TOWARDS A GREENER TOMORROW: BIODEGRADABLE FOOD PACKAGING MATERIALS AS A SUSTAINABLE SOLUTIONS

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Abstract
The environment has been greatly harmed by the excessive use of conventional packaging materials from diverse sources and through various chemical processes, and the length of time it takes for them to disintegrate has been a major research concern. Innovative ideas and technological advancements have paved the path for sustainable alternatives to biodegradable packaging. Some naturally occurring and renewable materials, which are widely distributed in the environment, have the capacity to produce biofilms. Biodegradable polymers face several obstacles in their path to useful packaging applications, nevertheless. Particularly about the poor gas/moisture barrier concerns that severely restrict the use of conventional biodegradable polymers for food packaging. The current bio-based packaging material should be improved for the environment and its use should be assessed. The review article highlights the properties, application, limitations and future trends of the biodegradable packaging material.

Key words: Biodegradable, Hydrocolloids, Sustainability, Environmental pollution, Solid waste

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1. INTRODUCTION

Although packaging has different definitions, in common it is defined as a “element or a material which surrounds and cover up the product beginning from product manufacturing until it reaches to the consumer” Packaging plays a very important and essential role in all types of industries and is important for its proper and trustworthy functioning (Saha, 2020; Anukiruthika et al., 2020). Fig. 1 represents various functions of packaging materials. Packaging is of utmost importance in the food processing, preservation, supply, and distribution of processed and unprocessed food. The major concern and function of packaging material is to contain the food product and protect its nutritional quality both from internal and external conditions (Yildirim et al., 2018). Packaging materials used in food industry comes in a variety of material, shapes and colours that serve different functions in context to preserving the properties of the food item that they carry inside (Habel et al. 2018).

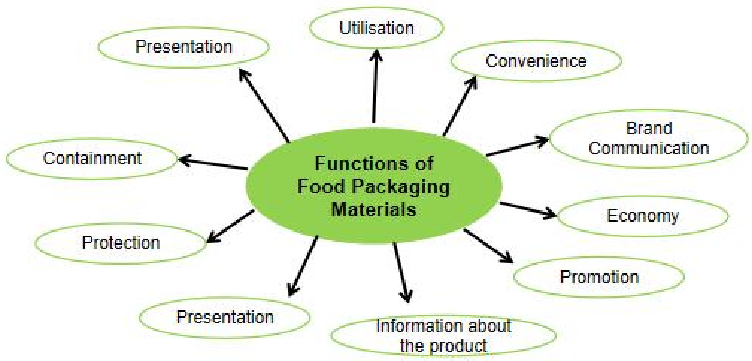


Fig. 1 Functions of packaging material

Over the years the demand for packaging material has increased tremendously, and the demand has increased to 917.1 bn US dollar in the year 2019. As per the studies conducted on the global packaging growth, it was expected that there will be an increase in the manufacturing and consumption pattern by 2.8 percent (*Packaging News, 2020).* The fifth largest sector in India’s economy, packaging is also one of the fastest growing segments in the country. As per Packaging Industry Association of India (PIAI), the industry is growing year-on-year at the rate of 24 to 27 percent (Kapil, 2020; Smruthi, 2021).

Thus, deciding on the best packaging material depends on the objectives that are sought after. This can include protecting food from moisture, temperature, oxygen, light, and biological microorganisms, among other things. Glass, metals (aluminium, foils and laminates, tinplate, and tin-free steel), paper and paperboards, and plastics are among the materials that have traditionally been used in food packaging. In addition, a broader range of rigid and flexible polymers has been introduced. (Kapil, 2020).

Synthetic food packaging materials have been used to pack the various food products and among them plastic bags have a significant environmental impact since they take a long time to degrade. The packaging industry uses 43% of the synthetic polymers generated annually in India (Shaikh et al., 2021). Fig 2., shows the plastic waste producedand as per the reports a total of 395,000 metric tonnes of plastic garbage were exported from the EU-27 to Turkey in 2021. Furthermore, to add on this when plastic bags decompose in the sun, hazardous compounds are released into the soil, and when plastic bags are burned, poisonous substances are discharged into the air, generating air pollution. The environmental impact of packaging waste can be reduced by carefully selecting materials, adhering to EPA requirements, and assessing packaging requirements in terms of environmental impact. (Kirwan & Strawbridge, 2003).

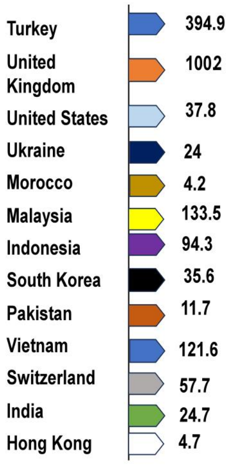


Fig 2. Plastic waste exported by the European Union 2021 (in 1,000 metric tons)

Most of the plastic packaging that is shipped to landfills winds up in our natural settings because there are ineffective waste management systems in place all over the world (Rajmohan et al.,2019). Every year, 8 million tonnes of plastic are poured into the ocean. In addition to endangering wildlife and ecosystems, plastic pollution also puts human health at risk (Hossain et al., 2021). Biodegradable polymers to reduce the risk posed by synthetic polymers in many industrial applications, biodegradable polymers have become a viable alternative (Kolybaba et al., 2006).

Biodegradable polymers are made from renewable agricultural feedstock, animal sources, waste from the marine food processing sector, or microbes. Biodegradable materials, in addition to renewable raw materials, degrade to produce environmentally friendly products such as carbon dioxide, water, and high-quality compost. (Tharanathan, 2003). Another type of biodegradable polymer is edible films, which are thin coatings of edible ingredients that are coated on food or deposited on or between food components. They have a variety of functions, including preventing moisture, gas, and fragrance migration as well as increasing the mechanical integrity and handling properties of the food. Zein (corn protein), whey (milk protein), collagen (a component of skin, tendon, and connective tissue), and gelatin are examples of edible films originating from plant and animal sources, Fig., 3 shows various polymer source (product of partial hydrolysis of collagen) (Marsh & Bugusu et al., 2007).

