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Ajesh Kumar
Central Institute of Agricultural Engineering

Muzaffar Hasan
Central Institute of Agricultural Engineering

Deepak Kumar Verma
Indian Institute of Technology Kharagpur

Prem Prakash Srivastav
Indian Institute of Technology Kharagpur

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Trends in Edible Packaging Films and its Prospective Future in Food: A Review

Ajesh Kumar V[1,*], Muzaffar Hasan[2,**], Shukadev Mangaraj[1], Pravitha M[2], Deepak Kumar Verma[3], Prem Prakash Srivastav[3]

[1] Centre of Excellence for Soybean Processing and Utilization, ICAR-Central Institute of Agricultural Engineering, Nabibagh, Berasia Road, Bhopal 462 038, India
[2] Agro Produce Processing Division, ICAR- Central Institute of Agricultural Engineering, Nabibagh, Berasia Road, Bhopal 462 038, India
[3] Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur, Kharagpur 721302, West Bengal, India

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ABSTRACT

Food packaging is an important area of food research due to its prime role in the protection and containment of foodstuffs. Traditionally petroleum-derived polymers fulfill the lion's share of packaging material requirements. However, present-day consumers are more concerned about the environmental impact and health hazards of these synthetic polymers. This necessitates the requirement of alternative packaging material with unique biodegradable and renewable characteristics. The edible film is considered a solution to replace these synthetic plastics with naturally available bio-macromolecules such as polysaccharides, proteins, and lipids. An enormous number of researches have been carried out across the world to explore its full potential. Their findings need to be consolidated for further development of this trending research area. Therefore, this article comprehensively reviews previous research progresses, such as different film formulations from various sources and their characteristics and product applications to guide the enthusiastic researchers. Finally, the last section of this article elaborates on safety and regulation aspects as well as recent trends and challenges to tackle all the obstacles in establishing a greener packaging option.

1. Introduction

The packaging is one of the most critical post-harvest operations for the preservation and shelf-life extension of fruits, vegetables, and processed foods. The major functions of food packaging include protection, communication, and convenience. Advancement in industrialization leads to the sharp growth in plastic use for food packaging. The production of plastic in the world has reached up to 380 million tonnes, and it has shown a steep increase in the past few decades, where 40% of the plastic produced is used in packaging applications (Groh et al., 2019). Although plastic is quite convenient as a packaging material, because of its low price, high mechanical strength, convenience in shape molding, heat sealability, and lighter in weight, enormous usage of plastic packaging material may lead to adverse effects on the environment (Cazón et al., 2017; Dehghani et al., 2018). For example, plastic waste virtually does not degrade, it will take hundreds of years for its disposal in a landfill, and the disposal of plastic through incineration can produce highly toxic gases (Otoni et al., 2017). Hence, plastic is considered the most significant menace in resolving earth pollution (Hasan et al., 2020).

In the past few decades, consumers are also aware of the impact of plastic on the environment. Therefore, the demands of alternate packaging materials which ensure an enhanced shelf-life with good quality and less impact on the environment are crucial in the food packaging industry. Edible packaging has been traditionally used to improve food appearance and preservation, and it captivated substantial attention in the last few decades due to the possibility of partial substitution of non–biodegradable synthetic packaging materials (Hassan et al., 2018).

The primary role of edible film is controlling the moisture loss and reducing the adverse chemical reaction rates to enhance the quality and safety of a wide range of processed as well as fresh foods (Debeaufort, F. et al., 1998). In addition, the incorporation of various food additives such as antimicrobials, antioxidants, flavors, and colors into the edible film matrix further extends their applications (Tavassoli-Kafrani et al., 2016). However, the permeability and mechanical properties of the edible film are not on par with conventionally used synthetic plastic films

* Corresponding authors: Ajesh Kumar V, Centre of Excellence for Soybean Processing and Utilization, ICAR- Central Institute of Agricultural Engineering, Nabibagh, Berasia Road, Bhopal, India, Phone number: +91 8075913057.
** Corresponding authors: Muzaffar Hasan, Agro Produce Processing Division, ICAR- Central Institute of Agricultural Engineering, Nabibagh, Berasia Road, Bhopal 462 038, India, Phone number: +91 8290767324.
E-mail addresses: ajeshmtr@gmail.com, ajesh.v@icar.gov.in (A.K. V), muzaffarhassan88@gmail.com (M. Hasan).

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Fig. 1. Application of different types of edible film in various foods. a) Soybean aqueous extract-based nanocomposite edible film applied as cheese slice separator, b.) Guava (left) and beetroot (right) purees produced edible film, c.) Sodium alginate based edible film applied in meat slice, soluble coffee (d.), powder medicine (e.), cheese slice (V et al., 2021; Otoni et al., 2017; Gheorghita (Puscaselu) et al., 2020; Puscaselu et al., 2019).

(Murrieta-Martínez et al., 2018). Hence, the present research contributions were geared towards these property enhancements.

This article reviews the recent progress in edible packaging, emphasizing standalone edible films. Information including different types, formulation methods, application on food products, safety and regulations, and recent trends in the edible film is comprehensively reviewed. Finally, the challenges faced in commercial application of edible film in food packaging with possible solutions are also covered.

2. Different materials used for edible film formation

Edible packaging materials are natural polymers obtained from polysaccharides, proteins (animal or vegetable), lipids, or combinations of these components (Khaoula et al., 2004; Galus & Kadzińska, 2015). According to Market Research Futures (MRFR), the edible packaging market (based on protein, lipids, polysaccharides, and other) will be worth USD 2.14 billion by 2030, with a compound annual growth rate (CAGR) of 6.79 percent (2022–2030), up from USD 783,32 million in 2021. North America will dominate the edible packaging market throughout the forecast period, followed by the United Kingdom, Japan, Indonesia, and Israel (Future, 2021). Several researchers formulated and characterized numerous edible films from different plant origin materials (Fig. 1). Researchers have continuously worked for the last three decades to develop edible films that can match the conventional plastic films to enable their commercial application. Varieties of edible packaging materials have been discussed in the following section.

2.1. Protein-based edible film

Edible packaging formed from proteins of plant origin includes corn zein, wheat gluten, soy protein, peanut protein, quinoa protein, sesame protein. In contrast, keratin, egg white protein, myofibrillar protein, collagen, gelatine, casein, and milk whey protein are film formers from animal sources (Mellinas et al., 2016). Among different edible film sources, protein-based material appears to be more attractive as they also provide nutritional value (Galus & Kadzińska, 2016). In addition, protein-based edible films have relatively higher mechanical and gas barrier properties with low moisture barrier properties. Protein-based films are better than lipid and polysaccharide films. They have excellent physical properties and gas-blocking effects because of their tightly packed and ordered hydrogen-bonded network structure (Kumari et al., 2017). Oxidation of lipid materials is the major cause of deterioration of quality and shelf life of high fat or fried foods. This can be controlled to a certain extent by using protein-based packaging, which inhibits oxygen permeation (Zhang, S & Zhao, 2017). The structure of protein also plays a crucial role in oxygen permeability. It is reported that corn zein, wheat gluten, soy protein, and whey protein-based edible film have greater oxygen permeability than collagen-based films due to the globular structured proteins (Wittaya, 2012). Protein-based edible films can also be used for the individual packaging of small portions of food, particularly products for which individual packaging is not practically feasible, such as beans, nuts, and cashew nuts (Bourtoom, 2009). Both wet and dry methods can be used to create the protein-based film.

2.1.1. Whey protein/milk protein

Whey protein or casein protein is preferred over the total milk protein for edible film formation as the latter results in crystallization due to the presence of lactose (Wagh et al., 2014). Edible films can be prepared from whey protein fraction, Whey Protein Isolate (WPI), and Whey Protein Concentrate (WPC) by adding different emulsifiers and plasticizers (Galus & Kadzińska, 2016; Soazo et al., 2016; Çakmak et al., 2020; Seydim et al., 2020). Whey protein film is characterized by its excellent oxygen, aroma, and oil barrier properties under low to medium relative humidity conditions. It also has the required mechanical properties for different applications like food coating, separating food layers, and pouch formation. In recent times, the addition of probiotics and prebiotics have been carried out to enhance the functional properties of the whey protein-based films (Fernandes et al., 2020; Zoghi et al., 2020).

