hisham, F., Akmal, M. M., Ahmad, F., Ahmad, K., & Samat, N. (2024). Biopolymer chitosan: Potential sources, extraction methods, and emerging applications. Ain Shams Engineering Journal, 15(2), 102424.
18. Kontominas, M. G. (2020). Use of Alginates as Food Packaging Materials.Foods,9(10), 1440. https://doi.org/10.3390/foods9101440
19. Bojorges, H., López-Rubio, A., Martínez-Abad, A., & Fabra, M. J. (2023). Overview of alginate extraction processes: Impact on alginate molecular structure and techno-functional properties. Trends in Food Science & Technology, 140, 104142.

20. Fatiroi, N. S., Jaziri, A. A., Shapawi, R., Mokhtar, R. A. M., Noordin, W. N. M., & Huda, N. (2023). Biochemical and microstructural characteristics of collagen biopolymer from unicornfish (Naso reticulatus Randall, 2001) bone prepared with various acid types. Polymers, 15(4), 1054.
21. Dey, A. K., Pal, S., Das, S., Mandal, D., Debnath, B., De, A., & Nayak, A. K. (2025). Versatility of Collagen as a Natural Biopolymer for Biomedical, Food, and Cosmetic Applications. Current Protein & Peptide Science.
22. Meenu, M., Kaur, A., Katiyar, S., Mradula, M., Rana, H., Yu, Y., & Liu, Y. (2025). Development and innovations in collagen-based packaging for enhancing food safety and shelf life. Trends in Food Science & Technology, 105321.
23. Sanz-Horta, R., Matesanz, A., Gallardo, A., Reinecke, H., Jorcano, J. L., Acedo, P., ... & Elvira, C. (2023). Technological advances in fibrin for tissue engineering. Journal of tissue engineering, 14, 20417314231190288.
24. Sabouri, F., & Khakyzadeh, V. (2024). Study of Soy Protein as an Unique Biopolymer in Modern Bio-Composite Systems.
25. Ly, Y. P., Johnson, L. A., & Jane, J. (1998). Soy protein as biopolymer. In Biopolymers from renewable resources (pp. 144-176). Berlin, Heidelberg: Springer Berlin Heidelberg.
26. Lu, Y., Luo, Q., Chu, Y., Tao, N., Deng, S., Wang, L., & Li, L. (2022). Application of gelatin in food packaging: A review. Polymers, 14(3), 436.
27. Xu, X., Xi, Y., & Weng, Y. (2025). Gelatin-based materials: fabrication, properties and applications in the food packaging system. RSC advances, 15(37), 30605–30621.
28. Ye, X., Liu, R., Qi, X., Wang, X., Wang, Y., Chen, Q., & Gao, X. (2022). Preparation of bioactive gelatin film using semi-refined pectin reclaimed from blueberry juice pomace: Creating an oxidation and light barrier for food packaging. Food Hydrocolloids, 129, 107673.
29. Rahman, M., Hasan, M.R. (2019). Synthetic Biopolymers. In: Jafar Mazumder, M., Sheardown, H., Al-Ahmed, A. (eds) Functional Biopolymers. Polymers and Polymeric Composites: A Reference Series. Springer, Cham. https://doi.org/10.1007/978-3-319-95990-0_1.
30. Perera, K. Y., Jaiswal, A. K., & Jaiswal, S. (2023). Biopolymer-Based Sustainable Food Packaging Materials: Challenges, Solutions, and Applications. Foods, 12(12), 2422. https://doi.org/10.3390/foods12122422
31. Trivedi, A. K., Gupta, M. K., & Singh, H. (2023). PLA based biocomposites for sustainable products: A review. Advanced Industrial and Engineering Polymer Research, 6(4), 382–395.
32. De Luca, S., Milanese, D., Gallichi-Nottiani, D., Cavazza, A., & Sciancalepore, C. (2023). Poly (lactic acid) and its blends for packaging application: a review. Clean Technologies, 5(4), 1304–1343.