Bio– Based Polymers

Synthetic biodegradable polymers	**Natural biopolymers extracted from biomass**	**Polymers produced by Micro Organism**
1. From Biomass □ Polylactic Acid (PLA) **2. From Petrochemicals** □ Polycaprolactone (PCL) □ Polyvinyl alcohol (PVA) □ Poly (glycolic acid) (PGA)	**1. Polysaccharide** □ Starch □ Cellulose □ Alginate □ Carrageenan □ Chitosan **2. Lipids** □ Glycerides □ Waxes **3. Protein** □ Gelatine □ Casein □ Whey □ Soy protein □ Zein □ Wheat □ Gluten	**1. Microbial** □ Bacterial cellulose □ Polyhydroxyalkanoates(PHA) □ Polyhydroxy butyrate (PHB) □ Poly (3- hydroxybutyrateco-3-hydroxyvalerate) (PHBV)

Fig 3. Classification of biodegradable polymers based on their sources

The litter argument for biodegradable plastics is valid in the sense that after being littered, biodegradable plastics will tend to break down and become less noticeable. In the maritime environment, where garbage poses a threat to marine life, biodegradability is crucial (Zhu & Wang, 2020). Biodegradability can also be beneficial in military situations where regular disposal methods are unavailable. Biodegradable polymers have specific but modest roles such as controlling moisture, fragrance, and lipid movement across food components (Kirwan & Strawbridge et al., 2003; Marsh & Bugusu et al., 2007).

Commercialization of bioplastics is under way. NatureWorks, LLC (a stand-alone company wholly owned by Cargill Inc.) manufactures polylactide from natural products (corn sugar). After the original use, the polymer can be hydrolyzed to recover lactic acid, thereby approaching the cradle-to-cradle objective (that is, imposing zero impact on future generations). In addition, Wal-Mart Inc. is using biopolymers by employing polylactide to package fresh cut produce (Bastioli, 2005; Marsh & Bugusu et al., 2007).

The following section delves into the primary sources of biodegradable polymers, with the goal of better understanding their characteristics so that a link may be made between potential sources and the practicality of using them for green, sustainable, and environmentally friendly food packaging.

2. FOOD PACKAGING – THEORY AND PRACTICE

Food nourishes our body, provides nutrition when consumed in a conscious way. Such food might come in contact with environmental factors like shocks, off odour, dust, temperature, humidity, micro-organism during preparation, transportation, storage and by the time it reaches to the consumer it gets spoils and won't be in good condition to consume. The food packaging is necessary to ensure safer and protected food (Ketelsen et al., 2020; Habel et al., 2018). Food products might undergo a lot of undesirable changes even after processing, which might be due to under or over processing, unhygienic packaging. This can be prevented by food packaging (Din et al., 2020).

Due to ease in handling, lower price, higher resistance for mechanical, chemical and physical stresses the non-biodegradable packaging materials have been opted for packaging wide range of food products (Ibrahim et al., 2021). Non-biodegradable packaging material such as polypropylene, polystyrene, and polyvinyl chloride are petrochemical based plastics and possess various characteristics to meet the requirements of packaging material so as to preserve and protect the food product (Mangaraj et al., 2019; Din et al., 2020). But such kind of packaging material on the other hand are harmful to environment due to their poor or nil recyclability, non- biodegradability which might lead serious environmental complications.

Fruits and vegetables are essential components of a healthy diet. The nutritional value of vegetables lies in their micronutrient content, fibre content, and bioactive phytochemicals (Ibrahim et al., 2021). Micronutrients in vegetables generally comprised of vitamins and minerals which are required by humans in small quantities to orchestrate a range of physiological functions. Although these micronutrients are required in trace amounts, yet their deficiency causes a number of diseases in human (Jafarzadeh et al., 2020; Mangaraj et al., 2019; Din et al., 2020).

3. BIODEGRADABLE PACKAGING MATERIAL

There are several bio-based, non-biodegradable packaging materials are available in the market which meets all industrial, market and consumer needs such as bio based PE, PET and PA which contributes around 0.8 million tonnes and 40 percent of total bioplastic production (Leal et al., 2021). As per the data collected by European bioplastics in the year 2020 it was found that the bioplastics are having wide range of applications including food sector. Segments, such as consumer goods or agriculture and horticulture products, continue to increase their relative share (Bioplastics, 2020).

Bio-based and biodegradable materials typically have relatively poor water vapor barrier properties and mechanical properties, heat stability, and processing properties compared to their fossil-based counterparts (Platt, 2006). Thus, the challenges to achieve suitable barrier and mechanical properties without compromising the biodegradability limit their widespread acceptance and use. Films prepared from modified celluloses have been applied in some studies for food packaging applications. For instance, shelf life of green tea was extended to 110 days in pouches made by CMC incorporated with Thai rice grass extracts microencapsulated powder (MP), as compared to 91 days in CMC pouches (Sarfraz et al., 2021; Campos et al., 2011; Mangaraj et al., 2019).

To obtain an environmental packaging material is preferred objective and polymers have been used and it is also considered as important material and has gained attention, and these polymers has been classified into three different components and these are -

- Polymers which are obtained directly by biomass which includes proteins such as gluten, suchaszein, soy protein, whey protein and caseinates proteins and Polysaccharides which are obtained by starch, cellulose and chitosan (Mangaraj et al., 2019; Fabra et al., 2014)
- Synthetic polymers – are obtained by oil-based monomers which includes PLA (Polylactic acid), PVA (Poly vinyl alcohol), EVOH (Ethylene vinyl alcochol) (Campos et al., 2011; Fabra et al., 2014)
- Polymers which are developed or obtained by natural microorganisms or by genetic modification such as polyhydroxy alcanoates or bacteriacellulose (Fabra et al., 2014)

There are several various methods by which a food packaging films can be formed and those are casting, lamination, coating or coextrusion processes from raw material plastic biopolymeric, polymer and also biodegradable materials. To develop food packaging material the raw materials are extracted from polymers which includes starch, cellulose, gelatine, cellulose and poly lactic acid. Apart from plant source, the films are even developed from bacterial extracted compounds which are xanthan, pullulan, cellulose and curlan. Films developed by chitosan are edible, non- toxic, natural polymer, biodegradable. Supplements or additives are added to the film so as to improve the properties of the biodegradable film. The hydrophilic nature can be stabilised by adding polysaccharides and proteins (Bourtoom, 2008; Campos et al., 2011; Galus et al., 2020; Mangaraj et al., 2019).

Bioplastics or biodegradable packaging material and its development is an environment concern; it was estimated that by the end of 2025 the production of bioplastic would reach to 2.8 million tonnes from being 2.1 million tonnes in 2020. It was also expected that there will be a threefold increase in the production capacity of the bio-based packaging materials by 2025. The use of bio-based PP is being more and its application is being versatile that it is been used in various sectors and is one of the most used plastic commodities. Packaging remains the largest field of application for bioplastics with almost 47 percent (0.99 million tonnes) of the total bioplastics market in 2020 (Bioplastics, 2020).

