



Microbial gums: introducing a novel functional component of edible coatings and packaging

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Abstract

In recent years, the accumulation of synthetic plastics has led to the development of a serious environmental problem. Nowadays, biodegradable films and coatings have been identified as a new approach to solve this problem by preparing renewable, abundant, low-cost materials. Gums are considered a large group of polysaccharides and polysaccharide derivatives that can easily form viscous solutions at low concentrations. Gums are mainly soluble in water and are composed of sugars like glucose, fructose, and mannose. These compounds are categorized into three groups: plant-origin gums, seaweed-based gums, and microbial gums. Microbial gums are listed as generally recognized as safe (GRAS) by the Food and Drug Administration and have a broad range of physicochemical properties suitable for various pharmacy, medicine, and food applications. In the food industry, they can be used as gelling, viscous, stabilizing, and thickening agents. Among the various materials that can potentially improve the properties of biodegradable packaging films, microbial gums such as gellan, xanthan, pullulan, bacterial cellulose, and curdlan have been the subject of numerous studies. These gums can be extruded into films and coatings with considerable barrier properties against the transport of moisture and oxygen. Microbial gums, due to their microbiological stability, adhesion, cohesion, wettability, solubility, transparency, and mechanical properties, can be used as edible films or coatings. Also, these gums can be applied in combination with bioactive compounds that induce the shelf-life extension of highly perishable products. This review focuses on the properties of films and coatings consisting of xanthan, curdlan, pullulan, gellan, and bacterial cellulose.

Keywords Gellan · Pullulan · Bacterial cellulose · Water vapor permeability · Tensile strength · Percentage of elongation at break

Introduction

Despite the 25-fold boost in the global manufacturing of synthetic plastics over the past decades, less than 5% of these

plastics are recycled. In recent years, packaging materials derived from petroleum products have become widely used in food packaging due to their low price, comfortable and extensive access, and desirable characteristics such as brightness, plasticity, and transparency. Nevertheless, the production and accumulation of synthetic plastics related to food packaging have caused many environmental problems since they are resistant to degradation, incompatible with the environment, and the possibility of migration of compounds from packaging to product and the ultimate endangerment of product safety and consumer health exist (Alizadeh-Sani et al. 2018; Espitia et al. 2014; Khalil et al. 2017; Muscat et al. 2012; Sutherland et al. 2015; Tavassoli-Kafrani et al. 2016). Although bioplastics are produced from renewable resources, they are not necessarily biodegradable. Currently, bioplastics comprise approximately one percent of the roughly 320 million tonnes of plastics produced annually. Global bioplastic production capacity is set to increase from around 2.05 million tonnes in 2017 to nearly 2.44 million tonnes in 2022 (Gontard et al. 2018).

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Nowadays, a large number of studies have focused on replacing common plastic packaging (food and non-food) with biodegradable, edible, renewable, and low-cost films and coatings (Alves et al. 2011; Espitia et al. 2014; Khezerlou et al. 2018; Moghaddas Kia et al. 2018). Films and coatings with the aforementioned characteristics can be utilized as supplements or substitutes of conventional materials (Cao et al. 2007; Cazon et al. 2017). For this reason, recent investigations have reported the use of edible films and coatings based on proteins (Ramos et al. 2012), polysaccharides such as chitosan (Dutta et al. 2009; Elsabee and Abdou 2013), hemicelluloses (Hansen and Plackett 2008), starch (Jiménez et al. 2012), pectin (Espitia et al. 2014), and lipids (Debeaufort and Voilley 2009). A biodegradable film can be defined as a packaging material or thin layer of edible material placed on or between food components (Espitia et al. 2014; Falguera et al. 2011), while an edible coating (EC) is a thin layer of edible material formed as a coating on a food product (Kang et al. 2013). Edible films have a layer thickness of below 0.3 mm and are wrapped around food products, whereas edible coatings are applied by immersing the food products in liquid solutions of the edible materials (Falguera et al. 2011). Furthermore, the biopolymers that have been used for producing edible films can feature suitable matrices for use as carriers that facilitate the incorporation of additives) such as antimicrobials, antioxidants, nutrients, colors, nanoparticles, and spices). These composite biopolymers are used to improve the properties of the films and prolong the food shelf-life (Ehsani et al. 2017; Espitia et al. 2014; Saha et al. 2016; Sallam 2007).

A group of biodegradable polymers have been referred to as “natural polymers” as they are produced during the growth of living organisms—especially bacteria, fungi, and yeasts. These biopolymers have a wide range of applications in the food and pharmaceutical industries (Freitas et al. 2014; Vijayendra and Shamala 2014). The types of microbial gums employed in various biomedical and pharmaceutical applications are summarized in Table 1. Since most biopolymers derived from microorganisms are carbohydrates in nature, films made of these biopolymers have hydrophilic structures as polysaccharides usually react strongly with water. The moisture content or sorption of water in the film is affected directly by the moisture barrier properties and water vapor permeability (Al-Hassan and Norziah 2012; Bertuzzi et al. 2007). Moreover, increasing the hydration causes an augment in elongation properties but a decrease in mechanical properties (Cuq et al. 1997). In this way, hydrophilic films have good barrier properties to oxygen, carbon dioxide, and lipids, but have poor control of water vapor migration (Pronmakool et al. 2011). In regard to their barrier properties, they can act as selective barriers to gases in order to generate modified atmospheres (Dehghani et al. 2018; Ramos et al. 2012; Shit and Shah 2014). Despite the fact that most functions of edible films and coatings are similar to those of traditional

packaging, their mechanical properties vary, as do their water and gas permeabilities (Galus and Kadzińska 2015).