33. Lyn, F. H., Ismail-Fitry, M. R., Noranizan, M. A., Tan, T. B., & Hanani, Z. N. (2024). Recent advances in extruded polylactic acid-based composites for food packaging: A review. International Journal of Biological Macromolecules, 266, 131340.
34. Roy, S., Ghosh, T., Zhang, W., & Rhim, J. W. (2024). Recent progress in PBAT-based films and food packaging applications: A mini-review. Food Chemistry, 437, 137822.
35. Jian, J., Xiangbin, Z., & Xianbo, H. (2020). An overview on synthesis, properties and applications of poly (butylene-adipate-co-terephthalate)–PBAT. Advanced Industrial and Engineering Polymer Research, 3(1), 19–26.
36. Itabana, B. E., Mohanty, A. K., Dick, P., Sain, M., Bali, A., Tiessen, M., ... & Misra, M. (2024). Poly (Butylene Adipate-Co-Terephthalate)(PBAT)–Based Biocomposites: A Comprehensive Review. Macromolecular Materials and Engineering, 309(12), 2400179.
37. Bolla, M., Pettinato, M., Ferrari, P. F., Fabiano, B., & Perego, P. (2025). Polyhydroxyalkanoates production from laboratory to industrial scale: A review. International Journal of Biological Macromolecules, 143255.

38. Kusuma, H. S., Sabita, A., Putri, N. A., Azliza, N., Illiyanasafa, N., Darmokoesoemo, H., ... & Kurniawan, T. A. (2024). Waste to wealth: Polyhydroxyalkanoates (PHA) production from food waste for a sustainable packaging paradigm. Food Chemistry: Molecular Sciences, 9, 100225.
39. Barletta, M., Aversa, C., Ayyoob, M., Gisario, A., Hamad, K., Mehrpouya, M., & Vahabi, H. (2022). Poly (butylene succinate)(PBS): Materials, processing, and industrial applications. Progress in Polymer Science, 132, 101579.
40. Aliotta, L., Seggiani, M., Lazzeri, A., Gigante, V., & Cinelli, P. (2022). A brief review of poly (butylene succinate)(PBS) and its main copolymers: synthesis, blends, composites, biodegradability, and applications. Polymers, 14(4), 844.
41. Briassoulis, D., Athanasoulia, I. G., & Tserotas, P. (2022). PHB/PLA plasticized by olive oil and carvacrol solvent-cast films with optimised ductility and physical ageing stability. Polymer Degradation and Stability, 200, 109958.
42. Stublić, K., Ranilović, J., Ocelić Bulatović, V., & Kučić Grgić, D. (2024). Advancing sustainability: utilizing bacterial polyhydroxyalkanoate for food packaging. Processes, 12(9), 1886.
43. Chouhan, A., & Tiwari, A. (2025). Production of polyhydroxyalkanoate (PHA) biopolymer from crop residue using bacteria as an alternative to plastics: a review. RSC advances, 15(15), 11845-11862.
44. Li, D., Yang, Y., Liu, R., Wu, Y., & Guo, F. (2025). Review of Biopolymer Polyhydroxybutyrate (PHB) and Blends: Modification of Thermal and Mechanical Properties via Additive Manufacturing Processing. Polymers, 17(22), 3083.
45. Richert, A., Olewnik-Kruszkowska, E., Malinowski, R., Kalwasińska, A., & Swiontek Brzezinska, M. (2023). Polycaprolactone-Based Films Incorporated with Birch Tar—Thermal, Physicochemical, Antibacterial, and Biodegradable Properties. Foods, 12(23), 4244.
46. Ntrivala, M. A., Pitsavas, A. C., Lazaridou, K., Baziakou, Z., Karavasili, D., Papadimitriou, M., ... & Bikiaris, D. N. (2025). Polycaprolactone (PCL): the biodegradable polyester shaping the future of materials–a review on synthesis, properties, biodegradation, applications and future perspectives. European Polymer Journal, 234, 114033.