4. HYDROCOLLOIDS AND FUNCTIONAL INGREDIENTS USED TO CONSTITUTE BIODEGRADABLE PACKAGING MATERIALS

Elaboration of edible films and coatings has been possible thanks to the filmogenic capacity of natural biopolymers. Hydrocolloids have good aptitude to form a continuous and cohesive matrix with adequate mechanical properties (Campos et al., 2011). Such ability is related to the chemical structure of these compounds, which allows the association through hydrogen bonding of their polymeric chains. In the following, the most usual filmmaking materials and their most relevant characteristics are mentioned.

4.1. STARCH

Starch is composed of amylose (10-30%) (poly- α-*1,4-D-glucopyranoside*) and amylopectin (70-90%) (poly-α-1,4-D-glucopyranoside and α-1,6-D-glycopyranoside), and found naturally in abundant form and is one of the natural polymers which has the properties of biodegradability and renewability (Torres & Arce, 2015; Arora et al., 2018). Cereals (40–90%), roots (30–70%), tubers (65–85%), legumes (25–50%), and immature or unripe fruits (40–70%) are the main sources of starch reserves (Yamaguchi, 2012). The commercial starch source is easily extracted from rice, wheat, corn, potatoes etc., and the percent starch source varies depending the source of extraction (Luchese et al., 2018; Jemima et al., 2021). The possible applications of starches in the food business are determined by their physico-chemical (e.g., gelatinization and retrogradation) and functional (e.g., solubility, swelling, water absorption, syneresis, and rheological behaviour of gels) qualities (Gani et al., 2010). Starch can be mixed either with resins as filler or it can form blends because it breaks the linkage and disintegration of granules happens at the temperature of 150 – 250˚C (Vroman & Tighzert, 2009).
Amylose (Fig. 4) molecules are made up of 200–20,000 glucose units connected by α-1,4 -glycoside linkages to form unbranched coiled helix or chains (Tester & Qi, 2011). As the amylose content rises, correspondingly increases the elongation and strength (Altayan et al., 2021).

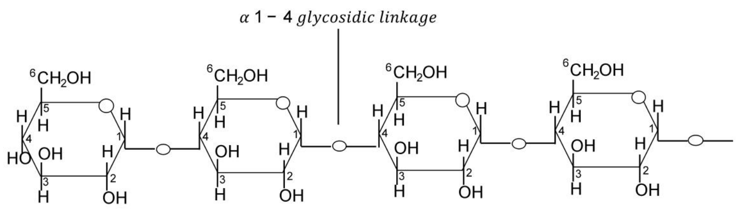


Fig. 4 Amylose

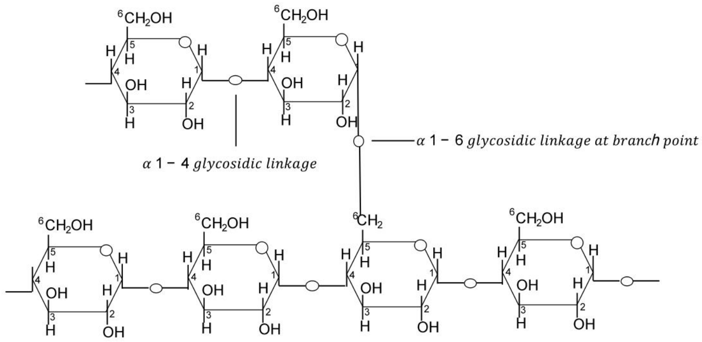


Fig. 5 Amylopectin

As seen in Figure 5, amylopectin molecules possess -1,4 and -1,6 -glycosidic linkages, which distinguishes their structure from that of amylose. The primary amylopectin chain is joined by glycosidic connections between the glucose molecules. Due to the -1,6 -glycosidic linkages with other glucose molecules, the main chain frequently forms branches (Pfister & Zeeman, 2016).

Table 1. Characteristics of starch

Sl No.	Source of starch	Amylose (%)	Amylopectin (%)	Gelatinization temperature (˚C)
1	Potato (*Solanum tuberosum*)	11.9 -20.1	75-80	58-60
2	Corn (*Zea mays*)	25	75	62-72
3	Wheat (*Triticum spp.)*	25	75	51-60
4	Triticale (*Triticum spp. X Secale cereale L.*)	13.7-167	75	55-62
5	Rice (*Oryza sativa*)	Milled rice (24)	71.7- 79.6	68-78
		Intermediate (20-24)		
		Low amylose (10-19)		
		Waxy rice (5)		
6	Tapioca (*Manihot esculenta*)	20.7	82	67- 70
7	Rye (*Secale cereale*)	20-28	72-78	51-60
8	Barley (*Hordeum vulgare*)	Wild barley (14.1-35.8) Barley	33.7 – 81.7	51-60
		landraces (5.7-26.8) Variety (13.9-		
		36.2)		
9	Sorghum (*Sorhum bicolor*)	18.57	34.13	68-78

4.2. CELLULOSE

Cellobiose repeating units are used to create the linear polymer known as cellulose (Fig. 6). The molecule can form long, straight chains because it is a polymer consisting of unbranched glucose residues connected by beta-1,4 linkages (Bajpai, 2019). This substance is a dietary fibre that is insoluble and is composed of glucose polymers, which are present in all plant cell walls, table 3 depicts the various sources of cellulose. Foods high in cellulose include leafy greens like kale, Brussels sprouts, and green peas (Khalid et al., 2022). By exposing concentrated mineral acids to high temperatures, cellulose can be broken down into glucose. It is harder and more crystalline than starch (Ilyas et al., 2018). However, starch transitions from crystalline to amorphous at a temperature of 60–70 degrees, whereas cellulose does so at a temperature of 320 degrees and a pressure of 25 megapascals (Nagarajan et al., 2017).