In the related literature, a comprehensive review on microbial gums for food packaging and pharmaceutical applications is scarce. Thus, there is a need to provide an insight into this matter using current trends and future projections. The aim of this review is to comprehensively discuss the types and properties of microbial gums and their applications, with special emphasis on pharmaceutical and food packaging applications.

Microbial gums for biodegradable films

Microbial polysaccharides are high-molecular-weight polymers that are produced by the cell wall-anchored enzymes of microorganisms such as bacteria, molds, and yeasts (Morris 2006). Microbial gums are composed of sugar residues linked by glycosidic linkages, and may be linear or highly branched (Fig. 1). Biopolymers produced by microorganisms, including exopolysaccharides (EPSs), endo-polysaccharides, and polyhydroxyalkanoates, are neutral or acidic in nature and have a wide range of physico-mechanical characteristics (Table 2). These microbial gums are composed primarily of carbohydrate components (glucose, mannose, rhamnose), non-carbohydrate components (acetate, pyruvate, succinate, phosphate), and uronic acid. Microbial polysaccharides are non-toxic compounds produced via batch submerged aerobic fermentation in two forms: EPSs and capsular polysaccharides (CPSs) (Sutherland 2001; Sutherland 2005; Vanhaverbeke et al. 2003).

The advantage of microbial gums over other polymers or synthetics is its potential for production on an industrial scale. On the other hand, it requires high-technology equipment, specific substrates, adequate power and water supplies, and well-trained staff. Among the various types of microbial gums, a number of them are utilized in the preparation of gels (gellan and curdlan), thickening agents (pullulan, xanthan), and film solutions (pullulan, cellulose, and gellan) that are used as packaging materials. Table 3 summarizes the types of microbial gum-based composites for various food packaging and coating applications.

Xanthan

Xanthan gum is a heteropolysaccharide that is produced by *Xanthomonas campestris* during fermentation (Fitzpatrick et al. 2013). The compound was initially isolated by Kelco-AIL (Keltrol) and, after various experiments, was recognized as a food additive by the FDA in 1969. The molecular structure of xanthan features a backbone like that of cellulose, a linear chain of β -D-glucopyranose with (1 \rightarrow 4) glycosidic bonds, and side chains having three sugars (β -D-mannose ($\beta \rightarrow 1,4$)-glucuronic acid ($\alpha \rightarrow 1,2$)- α -D-

Table 1 Pharmaceutical and biomedical applications of microbial gums

Types of composites	Pharmaceutical applications	References
Gellan/pectin	Intragastric drug delivery shuttles	Bera et al. (2018)
Gellan/chitosan	Nanocarrier for the delivery of epigallocatechin gallate	Dahiya et al. (2017)
Gellan/pectin	Controlled delivery of drugs	Prezotti et al. (2014)
Xanthan/chitosan	Oral tablet for delivery of quercetin	Caddeo et al. (2014)
Xanthan/hydroxypropyl methylcellulose	Control release gliclazide tablet	Othman et al. (2017)
Xanthan/lignin hydrogel	Carriers for controlled delivery pf bisoprolol fumarate	Raschip et al. (2015)
Pullulan/alginate	Bone tissue regeneration	Popescu et al. (2018)
Pullulan/chitosan	Nasal delivery of vaccines	Cevher et al. (2015)
Bacterial cellulose/montmorillonite	Wound dressing and tissue regeneration	Ul-Islam et al. (2013)
Bacterial cellulose/TiO ₂	Tissue regeneration	Khalid et al. (2017)
Bacterial cellulose/poly (acrylic acid) hydrogels	Oral protein delivery	Ahmad et al. (2014)
Curdlan/poly(D,L-lactide-co-glycolide)	Drug delivery applications	Tukulula et al. (2015)

mannose) as well as non-carbohydrate substitutes (acetate or pyruvate groups). Xanthan gum is an anionic, water-soluble polymer, stable at a wide range of pH and temperature values. It is commonly utilized in foods (e.g., dairy products, baked products, and beverages), pharmaceuticals, and cosmetics (Mohamed et al. 2013).

García-Betanzos et al. (2016) incorporated solid lipid nanoparticles (SLN) into xanthan-based films and

assayed the effect of hot homogenization methods on the properties of the prepared films. The researchers reported improvements in the mechanical properties of these films when 60–75-g/L SLN was incorporated at 4–25 °C under 60–90% relative humidity. The study revealed water vapor permeability (WVP) values of 0.50–0.70 gm⁻²h⁻¹kPa⁻¹ in xanthan gum-based films incorporated with SLN.