47. Kumbhare, M. B., Sapkal, V. S., & Sapkal, R. S. (2018). A Review: Membrane for CO2 Separation from Syngas and Hydrogen. Int. J. Basic Appl. Res, 8, 651-677.
48. Dhalsamant, K., Dalai, A., Pattnaik, F., & Acharya, B. (2025). Biodegradable carbohydrate-based films for packaging agricultural products—A review. Polymers, 17(10), 1325.
49. Pooja, N., Banik, S., Chakraborty, I., Sudeeksha, H. C., Mal, S. S., Srisungsitthisunti, P., & Mazumder, N. (2024). Comparative analysis of biopolymer films derived from corn and potato starch with insights into morphological, structural and thermal properties. Discover Sustainability, 5(1), 467.
50. Nasir, N. N., & Othman, S. A. (2021). The Physical and Mechanical Properties of Corn-based Bioplastic Films with Different Starch and Glycerol Content. Journal of Physical Science, 32(3).
51. Akinalan Balik, B., Argin, S., Lagaron, J. M., & Torres-Giner, S. (2019). Preparation and characterization of electrospun pectin-based films and their application in sustainable aroma barrier multilayer packaging. Applied Sciences, 9(23), 5136.
52. Pires, J., Paula, C. D. D., Souza, V. G. L., Fernando, A. L., & Coelhoso, I. (2021). Understanding the barrier and mechanical behavior of different nanofillers in chitosan films for food packaging. Polymers, 13(5), 721.
53. Kumbhare M. B. & Sapkal V. S. (2022). Evaluation of PVAc-MgO Nanocomposite Membrane. IJEP, 42(6): 716–721 : Vol. 42 Issue. 6
54. Öhman, S. (2018). Characterization of biopolymers for barriers in food packaging. Chalmers Univ. Technol.
55. Shah, Y. A., Bhatia, S., Al-Harrasi, A., Afzaal, M., Saeed, F., Anwer, M. K., ... & Faisal, Z. (2023). Mechanical properties of protein-based food packaging materials. Polymers, 15(7), 1724.
56. Shah, Y. A., Bhatia, S., Al-Harrasi, A., Oz, F., Khan, M. H., Roy, S., ... & Pratap-Singh, A. (2024). Thermal properties of biopolymer films: Insights for sustainable food packaging applications. Food Engineering Reviews, 16(4), 497-512.

57. Chirayil, C. J., Joseph, A. M., Joy, J., Unnikrishnan, T. G., & Thomas, S. (2024). Thermal properties of modified biopolymers. In Handbook Natural Polymers (pp. 427-451). Elsevier.
58. Mohammed, A. A., Hasan, Z., Omran, A. A. B., Elfaghi, A. M., Khattak, M. A., Ilyas, R. A., & Sapuan, S. M. (2022). Effect of various plasticizers in different concentrations on physical, thermal, mechanical, and structural properties of wheat starch-based films. Polymers, 15(1), 63.
59. Benitez, J. J., Florido-Moreno, P., Porras-Vázquez, J. M., Tedeschi, G., Athanassiou, A., Heredia-Guerrero, J. A., & Guzman-Puyol, S. (2024). Transparent, plasticized cellulose-glycerol bioplastics for food packaging applications. International journal of biological macromolecules, 273, 132956.
60. Florido-Moreno, P., Benitez, J. J., Gonzalez-Buesa, J., Porras-Vazquez, J. M., Hierrezuelo, J., Grife-Ruiz, M., ... & Guzman-Puyol, S. (2025). Plasticized cellulose bioplastics with beeswax for the fabrication of multifunctional, biodegradable active food packaging. Food Hydrocolloids, 162, 110933.
61. Soiklom, S., Siri-anusornsak, W., Petchpoung, K., & Soiklom, S. (2025) Development of a New Sustainable Biopolymer Film Based on Carboxymethyl Cellulose Derived from Spirogyra Sp. Available at SSRN 5369120.