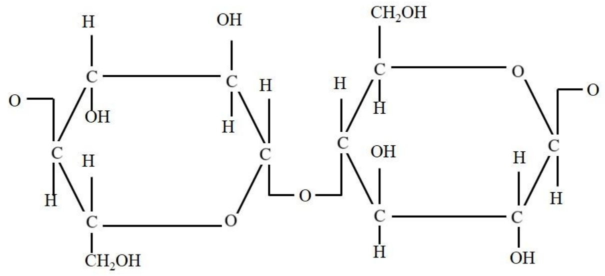


Fig. 6 Cellulose

Application of cellulose especially in the packaging industries can be organised and categorized into three topics. The first and foremost application being – to extract the cellulose plant material and to utilise it for preparation of various composite material (Mokhena & John, 2020). The second application is to produce plastics like material from cellulose. And the third one is that it can be used to prepare coating material, edible and inedible films out of cellulose (Francisco et al., 2020; Campos et al., 2011; Cazón et al., 2018).

Table 2. Various sources of cellulose

Sources of cellulose	
1. Agricultural waste	**2. Plant source**
➢ Sugarcane bagasse ➢ Rice husk	➢ Wood ➢ Bamboo

4.3. HEMICELLULOSE

Plant cell walls contain polysaccharides called hemicelluloses that have equatorial beta-(1-->4)-linked (Fig. 7) backbones (Gigli-Bisceglia et al., 2020). Xyloglucans, xylans, mannans, Hemicelluloses are soluble in alkaline solutions but insoluble in water. They reduce intestinal transit time together with other dietary insoluble fibres; hemicelluloses also increase faecal oweight and slow down starch breakdown (Maphosa & Jideani, 2016). Hemicelluloses with acids can bind to cations. Xylans, xyloglucans, mannans, glucomannans, and beta-(1-->3,1-->4)-glucans are all examples of hemicelluloses. Packaging, significant chemicals like xylan, and other saccharides are among the uses of hemicellulose-derived products (Qaseem et al., 2021). It is challenging to separate hemicelluloses from cellulose and lignin without changing the structure of the plant cell wall since these substances are naturally linked to one another (Sun et al., 2022).

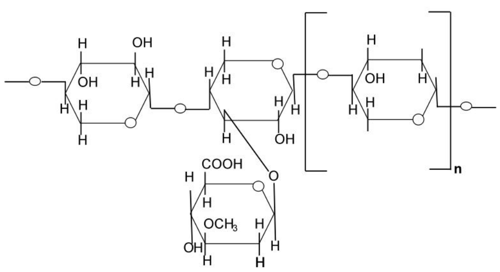


Fig. 7 Hemicellulose

4.4. CHITIN

It is commonly known that chitin, an abundant mucopolysaccharide found naturally in crustaceans, insects, and other organisms, is made up of 2-acetamido-2-deoxy-β-d-glucose via a β (1→4) linkage (Fig. 8) (Celikci et al., 2020). Chitin is most abundantly found in the nature after cellulose. It is a very insoluble substance with limited chemical reactivity and a solubility similar to cellulose (Khattak et al., 2019). Chitin is the main cause of surface pollution in coastal areas. It is a white, rigid, inelastic, nitrogenous polysaccharide (Zargar et al., 2015). The polymer contributes reinforcement and strength to the film, this can be extracted from exoskeletons of the arthropods that is in the shells of crabs and shrimps and even it is also found in insect cuticle, cell wall of yeas and fungi (Elieh-Ali-Komi & Hamblin, 2016). The first interpretation about chitin was made in the year 1811, as it was found to be the primary constituent mushroom cell wall (Rinaudo, 2006).

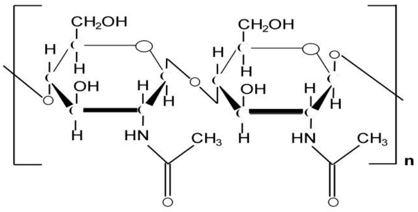
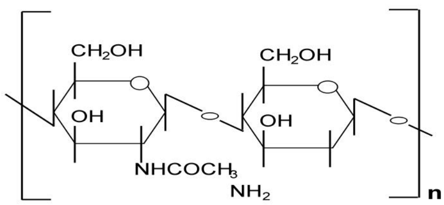


Fig. 8 Chitin

4.5. CHITOSAN

Chitosan (β- 1,4- poly-D-gucosamine) is derived from chiton by N- deacetylated method. For the production of chitosan from chitin crustacean cells are primarily and widely used. The chitosan is soluble in water and is more convenient biopolymer to handle. Chitosan has been used in various fields such as agriculture, food industry and pharmaceutical industry (Wang et al., 2018; Campos et al., 2011). Chitosan can easily be dissolved in aqueous weak acid solution such as hydrochloric acid, lactic acid, oxalic acid and acetic acid. Chitosan possesses anti-microbial property, enzymatic biodegradation, bioactivity etc. (Priyadarshi & Rhim, 2020).



Chitosan (β- 1,4- poly-D-gucosamine)

4.6PLASTICIZERS

Plasticizers are mostly used in polymer industries on a large-scale basis and they are important class of low molecular weight, non-volatile compounds which are used as additives. Such compounds are added to the film material to enhance the processibility and flexibility of the polymers (Borges et al., 2015). In the last decade, it was found that on an average over 5 million tons of plasticizers were produced worldwide per year. These plasticizers were used to apply on 60 various polymers and more than 30 groups of the products. Plasticizers can be used and manufactured for various purpose and is in not a new practice, its application and characterisation started in 1800's (Ibrahim et al., 2019).

Plasticizers are mainly liquid materials and are non-volatile natural compounds, when these plasticizers are incorporated into any elastomers or plastic material, they enhance the properties such as extensibility, processability and flexibility (Campos et al., 2011). Plasticizers improves the thermo-plasticity and flow of the polymer by reducing the viscosity of polymer, melting temperature, glass transition temperature and also elastic modulus of end product without any alteration in the basic chemical character of the plasticised material (Bergo & Sobral, 2007).

In the world of plastic industry, plasticizers are widely utilised additives. And it was found that they are the cheaper available additives as compared to other additives in polymer processing. After PE and PP, PVC is third most polymer wherein the plasticisers are being used and also used in producing various products. For example, Unplasticized PVC or it is also called as rigid PVC are used as application in sidings, pipes and window profiles. And plasticized PVC which is also called as flexible PVC has its application in cables, automotive interior trim, flooring, PVC film, wall coverings and roofing etc., while we choose any plasticizer, it is very importance should be given to the low toxicity and low migration rate (Ibrahim et al., 2019; Solano & de Gante, 2014; Vieira et al., 2011; Karmaker et al., 2021). Innovative things regarding plasticizers can be explored as an alternative for conventional plasticizers keeping in mind that the safety and biodegradability are choice of concern (Campos et al., 2011; Żołek-Tryznowska & Cichy, 2018).