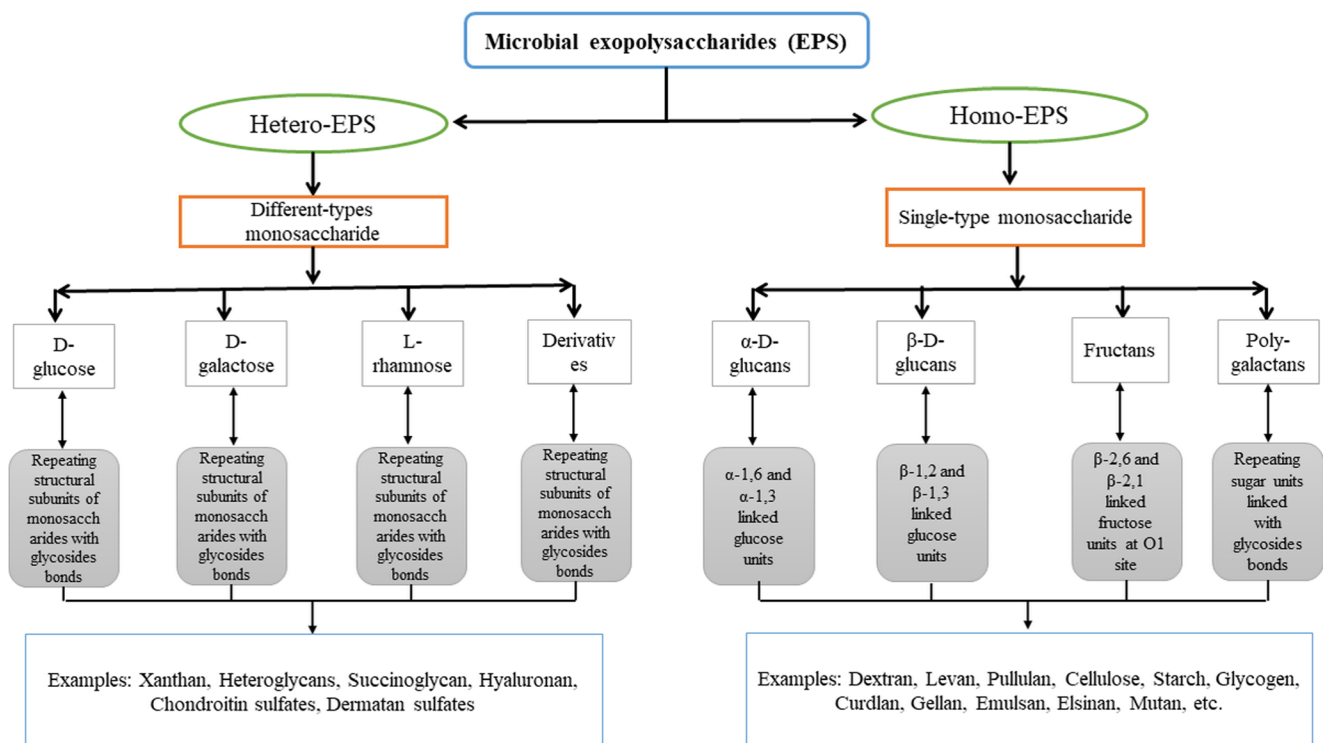
**Fig. 1** Classification of microbial exopolysaccharide

Table 2 Microbial EPS: summary of the most physicochemical, functional properties and main of application

EPS	Components	Charge–polymer localization	Molecular weight	Producer microorganism	Main properties	Main applications	Reference
Pullulan	Glucose (maltotriose)	Neutral Extracellular	$\sim 10^4$	<i>Aureobasidium pullulans</i>	Low viscosity, non-toxicity, slow digestibility, high plasticity, and excellent film-forming	- Thickening, stabilizing - Texturizing, gelling agents - Emulsifiers, film formers - Suspending agents - Foods, pet food - Pharmaceuticals - Research: agar substitute and gel electrophoresis - As stabilizer and suspending agent for foods	Prajapati et al. (2013), Singh et al. (2017)
Gellan	Glucose Rhamnose Glucuronic acid Acetate Glycerate	Anionic Extracellular	5.0×10^5	<i>Sphingomonas paucimobilis</i>	- Hydrocolloid - Stability over wide pH range - Gelling capacity - Thermo-reversible gels	- Foods, pet food - Pharmaceuticals - Research: agar substitute and gel electrophoresis - As stabilizer and suspending agent for foods - As gelling agent for solidifying culture media, especially for studying marine microorganisms	Rehm (2009), Fialho et al. (2008), Ullrich (2009), Bajaj et al. (2007)
Xanthan	Glucose Mannose Glucuronic acid Acetate Pyruvate	Anionic Extracellular	$2.5\text{--}50 \times 10^6$	<i>Xanthomonas</i>	- Hydrocolloid - High viscosity yield at low shear rates even at low concentrations - Stability over wide temperature, pH, and salt concentrations ranges	- Foods - Petroleum industry - Pharmaceuticals - Cosmetics and personal care products - Agriculture	Imeson (2011), Yang (2011)
Bacterial cellulose	Glucose	Neutral Extracellular	$\sim 10^6$	<i>Acetobacter</i> spp. <i>Alphaproteobacteria</i> , <i>Betaproteobacteria</i> , <i>Gammaproteobacteria</i> , Gram-positive bacteria	- High crystallinity - Insolubility in most solvents - High tensile strength - Moldability	- Foods (indigestible fiber) - Biomedical - Wound healing - Tissue-engineered blood vessels - Audio speaker diaphragms	Chawla et al. (2009), Imeson (2011), Bae et al. (2004)
Curdian	Glucose	Neutral Extracellular	$5 \times 10^4\text{--}2 \times 10^6$	<i>Agrobacterium</i> spp., <i>Rhizobium</i> spp., <i>Cellulomonas</i> spp.	- Gel-forming ability - Water insolubility - Edible and non-toxic - Biological activity	- Foods - Pharmaceutical industry - Heavy metal removal - Concrete additive	Yang (2007)