2.1.2. Wheat gluten protein

Wheat gluten, which contains more than 75% protein, is the protein part of the wheat flour after removing other starch granules by washing (Chavoshizadeh et al., 2020). It consists mostly of monomer gliadins and polymer glutenins in nearly equal amounts by weight. The cohesiveness and elasticity of gluten provide integrity and facilitate film formation (Fakhouri et al., 2017). Wheat gluten has very good oxygen and carbon dioxide barriers properties (Zubeldía et al., 2015). In addition, the ability to form cross-linking upon heating, visco-elasticity properties, low water solubility, low cost, and availability due to coproduct in the wheat starch industry make wheat gluten a favorite protein source for edible packaging (Ansorena et al., 2016). Although the wheat gluten-based films show brittleness and tendency to absorb water after being processed, the application of different methods such as adding plasticizers, incorporating additives possessing reactive groups (e.g. NH_2, –COOH, –OH, and –SH), and blending with polymers (e.g; aliphatic polyester, poly (hydroxy ester ether), poly (lactic acid), polycaprolactone, poly (vinyl alcohol) and cassava starch) can minimize the impact (Hemsri et al., 2011). Moreover, the mechanical properties of gluten-based films are strongly affected by pH and gluten concentration, while water vapor permeability may be correlated with pH and ethanol levels (Fakhouri et al., 2017). The physiochemical properties of the wheat gluten films can be improved by the incorporation of other different proteins, polysaccharides, and organic acids (Dong et al., 2022; He et al., 2020)

2.1.3. Soy protein

Soy protein isolate (SPI) is one of the major sources of protein for edible packaging obtained from dehulled and defatted soybean (Cristine De Souza et al., 2020). Soy protein-based formation of the edible film occurred in two steps process- 1) disruption of soy protein complex structure through alkaline or heating treatment and cleavage of native disulfide bonds lead to exposure of sulfhydryl groups and hydrophobic groups; and 2) new disulfide bonds, hydrophilic and hydrophobic bonds formation. Utilizing native soy protein is challenging in applications like edible packaging due to its structural characteristics (Gao et al., 2015). However, modification of soy protein is possible with cross-linking of protein structure by different methods like denaturation, thermal treatment, and application of natural cross-linking agents (Friesen et al., 2015; Xia et al., 2015). Most commonly used protein cross-linkers are aldehydic compounds such as glutaraldehyde, formaldehyde, and glyoxal, phenolic, and epoxy compounds. The SPI-based edible films exhibit properties such as transparency, flexibility, low oxygen permeability, even comparable to low-density polyethylene film with abundant availability and low cost (Nandane & Jain, 2018). The gelling ability of the SPI makes it convenient in forming a suitable matrix for composite films with lipids as well as bioactive compounds such as antioxidants and antimicrobial agents (Carpiné et al., 2015; Cristine De Souza et al., 2020).

2.1.4. Sodium caseinate

Sodium caseinate (SC) is a water-soluble form of casein produced by adjusting acid-coagulated casein to pH 6.7 using sodium hydroxide (Belyamani et al., 2014; Yin et al., 2014). The randomly coiled structure of the SC enables good film formation (Lin, Wang and Weng, 2020). The earlier studies addressed that surface modification of SC film with zein coating has yielded film with better barrier properties (Yin et al., 2014). The structural inversion approach of zein coating on SC film resulted in surface irregularities with high irregular projections, which ultimately led to enhanced water and oxygen barrier properties. Whereas the direct coating only reduced the oxygen barrier property in which the zein nano-spheres were evenly distributed on the film surface. In recent studies, cross-linking with genipinin (Lin et al., 2020; Qiu et al., 2020), and incorporation of essential oils and antimicrobial agents (Alizadeh-Sani et al., 2020; Di Giuseppe et al., 2022) have proven to enhance the mechanical and antibacterial properties of the SC films.

2.1.5. Corn zein

Corn zein is a major protein that can be utilized to prepare the edible film, edible coating, and pouches (Chen et al., 2014; Zhang & Zhao, 2017). Corn zein is extracted from corn gluten, a by-product of bioethanol production, which ensures plentiful availability (Escamilla-García et al., 2013). Zein is applied to other protein and polysaccharide-based films such as SPI and glucomannan (Wang Kai et al., 2017) to improve barrier properties and act as a finishing agent by imparting surface gloss (Cheng et al., 2015). The formation of zein coating on hydrophilic protein-based films via the specific protein-protein interactions has a promising potential to improve their barrier capability. Zein contains sharply defined hydrophobic and hydrophilic domains at its surface and is capable of self-assembly (Yin et al., 2014). The hydrophobic property of zein is contributed by the high proportion of non-polar amino acid residues, such as proline, leucine, and alanine. Thus, zein has been recommended as an edible film matrix material (Chen et al., 2014).

2.1.6. Collagen and gelatin

Collagen, an animal-sourced protein used in edible packaging, is a hydrophilic protein rich in glycine, hydroxyproline, and proline; hence it swells in polar liquids with high solubility parameters (Coppola et al., 2020). Studies have reported that usage of collagen casing for meat products dates back to the 1920s (Janjarasskul & Krochta, 2010; Yang et al., 2016). Similar to collagen, gelatin is an animal protein obtained by controlled hydrolysis of the fibrous insoluble collagen present in the bones and skins generated as waste materials during animal slaughtering and processing (Lopez et al., 2017). The application of gelatin as an edible film has been extensively studied in several research studies (Bonilla & Sobral, 2016; Jridi et al., 2019). Gelatin is known for its application advantages such as good film-forming ability, good gas and oil resistance, nontoxicity, low price, and biodegradable properties. At the same time, its poor mechanical property, low thermal stability, weak water resistance, and rapid biodegradation property need to be improved (Ge et al., 2017). This can be tackled by forming a composite film using appropriate starch materials (Cheng et al., 2022).

2.1.7. Other protein sources

For the sustainable use of protein sources, researchers started exploiting the use of protein from different sources to assess the edible film-forming abilities. These sources are chosen either as by-product utilization or for exploiting their unique properties and nutritional values. Protein from sources such as peanut protein and peanut protein isolate (Sun et al., 2013), lentil protein (Bamdad et al., 2006), a protein isolated from sesame (Sharma & Singh, 2016), myofibrillar proteins of fish muscle (Kaewprachu et al., 2016), pumpkin seed protein (Xu et al., 2019; Lalnunthari et al., 2020), egg white protein (Han et al., 2020; Huang X et al., 2020), and rice protein (Wang et al., 2020), etc. were also exploited for the formation of edible film. The major lacunae of these proteins are the inability to form a proper film-forming matrix. This can be overcome by cross-linking with transglutaminase and ultrasonication (Cruz-Diaz et al., 2019). These protein sources are used directly or in composite film formation.

2.2. Polysaccharide-based edible film

Polysaccharides are the most abundant natural polymer, and recently, they have been widely used to prepare edible film or coatings materials (Imre et al., 2019). Polysaccharides *viz* cellulose, hemicellulose, starch, pectin, and derivatives of all these alginates, pullulan, chitin, and chitosan, are intensively used for edible film and coating materials preparation (Cazón et al., 2017). Polysaccharides-based edible films have a well-ordered hydrogen-bonded network, making them efficient oxygen blockers. However, polysaccharides-based films are less efficient in working as a moisture barrier due to their hydrophilic nature. Polysaccharide coatings are free from oil content, colorless in appearance, and used to extend the product's shelf life without creating any anaerobic condition (Mohamed et al., 2020). The polysaccharide-based film can be developed using both wet and dry methods. Commonly used polysaccharide materials for film formation include the following.

2.2.1. Cellulose and its derivatives

Cellulose is the most abundant natural organic polymer, which can be applied for the preparation of the edible film. It is the primary structural component of the plant cell wall and is a linear homopolysaccharide comprised of β-1,4 glucose. Cellulose derivatives are derived from structural modifications like the addition of a small group (methyl, hydroxyl, and carboxyl) in cellulose (Fig. 2).

Principally four types of cellulose derivatives are used for edible coatings or films like Hydroxypropyl methylcellulose (HPMC; E464), Hydroxypropyl cellulose (HPC; E463), Methylcellulose (MC; E461), and Carboxymethylcellulose (CMC; E466) (Bourtoom, 2008). MC-based coatings create a barrier to in and out the movement of oil or lipids therefore used in confectionery foodstuffs. Similarly, HPMC-based film or coatings hinder the oil absorption consequently used for fried food products (Ngatirah et al., 2022)