Widely known bioplastic materials are extracted and developed from starch-based biopolymers from legumes, cereals and tubers (Vieira et al., 2011). While developing a bioplastic out of starch additives such as plasticizers, flexibilizrers, stabilizers and glycerol are added. Once after the addition of plasticizers and its application on mechanical and thermal energy, the constitute thermoplastic starch can be used as a substitute for polystyrene (Campos et al., 2011; Reshmy et al., 2021).

4.7. ANTI-MICROBIAL AGENT

The pathogens or microorganisms which emerges from food will affect the quality of food and the person who consumes the infected food (Fang et al., 2017). To prevent the infest station of microorganisms or food borne pathogens packaging or coating of food product with anti-microbial packaging is major concern. Active packaging is such a packaging technique wherein it will check the entry of microorganisms, blocks the functioning of microorganism (Camo et al., 2008). Incorporation of antimicrobial property in the packaging material reduces the attack of microorganisms and ultimately increases the shelf life of the food (Kuorwel et al., 2011). Incorporation of anthocyanin phenolic components will possess an antimicrobial property (Wang et al., 2019). This anthocyanin will damage the membrane of the bacterial cells and affect the biosynthesis of pathogens and leads to decomposition of the bacteria resulting to death of the organism. Sun et al., (2018), observed that anthocyanins could damage the bacterial cell membrane, affecting the pathogenic biosynthesis, which leads to bacterial decomposition and,finally, death. Wu et al., (2020) examined the antibacterial activity of glucomannan films containing red cabbage anthocyanin's against *Escherichia coli (E. coli)* and *Staphylococcus aureus (S.aureus),* and the film showed hindrance to pathogenic growth. Anthocyanin rich purple corn exhibits great antimicrobial activity (Bhargava et al., 2020). Chitosan and k-carrageenan based films containing purple corn and pomegranate flesh and peel anthocyanin's respectively were analysed for antimicrobial effect against *S.aureus, E. Coli, and, Salmonella* (Campos et al., 2011).

4.8. ANTI OXIDANTS

The freshly packaged food products may undergo oxidation reaction which results in development of off flavour and discolouration of the food product which ultimately affects the quality, appearance and nutritional content of the food (Liu et al., 2017). To prevent oxidative reactions and rancidity active antioxidant packaging materials are in use now. There are some of the synthetic oxidants to combat development of rancidity such as Butylated hydroxyanisole and hydroxytoluene which are a better substitute for natural components and are effective in reducing oxidative reaction ultimately reduces health risk (Shahid & Mohammad, 2013). Phenolic compounds extracted from the plants posess antioxidant property (Shahidi & Ambigaipalan, 2015). Hence, polyphenols like flavonoids and phenolic acids are added to biopolymer films to develop active packaging (Bai et al., 2019).

5. FUNCTIONAL PROPERTIES OF BIOPOLYMER

5.1. PHYSICAL PROPERTIES

The physical properties of a packaging material mainly depend on molecular weight, density, and molar volume of the packaging material (Hanumantharaju et al., 2019). Higher the density of the packaging material, higher the transportation cost and this in turn affects the mechanical properties of the packaging material too (Souza et al., 2017; Ilyas et al., 2019).

Melting, boiling points with form, density, and viscosity are the primary physical parameters related to biopolymers and biopolymer composites. It has been discovered that the internal structure of biopolymers is altered by the interaction of water molecules, making them more susceptible to moisture (Udayakumar et al., 2021). It was discovered that the biopolymers' internal structures and other characteristics change when they come into touch with water molecules, making them more susceptible to absorbing moisture. Another study reveals that biopolymer swelling is directly proportional to the area that is generated by adsorbed molecules. As a result, the number of hydrogen bonds in the biopolymer decreases, weakening its mechanical and physical properties (Azwa et al., 2013; Udayakumar et al., 2021).

5.2. TRANSMISSION PROPERTIES

The transmission properties of the materials include: oxygen transmission rate, carbon dioxide transmission rate, water vapour transmission rate. To extend the shelf life of the food, hygienic practices and required atmospheric conditions to be maintained during storage, transportation (Hanumantharaju et al., 2020). As most of the food material respire in the presence of oxygen which leads to quick deterioration in the quality of the food product. So, the packaging material should possess and acts as a barrier for gases and these gases depends upon the presence of humidity in the atmosphere (Dyshlyuk et al., 2017; Khalil et al., 2018).

Carbon dioxide permeation coefficient and oxygen permeation coefficient are used for quantifying the carbon dioxide and oxygen barrier capabilities respectively. This indicates that the oxygen and carbon dioxide permeation per unit are and time required in a packaging material. And this is expressed as $kgmm^{-2}s^{-1}Pa^{-1}$ (Weizman et al., 2017; Campos et al., 2011).

When biopolymers are exposed or come in contact with the atmospheric or any water molecules, it uptakes the water into the packaging material due to its nature of hydrophilicity (Li et al., 2018). And this is quantified by water vapour permeability coefficient, this rate indicates that the actual amount of water vapour that has permeated through per unit area and time required in to the material and is expressed as $kgmm^{-2}s^{-1}Pa^{-1}$. The disturbance in the fibre or polymer is due to migration of water which in turn reduces the strength of the composite (Ilyas et al., 2018; Ivonkovic et al., 2017).

5.3. THERMAL PROPERTIES

Thermal properties include melting temperature and glass transition temperature. The amorphous region or part of the polymer determines the property of glass transition temperature whereas the melting point property is determined by crystalline region of the polymer. The intermolecular forces, molecular weight and plasticizer depicts the glass transition temperature of the biopolymer. If the food is to be stored at lower temperature, the polymer used for packaging should possess higher transmission temperature and also it is applicable for those food to be stored at higher temperature should possess higher melting point (Malmir et al., 2017; Mangaraj et al., 2019).

The thermal characteristics of starch-based products must be understood for their production, application, and disposal (Wang et al., 2021). Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) are two of the most often used analytical methods for describing the thermal properties of starch-based materials (Nurazzi et al., 2022). Any component in a film that goes through a phase transition can have its glass transition temperature (Tg) and melting point (Tm) measured using DSC. The compatibility and miscibility of the constituents affect a film's glass transition temperature (Tg). If only one Tg is found in the sample film, the compounds are all evenly distributed and get along with one another (Wei et al., 2017).