Table 3 Formulation of prepared microbial-based edible films used for food packaging applications

Microbial gum type	Biocomposite components	Amount of microbial gum	Applications	Food usage of fabricated film	Significant results	References
Gellan	Aloe vera	0.5% (w/v)	Film	–	Improvement of physicochemical properties	Alvarado-González et al. (2012)
Carboxymethyl gellan	Pullulan	–	Film	–	Improving film properties	Zhu et al. (2014)
	Pullulan	1% (w/v)	Film	–	Improvement of film properties	Zhu et al. (2013)
–	Whey protein concentrate	0.05–4% (w/v)	Packaging (coating)	Apples	Reduction of weight loss, improvement of sensory attributes	Javanmard (2012)
	Alginate	0–1% (w/v)	Coating	Fresh-cut pineapple	Reduction of weight loss and respiration rate, extension of shelf-life	Azaraksh et al. (2012)
–	–	0.56% (w/v)	Coating	Fresh-cut pineapple	Reduced weight loss and respiration rate; maintenance of firmness and color; little change in acidity, pH, and soluble solids	Azaraksh et al. (2014)
–	–	2% (w/v)	Film	–	Improvement of water vapor barrier properties	Yang et al. (2010)
–	–	0.45–1.5%	Coating	Ready-to-eat mango bars	Improved sensory acceptability, reduced loss of syneresis and aroma compounds	Danalache et al. (2016)
–	–	0.5% w/v	Coating	Litchi fruit	Good water barrier properties, retained overall appearance and color	Farina et al. (2016)
–	–	0.5% w/v	Prebiotic coating	Fresh-cut apple	Less softening and browning, better antioxidant activity	Moreira et al. (2015b)
–	–	1% (w/w)	Antioxidant film	–	Improvement of film properties	Criado et al. (2016)
Purple sweet potato	–	0.3–0.5% w/v	Active and intelligent packaging	–	Good antioxidant, water-resistant, and mechanical properties	Wei et al. (2017)
–	–	1% w/v	Antifungal film	–	Improvement of physicochemical, mechanical, and structural properties; inhibition of <i>Fusarium verticillioides</i> , <i>Fusarium</i> sp., and <i>Colletotrichum gloeosporioides</i>	Mirón-Mérida et al. (2019)
Xanthan	–	–	Antioxidant coating	Fresh-cut Asian pear	Less browning	Sharma and Rao (2015)
–	–	0.3–0.5% w/v	Coatings	Fresh-cut red delicious apples	Less production and oxidation of phenolic compounds	Galindo-Pérez et al. (2015)
–	SLN	4% w/v	Film	–	Improvement of film properties	García-Betanzos et al. (2016)
–	Tapioca starch	0–1% w/v	Antimicrobial film	–	Inhibition of <i>Zygosaccharomyces bailii</i> , low capacity for water sorption	Arismendi et al. (2013)
–	–	0.3% w/v	Nanocoating	Fresh-cut apples	Increase shelf-life, less browning index	Zambrano-Zaragoza et al. (2014)
Pullulan	Sodium alginate	100:0, 60:40, 40:60, 0:100	Film	–	Moisture sensitive	Xiao et al. (2012)
–	–	7.5% w/v	Antimicrobial film, coating	Apples	Inhibitory effect on bacteria and mold growth	Gniewosz et al. (2014)
–	Starch	20% w/v	Film	–	Excellent carrier for probiotic strains	Kanmani and Lim (2013)
–	Whey protein isolate	5% w/v	Bionanocomposite	–	Improvement of mechanical and barrier properties	

Table 3 (continued)