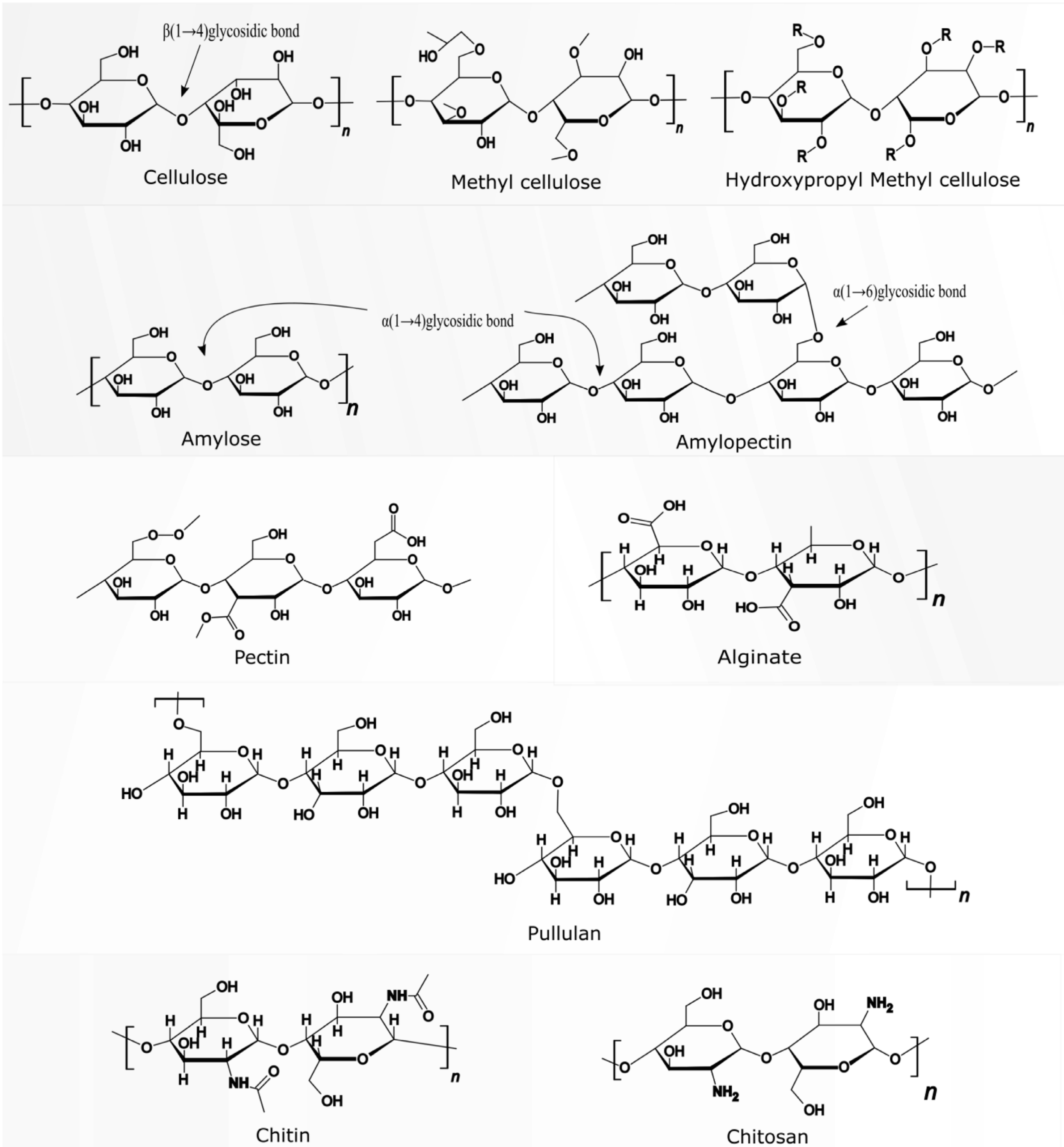

Fig. 2. Chemical Structure of different polysaccharides.

2.2.2. Starch and modified starch

Starch is a homo polysaccharide, comprised of amylose and amylopectin, used to develop biodegradable films because it can form a continuous matrix and is a renewable and abundant resource. Amylose is a linear polymer of (1→4) glucose, while amylopectin is a branched polymer of α (1→4) glucose and α (1→6) glucose (Fig. 2). Among amylose and amylopectin, amylose is generally used for film formation because of its high flexibility, low oxygen permeability, and water solubility (Cazón et al., 2017). However, the inherent hydrophilicity of amylose makes it a poor barrier for water vapor. Therefore, improvising the property of the starch-based edible film, starch modification is needed (Askari et al., 2018).

2.2.3. Pectin

The polysaccharide pectin predominantly consists of galacturonic acid and its derivatives (Fig. 2**).** These polysaccharides are largely extracted from citrus peel and apple pomace (Morales-Contreras et al., 2020). The degree of esterification of pectin with methanol directly affects the gelation and film-forming ability. Methoxy pectin (or esterified pectin) can be classified as low methoxy pectin (LMP) and high methoxy pectin (HMP) according to the degree of esterification (Espitia et al., 2016). Pectin is widely used in the edible film industry due to its biodegradability, biocompatibility, edibility, versatile chemical and physical properties such as selective gas permeability, and gelation (Chodijah et al., 2019)

2.2.4. Alginate

Alginates have mannuronic acid and guluronic acid in structure (Fig. 2) and the composition of mannuronic acid and guluronic acid affects the physical property and molecular weight of alginates (Madsen et al., 2021). Alginate polysaccharides are mainly isolated from brown seaweeds. The colloidal nature of alginate, which includes thickening, stabilizing, film-forming, and suspending properties, makes it competent for edible film-forming material (Hassan et al., 2018). The presence of both the anionic sugar-acid enables it to bind divalent cations like Ca^{+2}, Mg^{+2}, Mn^{+2}, and Fe^{+2}. Therefore, incorporating divalent cations as a gelling agent causes the alginates-based edible film to be attributed to other physical properties like retaining moisture and color (Senturk Parreidt et al., 2018). The alginate-based edible film or coatings show lesser resistance to moisture or water because of the inherent hydrophilic nature of alginates (Dhanapal et al., 2012).

2.2.5. Pullulan

The pullulan polysaccharide is secreted by the fungus *Auerobasidium pullulans* to resist desiccation and predation. The structure of pullulan mainly comprises maltotriose units (Fig. 2). Pullulan works as a thickener in edible film formation, and pullulans-based coatings are helpful to increase the shelf life of fruits (Diab et al., 2001). The edible coating property of pullulan can be enhanced by the use of glutathione (reducing agent) and chito oligosaccharide (antibacterial) in combination (Hassan et al., 2018). Like other polysaccharides, pullulan is hydrophilic in nature, which negatively affects its water barrier and mechanical properties. This limitation can be negotiated by adding lipids and fatty acids such as beeswax (BW), palmitic acid, and oleic acid (Omar-Aziz et al., 2021).

2.2.6. Chitin and chitosan

Chitin is the primary component of the cell wall of fungi and invertebrates. Deacetylation of chitin in alkali solution, convert it into chitosan. The repetitive unit in chitin polysaccharide is *N*-acetylglucosamine, a derivative of glucose monosaccharide (Fig. 2**)**. Chitosan-based edible films have barrier properties for O_2 and CO_2 as well as possess inherent antimicrobial properties. The physicochemical properties of chitosan-based edible film or coatings are varied with the degree of deacetylation of chitin (Kumar et al., 2020). Chitin is characterized by its excellent biodegradability, biocompatibility, antibacterial activity, and low immunogenicity (Li et al., 2019). Chitosan products are highly viscous, resembling natural gums with antimicrobial properties due to active amino groups (Nguyen et al., 2020**)**, and they can form transparent films to enhance the quality and extend the storage life of food products (Ribeiro et al., 2020).

2.3. Lipids-based edible film

Lipids are naturally originated compounds from plants, animals, and insects. The diversity of the lipid functional groups is made up of mono-, di-, tri-glycerides, phospholipids, phosphatides, terpenes, cerebrosides, fatty acids, and fatty alcohol (Mohamed et al., 2020**)**. Unlike protein and polysaccharides, lipids alone cannot form an edible film. Though they are capable of forming an edible coating, the lack of a large number of repeating units connected by covalent bonds prevents the formation of a stand-alone film. Therefore, different plant and animal-based lipids (oils and fats) are incorporated in film-forming solution (FFS) to the emulsion-based edible film to impart more hydrophobic properties due to their low polarity (Janjarasskul & Krochta, 2010**;** Galus & Kadzińska, 2015**)**. Oils and fats are chemically similar mixtures where main components are triglycerides but differ in origin and physical appearance. Oils come from plants and liquids in nature, whereas fats originate from animals and are solid in appearance at room temperature. Different vegetable oils (sunflower oil, olive oil, rapeseed oil, etc.), plant-based waxes (candelilla, carnauba, and sugar cane waxes), animal-based waxes (beeswax, lanolin, and wool grease), and synthetic waxes like paraffin wax and petroleum wax were added to form FFS (Rhim & Shellhammer, 2005**)**. Waxes are made up of alcohol and/or esters of a long-chain acid; therefore, waxes have a larger molecular weight with potent hydrophobicity. Vegetable oil is a raw, oily material produced from nuts, seeds, or newly cut flowers after being pressed cold. On the other hand, essential oil is a highly aromatic compound produced through steam distillation from various parts of a plant (leaves, roots, fruit, wood, and flower). Essential oils are highly rich in hydrophobic, aromatic, and volatile compounds like terpenes and terpenoids. Furthermore, essential oils have potent antimicrobial properties.