62. Bhuvaneshwari, S., Sruthi, D., Sivasubramanian, V., Niranjana, K., & Sugunabai, J. (2011). Development and characterization of chitosan film. Int. J. Eng. Res. Appl, 1(2), 292-299.
63. Zhou, T., Wang, H., Han, Q., Song, Z., Yu, D., Li, G., ... & Chen, X. (2024). Fabrication and characterization of an alginate-based film incorporated with cinnamaldehyde for fruit preservation. International Journal of Biological Macromolecules, 274, 133398.
64. Yang Hua, Y. H., Guo XiaoFeng, G. X., Chen XueXu, C. X., & Shu ZiBin, S. Z. (2014). Preparation and characterization of collagen food packaging film.
65. Momtaz, M., Momtaz, E., Mehrgardi, M. A., Momtaz, F., Narimani, T., & Poursina, F. (2024). Preparation and characterization of gelatin/chitosan nanocomposite reinforced by NiO nanoparticles as an active food packaging. Scientific reports, 14(1), 519.
66. Di Maio, L., Scarfato, P., Avallone, E., Galdi, M. R., & Incarnato, L. (2014, May). Preparation and characterization of biodegradable active PLA film for food packaging. In AIP conference proceedings (Vol. 1593, No. 1, pp. 338-341). American Institute of Physics.
67. de Matos Costa, A. R., Crocitti, A., Hecker de Carvalho, L., Carroccio, S. C., Cerruti, P., & Santagata, G. (2020). Properties of biodegradable films based on poly (butylene succinate)(PBS) and poly (butylene adipate-co-terephthalate)(PBAT) blends. Polymers, 12(10), 2317.
68. Niksefat, M., Bagheri, R., & Pourjavadi, A. (2025). Biodegradable PBAT films with in situ synthesized tannic acid/ZnS nanohybrids for active packaging, offering antioxidant, antibacterial, and UV-shielding properties. Scientific Reports.
69. Pérez-Arauz, A. O., Aguilar-Rabiela, A. E., Vargas-Torres, A., Rodríguez-Hernández, A. I., Chavarría-Hernández, N., Vergara-Porras, B., & López-Cuellar, M. R. (2019). Production and characterization of biodegradable films of a novel polyhydroxyalkanoate (PHA) synthesized from peanut oil. Food Packaging and Shelf Life, 20, 100297.
70. Mittal, M., Ahuja, S., Yadav, A., & Aggarwal, N. K. (2023). Development of poly (hydroxybutyrate) film incorporated with nano silica and clove essential oil intended for active packaging of brown bread. International Journal of Biological Macromolecules, 233, 123512.
71. Barbato, A., Apicella, A., Palmieri, F., & Incarnato, L. (2023). Development of biodegradable PBS/PVOH-based films and evaluation of performance for food packaging applications. Chemical Engineering Transactions, 102, 97-102.
72. Lyu, J. S., Lee, J. S., & Han, J. (2019). Development of a biodegradable polycaprolactone film incorporated with an antimicrobial agent via an extrusion process. Scientific reports, 9(1), 20236.
73. Moraczewski, K., Stepczyńska, M., Raszkowska-Kaczor, A., Szymańska, L., & Rytlewski, P. (2025). PLA/PCL polymer material for food packaging with enhanced antibacterial properties. Polymers, 17(9), 1134.
74. Priyadarshi, R., & Rhim, J. W. (2020). Chitosan-based biodegradable functional films for food packaging applications. Innovative Food Science & Emerging Technologies, 62, 102346.

75. Hasanoglu, Z., Sivri, N., Alanalp, M. B., & Durmus, A. (2024). Preparation of polylactic acid (PLA) films plasticized with a renewable and natural Liquidambar Orientalis oil. International Journal of Biological Macromolecules, 257, 128631.