Microbial gum type	Biocomposite components	Amount of microbial gum	Applications	Food usage of fabricated film	Significant results	References
						Hassannia-Kolae et al. (2016a)
	–	5 to 10% w/v	Antibacterial film	Meat and poultry	Inhibitory effect on growth of pathogens	Morsy et al. (2014)
	–	5% w/v	Antibacterial film	Turkey deli meat	Inhibitory effect on growth of pathogens	Khalaf et al. (2013)
	Chitosan, carboxymethyl chitosan	0 to 4% w/v	Film	–	Improvement of barrier and mechanical properties	Wu et al. (2013b)
	–	7.5% w/v	Antimicrobial–antioxidant film and coating	Refrigerated apple	High antifungal activity, lower weight loss, color and soluble solids changes	Synowiec et al. (2014b)
	–	10% w/v	Antimicrobial coating and film	Pepper and apple fruit	Extension of shelf-life, lower weight loss	Kraśniewska et al. (2014)
	–	100–150 g/L	Film	–	Improving film properties	Pattanayaying et al. (2015b)
	–	7.5% w/v	Antifungal coatings	Cold-stored red pepper	High antifungal activity, lower soluble solids changes	Synowiec et al. (2014a)
	–	10% w/v	Antimicrobial Coating	Chicken eggs	Extension of shelf-life, lower weight loss	Morsy et al. (2015)
	–	–	Pharmaceutical oral films	–	Improving film properties with glycerol	Vuddanda et al. (2017)
Bacterial celluloses	Pullulan	5, 10, 20, 40, and 60%	Nanocomposite film	–	Good mechanical and thermal properties	Trovatti et al. (2012)
	Gly, Sor, and CMC	–	Composite films	–	Decreased tensile strength and increased elongation	Indrarti et al. (2016)
	–	–	Antimicrobial films	–	Inhibition of <i>Listeria monocytogenes</i> and <i>Escherichia coli</i> growth	Padrão et al. (2016)
	Pectin–fruit purees	0, 25, 50, 75, and 100%	Film	–	Improvement of physicochemical and barrier properties	Viana et al. (2018)
	–	1% w/v	Coating	Drug delivery system	Suitable for drug delivery	Amin et al. (2012)
	–	–	Antimicrobial films	–	Good barrier and mechanical properties, controlled release of ZnO	Shahmohammadi Jebel and Almasi (2016)
	Graphene oxide	–	Film	–	Good mechanical, homogenous and flexible film	Feng et al. (2012)
	–	10–50 wt%	Nanocomposite film	Organic light-emitting diode	Substrate for flexible OLED	
Curdian	Konjac glucomannan	1% (w/w)	Film	–	Improving moisture barrier properties	Wu et al. (2012)
	Chitosan	2% (w/v)	Coating	Packaging paper	Good mechanical and barrier properties	Brodnjak (2017)

Gly glycerol, Sor sorbitol, CMC carboxymethyl cellulose, PVA poly(vinyl) alcohol

Gellan

Gellan gum is the deacylated form of an EPS produced by *Pseudomonas elodea*. β -D-Glucose, L-rhamnose, and D-glucuronic acid are the units that form the gellan gum structure (Banik and Santhiagu 2006). Gellan gum has the ability to form 3D gel networks with monovalent or divalent cations (such as Na^+ or Ca^{2+}), and gel properties depend on ion-related factors (presence of ions; cation type; ionic strength) and the degree of acylation. Gellan gum is divided into the low-acetyl (brittle gel) and non-deacylated (elastic gel) forms (Bertoni et al. 2006; Fialho et al. 2008). Gellan gum is utilized as a gelling agent in jellies, dairy products, and confectioneries. It is a suitable hydrocolloid for edible film preparations. Initial experiments have shown that gellan films are transparent and have good mechanical properties (Yang and Paulson 2000a).

Composite films have been prepared by the incorporation of gellan/gelatin and different levels of sodium chloride. Results showed that the higher the sodium chloride content, the higher the tensile strength (TS) of the gellan film. When the sodium chloride concentration was 50 mM, the highest tensile elongation (TE) was observed. Also, with increasing gelatin amounts, the TS of the films decreased, while the TE increased (Lee et al. 2004).

Pulsed light (PL) has attracted much interest in recent years as a non-thermal method for the superficial decontamination of fresh foods. In one study, the effect of PL in combination with a gellan gum-based edible coating containing apple fiber on the shelf-life of fresh-cut apples has been investigated. Shelf-life was assessed by evaluating changes in color, firmness, antioxidant capacity, microbial growth, and sensory attributes of a fresh-cut apple stored for 14 days at 4 °C. The combination treatment led to reduced microbiological deterioration, enhanced preservation of antioxidant properties, and reduced softening and browning of apple pieces during storage. These results demonstrated the prebiotic potential and shelf-life extension capabilities of gellan gum-based coatings for fruits such as apples (Moreira et al. 2015).

Yang and Paulson (2000b) evaluated the mechanical properties and water vapor permeability (WVP) of gellan films. Their results showed that increasing the ratio of glycerol to gellan film entailed an increase in WVP and decreases in TS, elastic modulus, and glass transition temperature. Yang and Paulson (2000a) developed an edible gellan film by adding a mixture of lipids (beeswax and stearic-palmitic acid) and showed that adding lipids resulted in significantly improved WVP and mechanical properties. Here, the effect of beeswax on the mentioned properties was greater than that of stearic-palmitic acid. Xiao et al. (2011) investigated the properties of edible gellan membranes prepared under different conditions, namely gellan gum powder concentrations of 0, 0.02, 0.04, 0.06, 0.08, and 0.10% and drying temperatures of 40, 50, 60, 70, and 80 °C. The study demonstrated that the incorporation

of 0.08% gellan at drying temperatures of 60–70 °C resulted in significantly better TS and gas barrier and moisture resistance compared with the other experimental conditions.

The mechanical, physical, and antimicrobial properties of a starch/gellan-based film containing emulsified or lecithin-encapsulated thyme (*Thymus zygis*) essential oil (EO) were studied by Sapper et al. (2018). Their results showed that lecithin improved the film's water barrier properties and gloss, while reducing film stiffness, resistance to break, and extensibility. This means that incorporating lecithin to the starch-gellan film improved its mechanical and physical properties. The prepared films were also tested against *Alternaria alternata* (AA) and *Botryotinia fuckeliana* (BF) to determine their antifungal ability, which was found to be greater against the latter species.

Xu et al. (2007) blended konjac glucomannan with gellan gum and analyzed the mechanical properties of the resulting blend films. The obtained data exhibited that as the konjac glucomannan content in the blend film reached approximately 70%, the TS reached 17.5 MPa.