Some lipid materials like virgin coconut oil added to the FFS have reduced the water vapor permeability (WVP) of the edible film prepared from SPI (Carpiné et al., 2015**;** Fangfang et al., 2020**)**. To give antioxidant and antimicrobial properties, essential oils from many aromatic spices of clove, rosemary, cinnamon, lemon, thyme, garlic, oregano were added into FFS during the emulsification process. Encapsulating essential oils in the edible film also gives them stability against their volatile nature (Alexandre et al., 2016**;** Perdones et al., 2016**;** Hashemi & Mousavi Khaneghah, 2017**)**. The main disadvantage of lipid film material is its fragile nature. It also makes the film waxy and greasy in texture and taste, which is not desirable for packaging material on many occasions. To have the desired properties for the film, the compatibility of the lipid phase with the polymer matrix is essential. The use of different essential oils in edible film formulation for improving the WVP as well as the functional properties such as antibacterial and antioxidant properties are listed in Table 1**.** The lipid-based self-supporting edible film is generally prepared with an FFS containing any of the high molecular weight polymers (protein or polysaccharide) using the solvent casting method (Rhim & Shellhammer, 2005**)**.

2.4. Composite edible film

Composite films are multi-component systems in which different hydrophobic, as well as hydrophilic compounds are blended to achieve better functional properties. Many times, single functional compounds forming the polymer matrix, which is capable of forming a structural matrix with sufficient cohesiveness, may not be sufficient to provide all of the required properties, such as mechanical, barrier, and so on (V. et al., 2022**;** Dhumal & Sarkar, 2018). Polar bio-polymeric edible films like polysaccharides and protein generally show good gas barrier properties and reasonably good mechanical properties at low relative humidity. Nevertheless, they show poor water barrier properties due to their hydrophilic nature at high humidity. In contrast, hydrophobic lipids are reasonably efficient against moisture migration, but due to their non-polymeric nature, they show poor mechanical properties and are inferior to those of hydrocolloid films (Janjarasskul & Krochta, 2010). So, mixing this hydrophobic lipid with hydrophilic polysaccharides or protein can yield films with better properties than those formed from individual compounds. For example, Omar-Aziz et al. (2021) experimented with developing film by combining beeswax and pullulan. They have found a significant improvement in WVP and TS in the composite film than those films formed from pullulan alone.

Composite films are prepared either in layer form or in the emulsion of film-forming materials. Layered composite films are classified into binary or ternary based on the number of polymers used. Several combinations of carbohydrate-protein (Wang Kun et al., 2017**;** Tavares et al.,

Table 1
Use of different essential oils in edible film formulation.

Matrix Polymer	Essential Oil Used	Targeted Product	Film Formation Method	Observations and Remarks	Reference
Carboxymethyl chitosan: Pullulan	Galangal essential oil (GEO)	Mango	Casting	Developed film exhibited excellent thermal stability, biodegradability and mechanical properties and was able to provide good preservation effect on mango.	(Zhou et al., 2021)
Gelatin: Green tea extract	Lemon essential oil (LEO)		Casting	Incorporation of green tea extract and LEO helps to achieve good WVP for the developed film.	(Nunes et al., 2020)
Gelatin–chitosan blend	Ferulago angulate essential oil (FAEO)	Turkey meat	Casting	FAEO incorporated in gelatin-chitosan blend film improved the water solubility and WVP. Increased anti-microbial property of the film helped in enhancing the shelf life of turkey meat.	(Naseri et al., 2020)
Millet starch	Clove essential oil		Casting	Inclusion of clove oil enhanced the anti-oxidant activity and antimicrobial properties of the film.	(Al-Hashimi et al., 2020)
SPI-gum acacia conjugates	Oregano essential oil (OG-EO), lemon essential oil (LM-EO), fruit of Amomum tsaoko Crevost et Lemaire (ACL-EO) and/or grapefruit essential oil (GF-EO)		Casting	GF-EO contained film exhibited better WVP, mechanical properties and glass transition temperature than other EO containing films. However, radical scavenging activity and antimicrobial activity was superior for LM-EO incorporated films.	(Xue et al., 2019)
Basil seed gum	Oregano essential oil		Casting	The resulting film showed a significant reduction in WVP with antimicrobial and antioxidant activity.	(Hashemi & Mousavi Khaneghah, 2017)
SPI:Acetem: Tween 60	Carvacrol and cinnamaldehyde		Casting	The addition of emulsions significantly reduced the tensile strength of the films and improved their EAB. An only slight improvement is reported with the addition of essential oils	(Otoni et al., 2016)
Gelatin: MMT	Ginger essential oil (GEO)		Casting	Synergetic effect of GEO with MMT significantly improved the mechanical properties like EAB, puncture force and puncture deformation.	(Alexandre et al., 2016)
Zein	Zataria multiflora Boiss. essential oil (ZEO)	Minced meat	Casting	Addition of ZEO along with monolaurin significantly improved the antioxidant activity and antimicrobial properties against *L. monocytogenes and E.Coli*	(Moradi et al., 2016)
Chitosan	Cinnamon and Ginger essential oil	Pork	Casting	Cinnamon and Ginger essential oil has distinctly increased the thickness and opacity of the chitosan films. The WVP of films remained unaffected. Incorporating 1% EOs yielded the highest antimicrobial and antioxidant activities chitosan films	(Wang et al., 2017)
WPI	Almond and walnut oils		Casting	Addition of oils increased the opacity of the film whereas swelling, water vapor permeability, and surface hydrophilicity were reduced.	(Galus & Kadzińska, 2016)
Chitosan:MMT	Rosemary essential oil and ginger essential oil	fresh poultry meat	Casting	Incorporation EOs improved only the barrier to oxidation but not the antimicrobial properties. Overall performance of EOs in Chitosan/MMT film is not significant	(Pires et al., 2018)

***Abbreviations*:** EAB: Elongation at break, EO: Essential oil, MMT: Montmorillonite WVP: Water vapor permeability, SPI: Soy protein isolate, WPI: Whey protein isolate.

2021), protein-protein (Dong et al., 2022; Tsai & Weng, 2019), and carbohydrate–carbohydrate (Cheng et al., 2015; Fan, Yang, Duan, & Li, 2021) is possible in the case of binary film. A myriad of literature is available in the case of binary film, but limited numbers of works are reported in case of ternary composite edible films (Dhumal & Sarkar, 2018). Composite films formed by emulsifying the constituents give the better film than layered ones, as the layered film may tend to delaminate over time, and it also requires a greater number of casting and drying processes (Galus & Kadzińska, 2015). Composite film prepared by emulsifying the lipid phase into the hydrocolloid-based structural matrix provides better functionality and barrier properties (Ochoa et al., 2017). The proportion of various polysaccharides in the composite film can also influence the different physical and optical properties to an extent (Saberi et al., 2016). Several studies have been published on the composite film made by combining polysaccharides and lipids, with the goal of improving its water barrier properties. The size of the lipid particle on the composite film had a significant effect on WVP properties and mechanical properties due to its higher surface area (Otoni et al., 2016). It is also found that composite films using minerals and protein have shown a significant improvement in their mechanical properties (Wang et al., 2015).

Bi-layer films, predominant in composite edible films, can be prepared by casting one layer over the other, but this multi-step process involves the risk of layer delamination. A single-step process in which one compound is dispersed with other FFS and then cast to form the film can solve this problem (Valencia-Sullca et al., 2018; Zuo et al., 2019).

The incorporation of essential oil in nano-emulsion form is the recent trend followed by the researcher for better efficacy (Shen et al., 2021). Details of some composite edible films are given in Table 2.

2.5. Nanoparticle based edible films

In the last decade, nanotechnology has been used as an innovative approach to obtaining nano-scaled organic and inorganic compounds with unique properties due to their size (Espitia & Otoni, 2018**).** By definition, nanomaterials have at least one of its dimensional particle sizes of about 1-100 nm. The application of nanomaterials in the food packaging sector is an emerging area. Incorporating nanomaterials into matrix polymers proved to be a promising strategy for improving their physical and mechanical properties, which conventional components cannot achieve (Bizymis & Tzia, 2021). Moreover, it can be used for the synthesis of efficient active packaging materials by the method of nanoencapsulation of bioactive natural materials. The nanoencapsulation technique improves the stability and solubility of bioactive compounds, thus leading to the formation of an active film with better performance than conventional ones (Pal et al., 2017). Various researchers have reported several combinations of the bio-based matrix polymer and nanoparticles. The application of nano clay is widely exploited due to its ability to improve the barrier and mechanical properties by their high aspect ratio and surface to volume ratio (Shekarabi et al., 2014). Çağrı Mehmetoğlu et al. (2021) demonstrated the effect of silver nanoparticles in whey protein-based films. Their findings show that adding silver nanoparticles to a film increases its tensile strength by 84% and its barrier properties by 67% over a control film. Similarly, other nanoparticles like zinc oxide, titanium oxide, nano cellulose, etc., have been widely used in food packaging (Dash et al., 2019**;** Malik & Mitra, 2021**;** Yekta et al., 2020).