5.4. MECHANICAL PROPERTY

The ability of packaging materials to resist deformation or breakage depends on their mechanical qualities. Strength, % elongation break, toughness, Young's modulus, and viscoelasticity are examples of mechanical parameters that are typically examined by a universal testing equipment. During transportation, storage and handling process, the food product might undergo several stresses. So, the packaging material should possess good mechanical properties like stiffness and modulus, and is having positive response as compared to other conventional polymers. And all these mechanical properties depend on molecular mass of the polymer (Almeida et al., 2018; Ivonkovic et al., 2017; Campos et al., 2011).

The most popular analytical methods used to describe fibre reinforced composites are tensile and impact strength (Saba & Jawaid, 2018). The orientation, off-axis angle, and alkali treatment of the aligned hemp fibre composites made from hemp/PLA wrap spun yarns were all examined. All the hemp composites may have adhered, according to results from SEM and DMTA. These aligned alkali hemp/PLA yarn biocomposite materials showed strong impact and tensile mechanical characteristics. When compared to other produced composites, it also shown small porosity and water sorption at various temperatures with tensile strength of 77.1 MPa, impact strength of 18.8 kJ/m2, and flexural strength of 100.9 MPa that were induced by hemp (Udayakumar et al., 2021).

5.5. BIODEGRADABILITY / COMPOSTABILITY

For a sustainable environment the biodegradable property is most useful one which involves biological activity for complete degradation process. In the composting process, the organic matter is converted into soil like material i.e., humus and carbon dioxide upon activity of microorganisms (Ivonkovic et al., 2017). Here the degradation process has been carried out in three steps and they are biodeterioration, bio fermentation, and assimilation. The time taken for degradation is less as compared to conventional packaging materials. This process is affected by several factors such as chemical chain, chemical structure, crystallinity, pH, temperature, oxygen, and moisture content (Gutiérrez, 2018; Sintim et al., 2019).

Biodegradable materials typically break down into CO_2 and H_2O in aerobic environments and H_2 and CH_4 in anaerobic environments (Cho et al., 2011). The amount of CO_2 emitted by the soil microbial community and the final weight loss of the samples in the soil burial degradation test are typically used to measure the biodegradability of starch-based films. According to studies, acetylating starch to a greater extent can improve the biodegradability of starch-based films.

Table 3. Properties of biodegradable packaging materials

Properties	Cellulose	Starch	Gums	Chitosan	Blends (PLA/ PHA)	Protein (soy protein)
Physical properties						
Density (g / cm^3)	1.45 – 1.59 (Sun, 2005)	1.2-1.6	1.4- 1.6	1.4- 1.8	Varies based on the blend	1.2- 1.4

Moisture absorption (%)	Varies with the form	60 -120 (gelatinised)	Varies with form	40 -80	Varies with the form	Varies with the form
Mechanical properties						
Tensile strength (MPa)	70- 120	10-30	10-40	30-70	Varies based on blend	Varies based on protein type
Flexural strength (MPa)	100-300	10-40	10-50	40-90	Varies based on ratio and composition	Varies based on protein type
Elongation at break (%)	1-5	5-100	5-100	1-15	Varies based on the components	Varies based on the protein type
Transmission properties						
Water vapor transmission rate (WVTR, g/m^2/day)	Varies based on the composition/ blend/components/form					
Oxygen transmission rate (OTR, cc/m^2/day)	Varies based on the composition/ blend/components/form					
Thermal properties						
Melting point (˚C)	260-340	120-170	N/A	N/A	Varies based on the blend	N/A
Glass transition temperature (˚C)	Appr. 300	Appr. 150	N/A	Appr.100	Varies based on the blend	N/A

6. APPLICATIONS OF BIODEGRADABLE PACKAGING MATERIALS TO FOODS

In the food sector, biodegradable packaging materials are used in a variety of ways. They are perfect for packing perishable commodities like fresh fruits and vegetables, meat and seafood, and dairy products because they enable the produce to breathe, which helps to keep its freshness (Ghoshal, 2018). Additionally, biodegradable packaging can be used for single-use products like cutlery, plates, and takeout containers, minimizing the amount of plastic waste generated in the food service industry. These materials could also be used to package dry items like cereal and crackers (Fieschi & Pretato, 2018). Biodegradable packaging materials are environmentally beneficial, which is in line with rising consumer demand for environmentally friendly and sustainable food packaging solutions (Guillard et al., 2018). By doing this, they help the food business match customer expectations while lowering its environmental impact.

6.1. FRUITS AND VEGETABLES

Fruit and vegetable tissues may stay physiologically active after harvest, undergoing numerous physiological changes during storage, and until ingested or processed (Chavan et al., 2023). Fresh or minimally processed fruits and vegetables are particularly perishable due to their features, and require a combination of approaches to extend their shelf life correctly. (Ponce et al., 2008; Geraldine et al., 2008). Edible films and coatings have long been known to protect perishable fruits and vegetables from deterioration by preventing dehydration, regulating respiration, increasing textural quality, retaining volatile taste components, and inhibiting microbiological development. (Han et al., 2004; Lin and Zhao 2007; Maftoonazad et al., 2007). Furthermore, they can be utilized to incorporate functional components including antioxidants, taste, pigments, antibacterial agents, and nutraceuticals. (Bifani et al., 2007; Garcia et al. 2008). Some of the previously mentioned capabilities are related to their capacity to prevent moisture loss and have selective gas permeability. (Vargas et al., 2008; Campos et al., 2011). Table 4 summarizes relevant applications of an edible films or coatings to prevent microbial spoilage.