Ismail et al. (2018) investigated the effects of gellan gum (GG), calcium chloride (CaCl_2), and glycerol concentrations on the physical appearance of blend films. Their results showed that while the prepared film was not well dried at 40 °C, the films formed at 70 and 100 °C were easily ruptured due to overheating (Fig. 2). At the highest amount of GG content studied (1.50 g), the film could not be produced due to the formation of a highly viscous and sticky suspension, as observed visually (Fig. 3a) and demonstrated by mildly rubbing between two fingers (Fig. 3b). Under optimized conditions (drying at 50 °C for 24 h), the films were successfully produced with 1.00 g GG, 5 mM CaCl_2 cross-linker, and 50% w/w glycerol as the plasticizer.

Pullulan

Pullulan (Pu) is an extracellular polysaccharide that consists of glucose and is produced by many *Aureobasidium* species, particularly *Aureobasidium pullulans*. Pu is composed of (1 → 4) and (1 → 6) α -D-glucopyranose residues. In this compound, the proportion of (1 → 4) to (1 → 6) linkages is about 1:2. The polymer mostly contains maltotriose units interconnected with each other by (1 → 6) bonds as well as scarce units of maltotetraose. The presence of α (1 → 6) bonds in Pu results in enhanced structural flexibility and increased water solubility compared with other linear polysaccharides. The viscosity of Pu solutions is good, but is unsuitable for gel formation. Non-toxic, non-mutagenic, and non-carcinogenic properties have been reported for Pu gum. In recent years, Pu has been surveyed in pharmaceutical (e.g., drug delivery) and biomedical (e.g., smart target delivery, surface modification, nanoparticle fabrication, gene delivery, cancer therapy, and bioimaging) applications. In addition, Pu has displayed dominant film-forming properties.

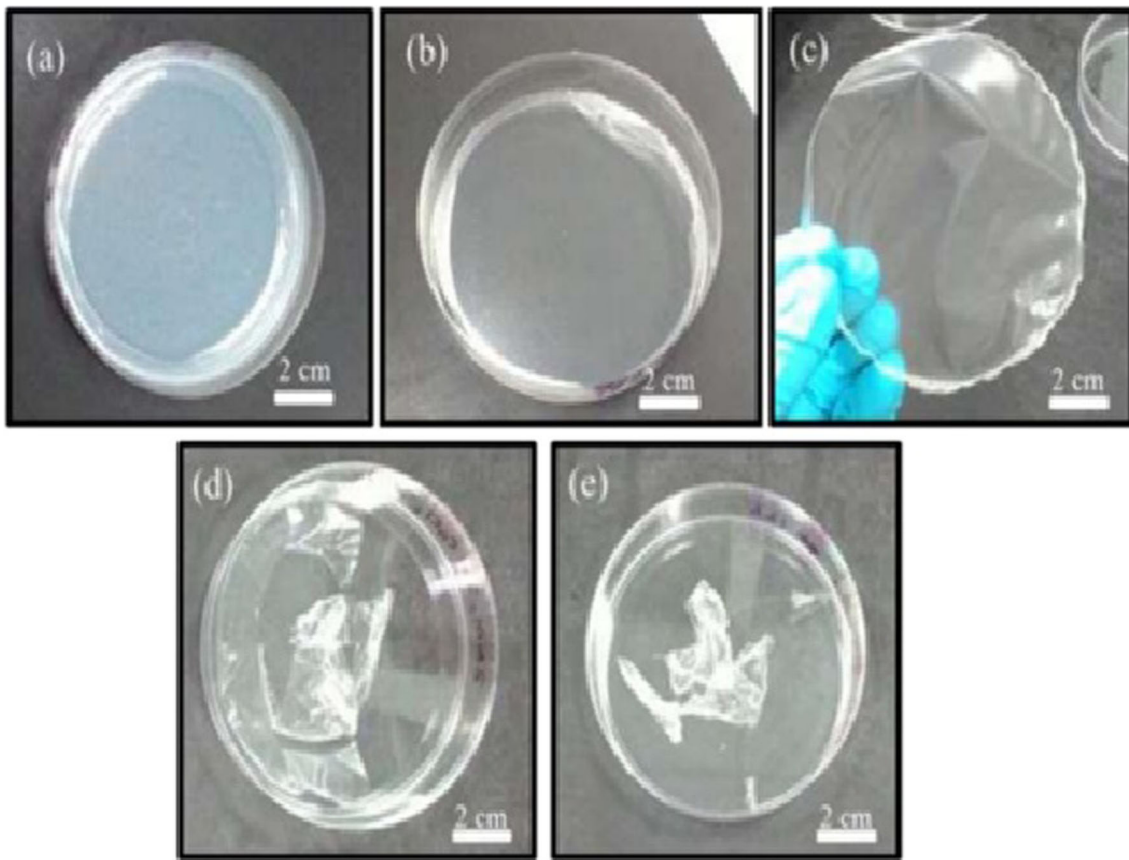


Fig. 2 Gellan gum samples after drying at **a** room temperature, **b** 40 °C, **c** 50 °C, **d** 70 °C, and **e** 100 °C for 24 h (With Courtesy to paper by Ismail *et al* 2018)

Recent studies have demonstrated that pure Pu films are colorless, transparent, odorless, and highly water permeable, with minor oil and oxygen permeability.