However, whether these nanomaterials are safe or not is still a controversial question for the scientific community. Nanomaterials can have various toxic effects depending on their chemical composition, particle size distribution, particle shape, and surface condition. The potential to cause oxidative stress and, in some cases, inflammatory responses or genotoxic effects are the most common effects observed in experimental studies. The intensity of this harmful effect further depends on the nanomaterial dose in that particular FFS (Malakar et al., 2021). Based on the size, their ability to penetrate the human cells also varies. For example, 100 nm particles can easily penetrate cells, 40 nm can enter nuclei, and below 35 nm can cross the blood-brain barrier. Moreover, smaller sized particles will have more catalytic ability, and their reactive oxygen species producing potential, adsorption rate, and binding capability may be comparatively higher than bigger-sized particles (Bumbudsanpharoke et al., 2015**;** Vlachogianni & Valavanidis, 2014). Reliable data on nanoparticles' safety and toxicological effects is still not available in the public domain. Hence, the effect of these nanoparticles on human health and environmental microbiota needs to be explored in detail to rule out any adverse effect.

3. Methods for edible film formulation

The edible film can be prepared mainly by the wet process and dry process (Fig. 3). In the wet process, biopolymers are solubilized or dispersed in an aqueous solution, water-based or alcohol-based, to form FFS followed by drying of the solvent. In the dry process, biopolymers were converted into the film by utilizing the thermoplastic behavior exhibited by some proteins and polysaccharides at low moisture levels (Cao et al., 2007**;** Nussinovitch, 2013).

The wet process, also known as solvent casting, is the most predominant technique used in edible film formulation (Fig. 4 **A).** The solvent casting process involves the following steps described by Rodríguez et al. (2020), they are as follows: 1) solubilizing the base biopolymer into a suitable solvent such as water or ethanol to form a FFS, 2) casting the FFS into suitable moulds or Teflon coated plates, 3) drying the casted film formulation solution, 4) peeling/removing the film and storing at suitable RH and temperature.

During the formulation of FFS, all the components are mixed in to homogenize solution with the help of low-speed stirrings, ultrasonication sometimes at a higher temperature suited for the solubilization of the components into the solvents (Abral et al., 2019). The FFS should be free from air bubbles to avoid the entrapment in the film matrix that can affect the structural integrity of the film. Air bubbles from low viscous FFS are normally removed by vacuum degassing (Ghasemlou et al., 2011**;** Kim & Min, 2012**;** Jouki et al., 2013). In the casting step, the amount of the solution is controlled for adjusting the film thickness. For example, V et al. (2022) developed an edible film from soybean aqueous extract by following steps like initial mixing of beeswax, clove essential oil, and span-20 using a magnetic stirrer and ultrasonication followed by solution casting on Teflon sheet and drying at ambient temperature. As of now, the majority of the works are limited to bench casting, which is a batch process. Some limited research on continuous casting is also reported. In the drying process, the solvent is evaporated to form an edible film. The drying is usually carried out at ambient air condition or at low temperature (below 60°C) in a hot air dryer. The drying condition plays a major role in determining the properties of the film (Bagheri et al., 2019). Although the drying time is considerably reduced by alternative drying methods such as microwave and IR drying, it had a significant negative effect on the quality and mechanical properties without affecting WVP of the film (Kaya & Kaya, 2000**;** Srinivasa et al., 2004**;** Cárdenas et al., 2008**;** Tapia-Blácido et al., 2013).

The dry process is mainly classified into extrusion, compression molding, and injection molding. The extrusion method is widely used for commercial synthetic plastic film formulation (Fig. 4 **B**), in which the film-forming matrix is subjected to structural changes by the effect of high temperature, pressure, and low moisture content (Hernandez-Izquierdo & Krochta, 2008**;** Dang & Yoksan, 2015). In this method, the edible bioplastic materials are first converted into pellets and extruded with suitable plasticizers (Huntrakul et al., 2020**;** Vedove et al., 2021**).** The film formulation through extrusion occurs in three steps; i) feeding the FFS to the extruder, ii) mixing of the FFS in the kneading zone of the extruder, iii) heating the FFS and either passing through the slit die followed by calendaring (slit-die extrusion) or blowing through circle die (blown-film extrusion).

The process variables in the extrusion of films, such as screw speed, temperature, feeding rate, and moisture content, have shown great influence on the properties of the film (Jebalia et al., 2019**;** Ochoa-Yepes et al., 2019). Extrusion of the film is considered as the most suitable for the large-scale commercial production of edible film with low energy consumption and short processing time. However, the high temperature generated during the extrusion causes undesirable changes in the biopolymer, such as nutritional and sensory losses in edible film, and application is limited to a certain polymer that is tolerant to high temperature with low moisture content FFS (Otoni et al., 2017**;** Suhag et al., 2020).

Compression molding is considered a sustainable process compared to the traditional solvent casting method due to its rapid formation and less energy requirement (Uranga et al., 2018). In compression molding, film-forming materials are subjected to high pressure and temperature in the mold until solidification (Lisitsyn et al., 2021). Processing parameters like temperature, pressure and time are critical in deciding the film properties. The compression method is frequently used with the extrusion method, in which the former is used for preparing the film-forming material prior to the thermoforming process in the latter. Ceballos et al., (2020) developed an edible film from cassava starch and yerba extract. The ingredients were extruded into thread form using a twin-screw extruder, followed by compression molding to yield the film. A compression-molded film can have higher thickness and more flexibility than solvent cast film (Krishna et al., 2012).

The injection molding method is popular for the industrial production of plastics. It is suitable for the mass production of edible films.

Table 2
Composite edible film using different polymer matrices.

Matrix Polymer	Plasticizer	Method of Preparation	Observations and Remarks	Reference
Ipomoea batatas: κ-carrageenan	Glycerol	Casting	Composite blend of *Ipomoea batatas* and κ-carrageenan yield film with good mechanical and optical properties.	(Bharti et al., 2020)
Chitosan: Nano-silicon aerogel: Okra powder	Glycerol	Casting	Combination of chitosan, Nano-silicon aerogel with okra powder improved mechanical, barrier, optical and anti-microbial properties with excellent surface characteristics.	(Lin et al., 2020)
Pearl millet starch: Carrageenan gum	Glycerol	Casting	Starch and carrageenan concentration has positive influence on the Tensile strength and barrier properties of the film. It enhanced optical, WVP and mechanical property values of the film.	(Sandhu et al., 2020)
Chitosan: WPI	Glycerol	Casting	Composite film resulted in high tensile strength, lower deformation, flexibility, malleability and good WVP than the films formed individually.	(Tavares et al., 2021)
PG: Modified starch		Casting	Incorporation of PG reduced WVP, WS, MC, and TS of the composite film with an increase in its % EB especially when gum percentage greater than 50. Result of Morphological analysis shows that developed film is having good homogeneity with smooth structure.	(Askari et al., 2018)
SPI: VCO:SL	Glycerol	Casting	Amalgamation of SPI, VCO and SL resulted in the formation of film with increased EAB and lower MC than the film obtained from SPI alone. However, this blending was not influenced the WVP value of the film.	(Carpiné et al., 2015)
Gelatin: DXG: NH_2-MMT	-	Casting	Cross-linking effect of DXG and NH2-MMT nanofiller resulted in the enhancement of water resistance, UV barrier property, and mechanical properties of the gelatin-based composite film. Enhanced hydrophobicity and compact structure resulting from the cross-linking slowed down the fungal degradation of the film.	(Ge et al., 2017)
Gelatin: GLU	Glycerol, Sorbitol	Casting	Gelatin in the composite film improved its WVP and gluten enhanced its flexibility. EAB was greatly influenced by glycerol concentration. However, presence of Sorbitol did not alter the EAB.	(Fakhouri et al., 2017)
Fish gelatin: Chitosan	Glycerol	Casting	Addition of glycerol caused significant increase in the TS and elastic modulus, leading to stronger films as compared with gelatin film, but significantly decreased the EAB. Chitosan drastically reduced the WVP and solubility of gelatin films.	(Fakhreddin Hosseini et al., 2013)
Gelatin: Starch: ε-PL	Glycerol	Extrusion blowing	Starch/gelatin mix is a suitable substrate for making ε-PL loaded antimicrobial edible packaging.	(Cheng et al., 2022)
Cassava starch: Pea protein	Glycerol	Extrusion blowing	Incorporation of pea protein isolate at 20% in cassava starch increased the strength of the composite film.	(Huntrakul et al., 2020)
Casein: wax powder: potassium sorbate	Glycerol	Extrusion blowing	Extrusion was used to create a new composite edible film based on casein and several edible waxes.	(Chevalier et al., 2018)
Cassava starch: YME	Glycerol	Compression molding	Tensile toughness of the cassava starch YME composite film highest was obtained for 10% YME	(Ceballos et al., 2020)
GLU: MMT	Glycerol	Injection molding	MMT showed and lubricating effect and facilitated the injection molding of GLU	(Cho et al., 2011)

***Abbreviations*:** DXG: Dialdehyde xanthan gum EAB: Elongation at break, GLU: Wheat gluten, MC: Moisture content, NH_2-MMT: Amino-functionalized montmorillonite, PG: Psyllium Gum, SL: Soy lecithin, TS: Tensile strength, VCO: Virgin coconut oil, WPI: Whey protein isolate, WS: Water solubility, WVP: Water vapor permeability, YME: yerba mate extract, ε-PL: ε-polylysine hydrochloride.