Table 4. Application of edible films and coatings to improve the quality of fruits and vegetables

Fruit/ vegetable	Hydrocolloid	Effect	Reference
Carrot slices	Starch/chitosan	During storage at 10 °C, yeast, mould, lactic acid bacteria, and total coliforms that are psicrotrophic are all inhibited.	Durango et al.,2006
Pumpkin cylinders	Cassava starch	The growth of lactic acid bacteria, yeasts, and moulds was inhibited.	Garcia et al., 2008
Potato cylinders	Alginate	The initial microbial load decreased while being stored in a refrigerator at 5 °C.	Younas et al., 2014
Butternutsquash	Chitosan,Casein, CMC	The number of mesophilic aerobic	Moreira et al.,2009

		bacteria was decreased by coating.	
Butternut	Chitosan, carboxymethyl cellulose, and casein	Listeria monocytogenes and native microflora were both slightly inhibited by coatings enhanced with rosemary and olive oleoresins.	Ponce et al., 2008
Fresh-cut melon	Alginate	The population of S. enteritidis and the growth of local flora were both reduced, which increased shelf life by more than 21 days.	Raybaudi-Massilia et al.,2008
Garlic	Agar-agar	During 6 days of storage at 25 °C, filamentous fungus and aerobic mesophilic were suppressed.	Geraldine et al.,2008
Carrotsslices	Chitosan	Low levels of the native microbial community were maintained.	Simoes et al.,2009
Mandarins	Hydroxypropyl methylcellulose-lipid	The coatings' antifungal activity was fungistatic as opposed to fungicidal.	Valencia- Chamorro et al.,2009
Mangoslices	Chitosan/cassava starch/gelatin	On the fruit surface, it was seen that Botryodiplodia theobromae inhibition had decreased.	Zhong and Xia2008

6.2. MEAT AND SEAFOOD PRODUCTS

Food-borne diseases such as *Salmonella typhimurium, Listeria monocytogenes, and E. coli* O157:H7 can be found in minimally processed ready-to-eat meats. Pathogen contamination could arise during subsequent processing or packaging. (Campos et al., 2011). Antimicrobial-infused edible films and coatings are a promising method for reducing the risk of pathogenic germs while simultaneously prolonging product shelf life. Application of a coating or film to meat products can minimise moisture loss during storage of fresh or frozen meats, hold juices of fresh meat pieces when packaged in plastic trays, reduce the rate of rancidity, and restrict volatile flavour loss and the uptake of foreign aromas, among other things (Quintavalla & Vicini 2002; Campos et al., 2011). During storage, the quality of seafood rapidly degrades, with chemical and enzymatic reactions causing the early loss of freshness and microbiological deterioration causing the end of the shelf life. The growth of L. monocytogenes, which is the greatest concern in freshly processed cold smoked salmon, is often the target of inhibition. (Datta et al., 2008; Ye et al., 2008). On the other hand, another important objective is to avoid oxidative spoilage, in the case of fat specimens, by the use of antioxidant agents, and also to prevent moisture loss (Gomez-Estaca et al., 2007; Campos et al., 2011). The most relevant edible films and coating systems developed for preserving meat and seafood products are presented in Table 5.

Table 5. Application of edible films and coatings to improve the quality of meat and seafood products

Meat and seafood product	Hydrocolloid	Effect	Reference
Ready to eat roast beef	Chitosan	*A chitosan covering was used to limit Listeria monocytogenes growth.*	Foster & Butt, 2011
Pork slices	Hsian-tsao leaf gum	*Growth of Staphylococcus aureus and Listeria monocytogenes was stopped*	Chiu et al., 2010
Chicken breast	κ-Carragenann	The application of a coating comprising ovotransferrin and EDTA reduced the overall aerobic count.	Mona & Waleed, 2017
Turkey frankfurter	Soy protein	*Growth of Listeria monocytogenes was stopped*	Theivendran et al., 2006
Fresh beef	Whey protein	The development of lactic acid bacteria, pseudomonas, and all aerobic bacteria was stopped	Zinoviadou et al., 2010
Smoked salmon	Calcium alginate	Delay in microbial growth	Neetoo & Chen, 2010
Sliver carp	Chitosan	During frozen storage, the total number of aerobic mesophiles dropped, and the shelf life was increased to 30 days.	Fan et al. 2009
Cold-smoked sardineprocess by high pressure	Gelatine, gelatin–chitosan	Reduced lipid oxidation and microbial growth	Gómez-Estaca et al., 2009
Herring cod	Chitosan	Microbial growth and reduced lipid oxidation were noted. There was no moisture loss.	Jeon et al., 2002
Cold-smoked salmon	Whey protein	*Growth of Listeria monocytogenes was stopped*	Min & Krochta, 2005
Salmon	Chitosan, chitosan–starch	Aerobic mesophile and pscrophile microbial growth were inhibited, and the duration of the quality was increased to 6 days at 2 °C.	Vásconez et al. 2009

6.3. DAIRY PRODUCTS

Dairy products are made up of a variety of dietary groups, the most common of which are casein, fat, and water. Microbial stability must be regulated in the case of fresh and semi-hard cheese. Edible films and coatings are primarily used to prevent microbial growth on surfaces and to reduce the danger of *L. monocytogenes* contamination during processing. In order to retain cheese quality, the coating or film applied must be able to allow gas exchange with the environment. (Campos et al., 2011). Applications of edible films and coatings to dairy products are shown in Table 6.

Table 6. Application of edible films and coatings to improve the quality of dairy products

Dairy product	Hydrocolloid	Effect	Reference
Semi-hard cheese	Chitosan Galactomannan	Water evaporation was reduced and mouldgrowth was stopped.	Cerqueira et al., 2009
Semi-hardregional cheese	Chitosan Galactomannan	Microbial populations and water loss wereboth reduced.	Fajardo et al., 2010
Emmenthal cheese	Chitosan	*The maximum population of Pseudomonas aeruginosa at the stationary phase droppedwhile the lag phase increased.*	Pranoto & Rakshit, 2008
Ricotta cheese	Galactomannan	Listeria monocytogenes' growth wasstopped for 7 days at 4 °C.	Martins et al., 2010
Kashar cheese	Casein	For one month, mould growth was stopped.	Yildirim et al. 2006

7. NEED FOR BIODEGRADABLE PACKAGING MATERIALS

Need for packaging material for preserving food has increased tremendously and dependency on synthetic polymers for the same is a matter of environmental and health concern. Most of the plastic packaging materials that we use are not environmentally friendly and also on the other hand these have higher strength and durability. The disposal causes many hazards as these take years for degradation. During the synthesis of these polymeric substances, the use of many toxic substances and formation of toxic substances as a by-product might harm the food as well as person along with nature (Ramesh et al., 2020; Stevens, 2021). The increase in problems due to the use of synthetic polymers has increased the attention on novel technologies to replace the current use of plastic materials. The truly biodegradable packaging materials are in existence and they are applicable to all the products, and it ranges from packaging of raw produce from the field, processed produce of all kind irrespective of shape, size and state. Such an eco-friendly material is also having water holding capacity, biocompatibility, less interaction with the packed food materials (Campos et al., 2011). The use of plastic material is not only harmful for human and animal life but also sea life affected badly. The plastic debris enters the ocean through leaching, the fishes and sea habitat consume it unknowingly and dies of toxicity and it is indigestible by them. This plastic contributes a large amount to the waste management, the awareness on use and disposal has gained importance from left over and throne waste from gatherings, functions and other organisations (Sadeghizadeh-Yazdi et al., 2019; Stevens, 2021).