Despite the many potential applications, the extensive usage of Pu has been limited by its high cost. Many researchers have focused on blending Pu with other polysaccharides such as alginate, chitosan, starch, and cellulose derivatives in order to produce films with improved physicochemical and mechanical properties. The developed films are easily dissolved in water, thus having the feature of melting in the mouth as edible food coatings (Singh *et al.* 2008). Pu film is suitable for the protection of oxidized fats and vitamins in foods due to its

resistance to oxygen permeation (Krochta and De Mulder-Johnston 1997). Pu films can be utilized as the coating or packaging material of dried foods including nuts, noodles, confectionaries, vegetables, and meats, and can also replace starch in low-calorie food formulations.

In one study, Pu was successively tested for its ability to generate bionanocomposite films. In that work, montmorillonite nanoparticle (MMT) was used for improving the physicochemical and mechanical properties. The results showed that the MMT improved the TS of the generated films, while decreasing the elongation at break, WVP, moisture content, moisture absorption, and water solubility. Atomic force

Fig. 3 **a** Highly viscous and **b** sticky GG suspension produced using 1.50 g GG (With Courtesy to paper by Ismail *et al* 2018)



microscopy (AFM) observation of Pu–whey protein isolate bionanocomposite films showed rough film surfaces. The uniform distribution of MMT into the polymer matrix was confirmed by SEM and X-ray measurements (Hassannia-Kolae et al. 2016b).

Kanmani and Lim (2013) blended probiotic bacteria and various starches with Pu. It was observed that by increasing the starch content, the relative cell viabilities and mechanical properties decreased, but adding probiotic bacteria did not significantly affect the physical and mechanical properties. The results exhibited that the Pu and Pu/potato starch films were the most suitable carrier matrices, with maximum relative cell viabilities of 70–80% after 2 months of storage at 4 °C. Wu et al. (2013) formulated chitosan and carboxymethyl chitosan (CMCH) into Pu films and observed that the added compounds improved the TS of the prepared films when the CMCH to Pu and chitosan to Pu ratios were 3:1 and 2:2, respectively. Hence, increases in CMCH and chitosan contents resulted in increased TS. The WVP of Pu films was increased by the addition of CMCH and chitosan.

Another useful hydrocolloid mixture was proposed by Tong et al. (2008). The authors blended Pu with alginate and carboxymethyl cellulose (CMC). The results indicated that the solubility of pure Pu films in water was greater compared with that of alginate and CMC films, whereas the WVP and mechanical properties of samples containing Pu < alginate < CMC were reduced in the blend films. Here, the addition of glycerol resulted in enhanced elongation at break and solubilization in water and reduced water barrier properties and TS.

In the study of Zhu et al. (2014), carboxymethyl gellan (CMGe) and Pu films were described and physically characterized. The results demonstrated that elongation at break and barrier properties improved by adding Pu to CMGe, though TS practically decreased.

Lipids have also been used to improve the barrier properties of Pu films, but negatively affect the mechanical properties. For example, the addition of rice wax (up to 46.4%) to Pu film wax significantly decreased the WVP value. Brunauer–Emmet–Teller (BET) and Guggenheim–Anderson–de Boer (GAB) sorption models gave a good fit up to the water activity (a_w) of 0.55 for BET and a full range of a_w (from 0.12 to 0.95) for GAB (Shih et al. 2011).

Plasticizers are generally required for producing polysaccharide- or protein-based edible films with appropriate mechanical properties. Vuddanda et al. (2017) analyzed the effects of different plasticizers and their concentrations on the physico-mechanical properties of Pu edible films. Films with 20% glycerol displayed the highest elongation. Pattanayaiying et al. (2015a) proposed an optimum combination of lauric alginate (LAE) and nisin Z in Pu film preparations in terms of mechanical properties. The authors reported that the two films with the best mechanical properties were as follows: (i) Pu = 150 g/L,

glycerol = 2.5 g/L, LAE = 2 mg/mL, nisin Z = 320 AU/mL, and no locust bean gum; (ii) Pu = 120 g/L, glycerol = 2.5 g/L, LAE = 2 mg/mL, nisin Z = 320 AU/mL, and 1-g/L locust bean gum.

Also, the influence of edible films made from Pu on the physiological responses of coated fruit has been reported in one study. Here, the results exhibited that the use of Pu films effectively maintained the quality and extended the shelf-life of strawberries. Pu films declined the rate of weight loss and improved firmness and color retention (Eroglu et al. 2014).

Curdlan

Curdlan (CL) is an extracellular polysaccharide produced by non-pathogenic and non-toxicogenic bacteria, such as *Rhizobiaceae* (*Alcaligenes faecalis* var.). CL has been recognized as a food additive by the FDA, and its linear structure is composed of (1–3) β -D-glycosidic linkages (Grandpierre et al. 2008). This polysaccharide is soluble in alkaline solutions, but cannot be solubilized in water, alcohol, or acid solution. According to the degree of heating and through thermo-reversible processes, CL forms two types of gels, namely high-set gel (above 80 °C) or low-set gel (55 to 60 °C). CL gels are highly elastic and, in contrast with agar gels, can be formed within a wide pH range of 3.0 to 9.5. Due to its unique functions (e.g., its gelling properties), CL cannot be used as a carrier for drug delivery. CL also has bioactive features, such as antitumor and anti-HIV properties. However, its application in food is limited due to its poor mouth-feel effect (Phillips and Williams 2009).