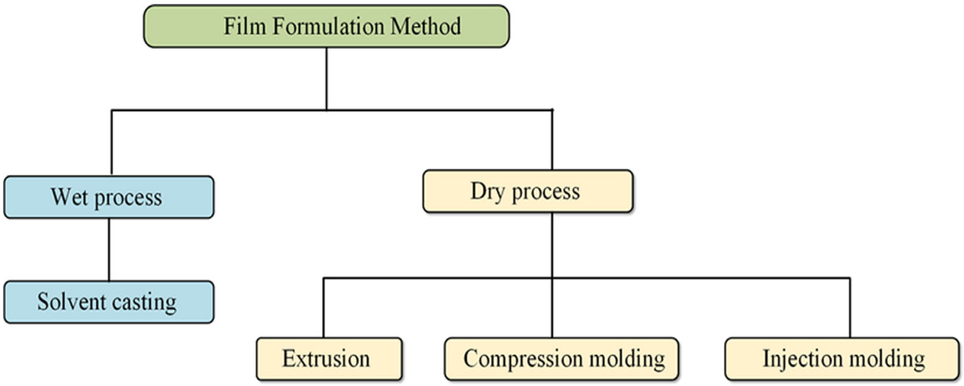

Fig. 3. Film formulation methods.

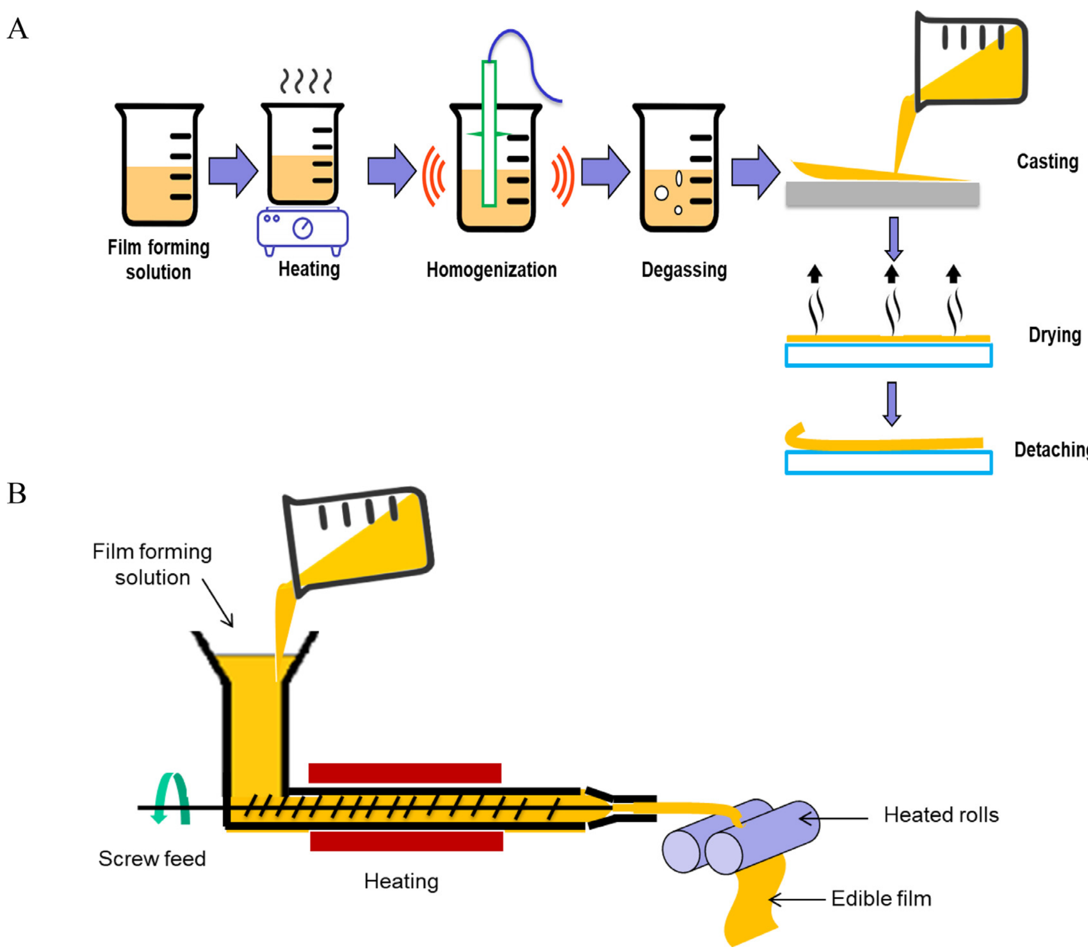

Fig. 4. Schematic representation of the edible film formulation: (A) Casting method and (B) extrusion method.

This method is used in combination with the extrusion method for obtaining the final film (Mellinas et al., 2016). However, limited research was reported in edible film injection molding (Mellinas et al., 2016). Cho et al. (2011) demonstrated the successful development of wheat gluten-based nanocomposite film using injection molding. The ingredients were pelletized with the help of a compression mold prior to injection molding using a three-phase screw injection-molding machine. Among the processing parameters, pre-injection temperature, molding temperature, and injection pressure are most critical for injection molding (Perez et al., 2016).

4. Application of edible film for packaging of foods

Every year the demand for the packaging material increases by 8% to meet the total requirement (Rodrigues et al., 2016; Tavassoli-Kafrani et al., 2016). This increases, and consumers' concern over green packaging triggers the spike in the utilization of bio-based food packaging materials for shelf-life extension of different food products (Falguera et al., 2011). Some of the successful applications of edible film explored to date are elaborated in the proceeding sections, and Table 3 summarizes the different applications of edible packaging on various food types.

Table 3
Application of edible film/coatings for essential functions in fruits, vegetables, meat and seafood.

Edible Film/Coating	Additives	Food Commodities	Significant Function	References
(A) Edible Packaging of Fruits				
Candielila wax	Mineral oil	Guava fruits	Color retention, weight loss	(Tomás et al., 2005)
Cabdielila wax	Jojuba oil + ellagic acid	Golden delicious apple	Weight loss and Sensory qualities	Ochoa et al., 2011
Candelilla wax	Guar gum +glycerol	Strawberry	Anti-fungal, increase shelf life	(Oregel-Zamudio et al., 2017)
Carnauba wax		Walnuts, pine nuts	Overall appearance by reduction in rancidity, taste	(Mehyar et al., 2012)
Polysaccharide + carnauba wax		Mango	During the storage of mango ripening improve the permeability	(Baldwin et al., 1999)
Carrageenan + whey protein	CMC salt+ PEG + CaCl2 + glycerol + oxalic acid additives	Apple	Browning on minimally processed apple slices	(Lee et al., 2003)
Pectin + LDH-salicylate	Glycerol	Apricot	Morphological, thermal and barrier properties	(Gorrasi & Bugatti, 2016)
Whey protein + pectin	Sorbitol + gallic acid + transglutaminase	Fresh apples, carrots, potatoes	Antioxidant, phenolic content, weight loss, texture and sensory attribute	(Rossi Marquez et al., 2017)
HPMC + lipid	potassium sorbate + sodium benzoate + sodium propionate + stearic acid + glycerol additives	Oranges	Improved antifungal property during storage	(Valencia-Chamorro et al., 2009)
Cabdielila wax	Jojuba oil + ellagic acid	Golden delicious apple	Sensory qualities, wight loss	(Hassan et al., 2018)
Candelilla wax	Guar gum +glycerol	Strawberry	Anti-fungal, increase shelf life	(Hassan et al., 2018)
Carnauba wax		Walnuts, pine nuts	Hydrolytic and oxidative rancidity, taste, overall appearance	(Bhartiya et al., 2020)
(B) Edible Packaging of Vegetables				
Chitosan + gelatin		Red bell peppers	firmness, CO_2, weight loss, and ethanol concentration	(Poverenov et al., 2014)
Calcium caseinate coatings	Acetylated monoglycerides + fatty acid esters + sodium salt of carboxymethyl cellulose	Zucchini (summer squash)	reduce water	(Hassan et al., 2018)
Candelilla wax		Brussels sprout	Reduces weight loss, Preservation of vitamin C and polyphenols, minimal softening, increased overall appearance during storage.	(Kowalczyk, 2011)
HPMC + Beeswax	Oleic acid + glycerol	Cherry tomato	Weight loss, peel color, fruit firmness, respiration rate, sensory qualities enhanced.	(Fagundes et al., 2015)
k-carrageenan or Tapioca starch coatings	Potassium sorbate + ascorbic acid + citric acid + glycerol	Fortified pumpkin	Color and antimicrobial activities Fresh-cut	(Genevois et al., 2016)
(C) ***Edible Packaging for Sea Foods and Meat Products***				
1.25 % chitosan	0.8% glycerol+ Tween 80+grape seed extract+carvacrol	Salmon	Reduce microbial growth Reduce lipid oxidation	(Alves et al., 2017)
Whey protein concentrate	Glycerol+green tea extract	Salmon	Retarded lipid oxidation	(Castro et al., 2019)
Gelatin	Olive leaf extract+glycerol	Cold smoked Salmon	Microbial growth inhibited by olive leaf extracts	(Albertos et al., 2017)
Chitosan (94.7% DD)	Bacteriocin (divergicin M35)	Cold smoked wild pacific sockeye salmon	Effective against L. monocytogenes	(Benabbou et al., 2018)
2 % chitosan (75-85 % DD) + gelatin	Glycerol + tween 80+ grape seed extract + Ziziphora essential oil	Rainbow trout	Improved shelf life by Deferring microbial growth and lipid oxidation	(Kakaei and Shahbazi, 2016)
1% agar + fish protein hydrolysates	Glycerol + Clove EOs	Flounder (Paralichthys orbignyanus)	Improved shelf life by improving biochemical and microbiological parameter	(da Rocha et al., 2018)
3% Chitosan + 3% Sarcoplasmic protein	Glycerol + Tween 80 with ginger EOs	Red sea bream	Extend the shelf life	(Cai et al., 2020)
1 % Chitosan + 0.5 % Locust bean gum	Glycerol + pomegranate peel extract	White shrimps	Reduce microbial spoilage and volatile bases production	(Licciardello et al., 2018)
1 % Basil seeds gum	Glycerol + (99.5%) Thymol	Pacific white shrimp	Reduced oil uptake and moisture loss during fryig	(Khazaei et al., 2016)
Sweet potato starch	Glycerol + Tween 80 + EOs (Thyme)	Shrimp	reduce melanosis prevent microbial growth and reduce lipid oxidation	(Alotaibi and Tahergorabi, 2018)
7% Chitosan (75.5% DD)	1% Protein (42.7%)- lipid (11.48%) concentrate	Shrimp	Delayed the onset of melanosis and maintained sensory qualities	(Arancibia et al., 2015)
1% Chitosan (85% DD)	3% gelatin	Shrimp	Reduced weight loss and improved texture and color changes	(Farajzadeh et al., 2016)
Chitosan (90% DD)	Pomegranate peel extract	Pacific white shrimp	Inhibited melanosis and improved the sensory qualities	(Yuan et al., 2015)
Chitosan (90% DD)	0.5% Tween 80, 0.5% carvacrol, and 1% caprylic acid	Pacific white shrimp	Extended the shelf life during the iced storage	(Q. Wang et al.,2018)

(*continued on next page*)

Table 3 (*continued*)

Edible Film/Coating	Additives	Food Commodities	Significant Function	References
0.5 and 1.5% Chitosan (91% DD)		Atlantic salmon	1.5% Chitosan maintained better quality and controlled microbial growth	(Soares et al., 2015)
4% Collagen	0.1, 0.3, 0.5, and 0.7% Lysozyme + 1% glycerol	Salmon	Reduced weight loss and improved texture and sensory qualities	(Wang et al., 2017)
1% Carrageenan	1% EOs (lemon)	Rainbow trout	Preserved physical–chemical, morphological, and olfactory characteristics	(Volpe et al., 2019)
1% Alginate	0.3% Tannic acid, 0.3% quebracho tannin, and 1% ascorbic acid	Rainbow trout	Reduced microbial counts and lipid oxidation	(Sáez et al., 2020)
Whey protein concentrate	Glycerol	Rainbow trout	Suppressed microbial growth and enhanced sensory attributes	(Oğuzhan Yıldız & Yangılar, 2016)
Whey protein	Glycerol+NaOH	Atlantic salmon	Improved the overall quality of salmon	(Rodriguez-Turienzo, Cobos and Diaz, 2012)
Caseiante	Ascorbic acid	Beef	Effect of gamma irradiation on microbiological characteristic of ground beef	(Hassan et al., 2018)

***Abbreviations*:** DD: de-acetylated, HPMC: Hydroxypropyl methylcellulose, EO: Essential oil.

4.1. Fruits and vegetables

Consumers always prefer to choose fruits and vegetables in fresh form, which has led to the continuous development of advanced methods that helps in maintaining quality and shelf life of the produce (Flores-López et al., 2016). Nevertheless, high moisture and microbial deterioration make these products highly perishable and limit their storability. Applying adequate packaging such as edible packaging can enhance its shelf life by creating a barrier against microbes, moisture, and gases (Pizato et al., 2019). A number of works have been reported based on bio-polymer application in fruits and vegetables (Table 3 **(A&B)**). For example, a chitosan-based film in combination with TiO_2 has experimented for the storage of grapes (Zhang et al., 2017), application of alginate-based composite film on shelf life of fresh fig was studied by Reyes-Avalos et al., (2016), the effect of beeswax content on hydroxypropyl methylcellulose-based edible film on postharvest quality of coated plums was evaluated by Navarro-Tarazaga et al., (2011).

Edible film/coatings can improve the quality and shelf life of various fruits by inhibiting lipid oxidation, delaying moisture loss, preventing discoloration, and maintaining the fruits' appearance during marketing by minimizing dirt and dust contact, entrapping volatile flavor compounds, and acting as carriers of food additives such as antimicrobial and antioxidative agents. Ochoa et al. (2011) successfully improved the quality and shelf life of delicious golden apples by applying edible layers comprised of natural wax extracted from Euphorbia antisyphilitica and potent antioxidant 0.01% ellagic acid (EA). Walnuts and pine nuts coated with a homogenized coating solution of whey protein isolate with carnauba wax exhibited lower oxidative and hydrolytic rancidity and improved sensory quality (Mehyar et al., 2012). Fagundes et al., (2015), evaluated the beneficial properties of composite edible films formulated with HPMC, beeswax, and different food preservatives having an antifungal property like sodium benzoate, sodium ethyl paraben, and sodium methyl paraben applied to cherry tomato with artificially inoculated black spot fungi Alternaria alternata during cold storage. The authors observed that sodium benzoate (2%) based edible packaging significantly reduced weight loss, respiration rate, and maintained the firmness of the cherry tomatoes.

4.2. Dairy products

Milk and milk products are considered a good source of dietary supplements for better health of both children and adults (Cardador & Gallego, 2016). The literature survey shows that cheese packaging is considered one of the potential application areas of the edible film (V et al, 2021). Packaging, especially with antimicrobial film in cheese observed to have considerable influences on its shelf life. Fajardo et al. (2010) evaluated the efficacy of chitosan-based film as a carrier of natamycin to improve storage stability of Saloio cheese, and observed that the product was stable until seven days at ambient storage conditions. Mahcene et al. (2020) assessed the preservative effect of sodium alginate-based edible film incorporated with essential oil on homemade cheese, and they concluded that edible packaging is an effective preservation method of cheese.

Martins et al. (2010) evaluated the shelf-life extension of Ricotta cheese, a soft Italian cheese, during cold storage (4°C) upon using galactomannan-based edible coatings in combination with nisin (50 IU g–1) against Listeria monocytogenes. Authors found that edible coatings with nisin delay the microbial growth significantly ($P<0.05$), increased the tensile strength (0.84 to 1.46 MPa), increased the opacity (3.68 to 4.59%), improved the elongation breakpoint (50.93 to 68.16%), increased the CO_2 permeability (1.96 to 6.31×10^{12}) cm^3. $(Pa.s.m)^{-1}$), and decreased the O_2 permeability (1.84 to 1.35×10^{-12}) cm^3) x $(Pa.\ s.m)^{-1}$). Similarly, whey protein (10% w/w) based coating in combination with chitooligosaccharide (20g L^{-1}) and lactic acid (6g L^{-1}) potentially inhibited the microbial growth (<2.0 cfu/g) on laboratory manufactured cheese after 60 days long storage at 10°C (Ramos et al., 2012).