Ahmad et al. (2015) investigated the effects of different ratios of fish gelatin/CL on the physico-mechanical and thermal properties of blend films. The results showed that the TS of gelatin/curdlan blend films was low, while the elongation at break, WVP, and water solubility were high. Moreover, contact angle and moisture content of blend films improved with higher CL contents. Furthermore, increased CL content in the fish gelatin/CL blend matrix led to decreases in redness (a^*) and transparency; however, lightness (L^*), yellowness (b^*), and DE^* values became enhanced. Furthermore, the fish gelatin/CL (8:2) blend film demonstrated more heat stability compared with the other samples, which was demonstrated by its higher heat-stable mass residues. Thus, CL can be used to develop a water barrier capability and thermal stability of fish gelatin films because of its water insoluble and thermo-gelable properties. Wu et al. (2012) studied a composite film composed of konjac glucomannan (KGM) and CL, which was prepared by a solvent-casting method. The results demonstrated that the WVP, tensile properties, and interaction of the blend film improved when the konjac glucomannan content in the composite was up to 70%.

Bacterial cellulose

Cellulose is produced by bacteria as well as by plants and other organisms. Cellulose has several unique properties, such as its high TS and water content. Recently, studies have focused on its potential applications in different fields. Bacterial cellulose (BC) can be produced in substantial amounts via the microbial fermentation of glucose (as a carbon source) by *Gluconacetobacter xylinus* strains and Gram-negative acetic acid bacteria. BC is well recognized for its greater characteristics compared with other celluloses (Iguchi et al. 2000), such as its higher mechanical strength, crystallinity, hydrophilicity (Rozenberga et al. 2016), purity, and water holding capacity, thereby displaying a decent potential for a variety of applications. The main advantage of BC is that it can be easily processed into microfibrils, nanofibrils, and nanocrystals for use in the production of edible nanocomposite films. In fact, BC has been used in its native form in the preparation of packaging materials (Shi et al. 2014). Recently, BC membranes have been utilized as antimicrobials in active packaging. BC membranes and films can be incorporated with antimicrobial agents to create an active packaging system that maintains antimicrobial activity during food storage. BC also has extensive applications in cosmetics and medicine (Jagannath et al. 2010), acoustic diaphragms (Nishi et al. 1990), ion exchange membranes (Choi et al. 2004), and electronic devices (Nogi and Yano 2008).

Wan et al. (2016) investigated the water resistance properties of multilayer films based on BC–zein, in which the strong BC film formed the outer layer and the electrospun zein fibers formed the inner layer. They found that the incorporation of electrospun zein fibers made multilayer films become rigid; however, the zein interlayers did not have a significant impact on the surface characteristics and thermal stability of the films. Due to the hydrophobicity of the zein protein, the water resistance properties improved. Jipa et al. (2012) prepared mono- and multilayer films based on powdered BC (BCP) and poly(vinyl) alcohol (PVA) containing sorbic acid (SA). The results displayed that sensitivity to water, antimicrobial ability, and release rate impressed with higher SA and BCP concentrations. By adding SA and BCP, the swelling degree increased, while the WVP and water solubility decreased.

Lately, several studies have focused on nanotechnological methods for improving the barrier properties of films. For example, the addition of nanoclays to the polymeric matrix of polysaccharide based–films has been investigated (Chivrac et al. 2009; Eroglu et al. 2014; Hassannia-Kolae et al. 2016b). Gelatin nanocomposite films containing BC have been studied by George (2012). The formation of networks of cellulose nanocrystals within the gelatin matrix resulted in improved mechanical properties of nanocomposites and significantly reduced the WVP. In another study, Jebel and Almasi (2016) investigated the combination of BC with

ZnO NPs in the production of monolayer and multilayer films. The results showed that incorporating ZnO NPs improved the mechanical properties but diminished the WVP and moisture absorption of BC films.

Conclusion

The applications of edible films in food technology open new opportunities for producing innovative biodegradable food packaging as a good alternative for replacing synthetic plastics. This can solve the problem of the accumulation of wastes related to non-biodegradable petroleum-based plastics. Film-forming microbial biopolymers such as gellan, bacterial cellulose, xanthan, pullulan, and curdlan are non-toxic, biocompatible, and biodegradable. They are used in the food industry as edible food films for coating and packing purposes. The films prepared from these polymers are transparent and have good mechanical, moisture, and oxygen barrier properties, but weak water barrier properties. The blending of microbial gums with lipids, hydrocolloids, or reinforcement agents improves the functional properties of edible films. Overall, an interdisciplinary approach for exploring novel applications is essential for preparing new composites of these microbial polymers with other polymers and hydrocolloids.

Compliance with ethical standards

Ethical statement/
conflict of interest

The authors, whose names appear on the submission, declare that they have contributed sufficiently to the scientific work and therefore share collective responsibility and accountability for the results. This manuscript has not been published or presented elsewhere in part or in entirety, and is not under consideration by another journal. All the authors have approved the manuscript and agree with its submission to your esteemed journal.

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