4.3. Meat and meat products

Meat and meat products are considered favorable food among consumers due to their unique taste and nutritional benefits. Nevertheless, meat is highly susceptible to spoilage due to microbial and chemical changes; therefore, its preservation requires special attention. Advanced packaging techniques such as intelligent and antimicrobial packaging have emerged as food safety hurdles technology primarily for the products like meat (Soni et al., 2018). The edible packaging concept is gaining much popularity among meat and meat products due to its significant role in improving physicochemical and sensory properties (Galus & Kadzińska, 2015). Research progress in applying edible film in meat and meat products was briefly summarized in Table 3 **(C).**

Essential oils have become more widely used in edible films due to their antioxidant and antimicrobial properties in recent years. Moradi et al. (2016) assessed the antimicrobial effects of zein-based films in combination with *Zataria multiflora* Boiss. essential oil (ZEO) (3%) and monulaurin (1%) against *E. coli* O157: H7 and *Listeria monocytogenes in vitro* and minced beef. The authors found that ZEO significantly enhanced the antimicrobial activity of the film. Similarly, Ferulago Angulate Essential Oil (FAEO) (0.05%) incorporated with gelatin-chitosan-based film inhibited the microbial growth and improved the shelf life of turkey meat (Naseri et al., 2020).

4.4. Seafoods

Seafood, which includes fish and fish products, generally has a limited shelf life due to the rapid growth of microbes, which can pose a threat to consumers' health as well as result in economic loss. (Gómez-Estaca et al., 2010**;** López de Lacey et al., 2014). In recent years, the edible packaging concept is evolved as an efficient strategy to enhance the storage stability of fish (Günlü & Koyun, 2013). Successful application of several polysaccharides such as chitosan (Remya et al., 2016), sodium alginate-carboxy methylcellulose (Rezaei & Shahbazi, 2018), whey protein (Seyfzadeh et al 2013), etc., which various researchers have already explored. Some of the recent progress and their major findings are given in Table 3 (C).

The edible film/coatings, which are primarily chitosan-gelatin based, effectively preserve the desired quality, extend the shelf life, and improve the texture and color of sea and meat products by reducing spoilage, reducing the accumulation of volatile compounds and oxidation substances, and minimizing weight loss. Castro et al., (2019), verified the potential of whey protein concentrate film in combination with green tea extract applied on fresh salmon and found that their combination effectively delayed the lipid oxidation of fresh salmon until the fourteen days of storage. The incorporation of essential oils into edible films due to their antioxidant and antimicrobial activity has been more documented in the past few years. Ginger essential oil incorporated with fish sarcoplasmic protein and chitosan applied to red sea bream significantly reduced the oxidation, protected from microbial degradation, and extended shelf life of the red sea bream (Cai et al., 2020).

5. Safety and regulation for edible films

Food safety and regulation vary from country to country. According to EU and US regulations, edible film and coating can be considered food ingredients, additives, contact materials, or packaging materials. As a result, the constituents used for its formulation should have Generally Recommended As Safe (GRAS) status as per the regulations of the Food and Drug Administration (FDA) regulation (Dhall, 2013). Nevertheless, there are chances for the transformation of FFS into toxic substances due to changes that occur during the film development process (Giteru et al., 2020). Different cross-linking agents used for enhancing the film properties and interaction with gastrointestinal substances can also trigger the formation of toxic materials (Chiralt et al., 2018). In one study (Roșu et al., 2017), the effect of graphene oxide and its derivatives on the cytotoxicity of the methylcellulose-based film on human lungs was investigated, and lower toxicity was reported for reduced graphene oxide compared to graphene oxide. The effect of modification techniques and ingredient selection plays a critical role in edible film safety but is rarely reported in edible film studies. Moreover, the addition of nanomaterials in the film may cause several toxicological effects on human bodies, as explained in section 2.5. At present, there is no specific legislation for nanomaterial use in food packaging, and the recommendations differ by nation. As per the guidelines of the Institute of Food Science and Technology (IFST) in the United Kingdom, nanomaterials should be considered hazardous unless clear safety proof is available (Jeevahan et al., 2020). According to EU and Switzerland legislation, information on nanomaterial risk and/or legally binding definitions of nanomaterial need to be produced. Labeling the presence of nanomaterials in a specific film is critical for communicating risk elements to consumers. In EU definitions, size is used as an identifier for nanomaterials in regulatory purposes (Bizymis & Tzia, 2021). The USFDA publishes a list of food ingredients and contact substances and advises manufacturers to research and develop a toxicological profile for each container containing nanomaterial (USFDA 2014**).** Most countries, presently, do not have any regulations for the use of nanotechnology. More research on the nanomaterial's toxicological effects can help formulate new safety and regulations for its application.

6. Recent trends, challenges, and future perspectives in edible film

The edible film research area is constantly evolving, with new raw materials for film formation, active packaging development, nanotechnology applications, etc. All these efforts were targeted to develop biopolymers having properties par with conventional synthetic polymers and their economic production by utilizing agricultural by-products as raw material. The development of active films has been identified as one of the primary focus areas in packaging research in the last decades, which enable the shelf-life extension of perishable fruits and vegetables by the addition of various antimicrobial and antioxidant components into their base polymer matrix (Deng et al., 2020**;** Nair et al., 2020**;** Orozco-Parra et al., 2020). Active edible films have active interaction with contained food and contribute health benefits to consumers (Moradi et al., 2021**).** For example, Orozco-Parra et al. (2020) developed a synbiotic film from cassava starch with the incorporation of insulin as a prebiotic molecule and L.casei as the probiotic bacteria. The developed film has shown decreased viability loss of probiotic bacteria during simulated gastric condition study.

Similarly, the successful use of edible film for the transport of probiotic bacteria was also reported by other authors (Ebrahimi et al., 2018**;** Soukoulis et al., 2017). In recent years food-processing by-products-based edible films are gaining popularity. It allows the valorization of industrial by-products, and their low-cost helps develop edible film economically. By-products of fruits and vegetable processing, marine food processing, and edible oil processing industries proved the promising potential for the film preparations (Aloui et al., 2019**;** Benbettaïeb et al., 2019**;** Hromiš et al., 2022**;** Moghadam et al., 2020**;** Shroti and Saini, 2022 Valdés et al., 2020**).** As explained in the section 2.4 **&** 2.5, the edible films with tailored properties have been experimented with composite film formulation and nanotechnology application. Moreover, several attempts were also made to achieve this goal by cross-linking various biopolymers (Peng et al., 2021**;** Yerramathi et al., 2021**;** Zhang et al., 2022**).**

Despite all advantages, like all other newly developed technologies, edible films also face great challenges that need to be overcome to make them a commercial success. Even though a number of ways are experimented to improve the properties of the film to make it on par with petroleum-based polymers, poor mechanical properties, weak resistance against water and gases, and insufficient physical properties are the hurdle for its use in various food applications. Investigations were carried out to address these challenges by developing composite films and nanocomposite films. However, composite film production by multilayer approach tends to fail by delamination of layers, and time, energy, and cost requirement for the formation of the multilayer film are high. Another crucial property of films is their heat sealability. The range of optimum sealing temperature is narrow for biobased films. So, chances of undersealing and charring due to overheating are higher for these films. This negatively affects its applications in the formation of pouches and covers. The main reason restricting the commercial application of edible film technology is the inability to make large-sized films (>25cm), difficulties in maintaining the thickness, and a long-time requirement for drying (2-3 days). Application of nanotechnology is considered a trending area for edible films. Still, practical difficulties in isolation and homogeneous dispersion of nanomaterials in matrix polymers and economic aspects always create a challenge. Moreover, a lack of information on the toxicological effect of nanomaterial and other film-forming components generates fear and reluctance in consumers. Only limited studies were reported on the evaluation of how the aging of the film affects its properties. Since the primary intended use of packaging material is to contain the food and extend its shelf life during storage, thus this factor needs to be considered (Jeevahan et al., 2020). Among the reported research on edible film, emphasis on sensory analysis is relatively low. The sensory attributes of the film are the first and foremost important factor that decides the acceptance of the edible packaging film. Ultimately consumer acceptance is the only deciding factor in changing our packaging concept. For achieving its commercial success, complete study and documentation are required to prove its biodegradability, organoleptic aspects, safety and security, and legal confirmation. In order to overcome these challenges, considerable research efforts need to concentrate on the following essential aspects. A detailed toxicological study of the film-forming components by emphasizing nanoparticles is required to be carried out. Any technology on a laboratory scale cannot benefit the consumers. So, the method for the production of the continuous edible film with consistent properties needs to be developed. Change in properties of edible film during aging and under different temperature and relative humidity conditions is also essential to confirm its utility in food storage purposes. Consumer awareness programs and advertisements of edible films can also increase their acceptability.

7. Conclusion

Edible films have been identified as a healthy source of food protection from various elements, as they are naturally occurring, inexpensive, and renewable. The possibility of incorporating functional ingredients and excellent biodegradability further glorifies its attraction. Extensive research has been conducted to determine the best outcome and minimize drawbacks with new concepts such as composite film approach and nanotechnology application. More research on important aspects like property improvement, implementation of safety and regulation, exploration of new and economic sources, and commercial scale-up by continuous production is essential to its successful adoption.

Conflict of Interest Form

The following authors have declared that there is no conflict of interest in publishing manuscript entitled "***Trends in Edible Packaging Films and its Prospective Future in Food: A Review***"

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