7.1. ENVIRONMENTAL ASPECTS

The rise in the negative impact on environment and public awareness has created a way to develop novel technologies in the field of packaging. Packing of food material with plastic goes as a waste and burden to the environment. So, the manufacturing companies are looking forward for an alternative packaging material for conventional plastic materials. Fresh food commodities are found to be the most wasted one, due to the fact that, they respire and deteriorate quickly and it is wasted too along with the packaging material (Regubalan et al., 2018; Stevens, 2021; Dilkes- Hoffman et al., 2018). The effect of edible films, biopolymers on the environment as compared to plastic is not yet clearly mentioned. But the use of plastic on environment is worse and dire need to replace is a matter of concern. To resolve this issuelot more research, need to be carried out. Dissemination of information to the public so that one can minimise the wastage generated from household will leads to sustainable growth of the environment (Campos et al., 2011; Sadeghizadeh- Yazdi et al., 2019; Stevens, 2021). The disposal of fresh produce such as fruits and vegetables, food packed in plastic package can be minimised, the initiation might benefit the environmental pollution caused due to package disposal (Dilkes-Hoffman et al., 2018). Table 1, 2, 3, and 4 highlights the efforts made towards replacement of plastic polymers.

7.2. ECONOMICAL ASPECTS

The development of high performance and high-quality packaging material to make things consumer friendly, helps in research activities and also to the local authorities. The main target is on environmental sustainability irrespective of the source of origin, whether the product is manufacture from renewable resource or from the fossil source. From consumer point of view, environmental point of view the packaging material should be safer to environment, cost efficient, beneficiary to the society. It should also be checked that up to what extent the biodegradability offers an added value (Stevens, 2021; Dilkes-Hoffman et al., 2018; Sapuan et al., 2021).

Residues and by-products generated in larger quantities include fruit and vegetable residues (husks, seeds and stems), grain residues (rice, wheat, soy) and protein products (chitosan, gelatin, whey protein). Approximately 26% of food waste is generated from the beverage industry, followed by the dairy industry (21%), fruit and vegetables (14.8%), cereals processing (12.9%), preservation of meat products (8%), processing of oils of vegetable and animal origin (3.9%), among others (12.7%) (Rosseto et al. 2019). The use of residues is seen as an opportunity for sustainability due to its ease of production and low cost, non-toxicity, biocompatibility, biodegradability, chemical and thermal stabilities (Habibi et al., 2010; Rosseto et al., 2019).

It is very difficult to replace a conventional packaging material with that of bioplastics, but it can be considered and applied as a novel material for our food products with its novel properties. The biopolymers will not only contribute to the food waste minimisation but also give back the nutrients to the soil for increasing its fertility and even avoids the plastic accumulation in the soil. These biopolymers will be a great contribution to the environment as well as to our economy as it uses the nature product in a best possible way and give it back to nature in as a good return. This circular economy, will helps to use the resources in longer way (Chandrasekar et al., 2021, Cheng et al., 2021; Dilkes-Hoffman et al., 2018; Sapuan et al., 2021).

8. LIMITATIONS AND CHALLENGES IN BIODEGRADABLE POLYMER RESEARCH AND APPLICATION

A challenge for the use of edible films and coatings is their compatibility with other emergent stress factors like high pressures, electric fields, ultrasound, microwave radiation, and gamma radiation. Modifications that can be produced in edible film structure without endangering the safety of the food product might help to achieve target purposes. Information nowadays about all these topics is abundant but not systematic because researchers have a great variety of objectives when designing their experiments and not all of them areworking for the production of edible films and coatings as supporters of antimicrobials (Campos et al., 2011). A deeper insight concerning thissubject is needed to elucidate the magnitude of the ratio benefit/cost and not only from a financial point of view.

Even with promising trends for applicability, biodegradable polymers obtained from renewable sources present some disadvantages, such as low mechanical properties, rapid degradation rate, high hydrophilic capacity, and in some cases, poor mechanical properties, especially in humidenvironments, rendering their application unviable (Demirgöz et al., 2000; Shankar & Rhim 2019; Rosseto et al., 2019). In this context divergent opinions arise about the acceptability of biodegradable polymers in industry. While some believe in their potential to replace petroleum polymers, others presume that their shortcomings, both in technical and economic aspects, hindertheir rapid adoption, at least in the near future (Meraldo, 2016; Rosseto et al., 2019).

9. LEGISLATION RELATED TO APPLICATION OF BIOPOLYMER FOR FOOD PACKING

Biopolymers supporting antimicrobials can be considered as an active film. Definitions stated in Regulation 1935/2004/EC and in Regulation 450/2009/EC consider that "active materials and articles are intended to extend the shelf life or to maintain or improve the condition of packaged food". They are designed to deliberately incorporate components that would release or absorb substances into or from the packaged food or the environment surrounding the food (Restuccia et al., 2010; Campos et al., 2011). Each country has clear regulations regarding the addition of preservatives to food, which often include purity requirements, analytical methodology, labeling, and maximum allowed levels. According to legislation and labeling in the USA, biopolymers and edible coatings films are considered part of the food; as a consequence, their ingredients must comply with the Code of Federal Regulations and be declared on the label under the Federal Food, Drug, and Cosmetic Act (Franssen and Krochta, 2003). The EU considers that an edible film is a special active part of the food and, seen from a legal point of view, it is to be regarded as a foodstuff, along with the food packed in the film, having to fulfill the general requirements for food (Campos et al., 2011). According to Rojas-Graü et al., (2009), another important topic within regulatory status is the presence of allergens because many edible films and coatings are made with or can contain ingredients that could cause allergic reactions such as wheat protein (gluten) or peanut protein. Therefore, the presence of a known allergen on a film or coating on a food must be also clearly stated in the label.

At the start of 2020, the Food Safety and Standards Authority of India (FSSAI) declared newpackaging norms and regulations. Some measures under the new protocol include, among other things, banning of recycled plastics and newspaper used. Post COVID19 lockdown, the industry is expecting new, more stringent regulations on practical packaging options to promote aggressiveuse of environment-friendly packaging materials.

10.FUTURE TRENDS

There have been various research activities conducted and effectively implemented in employing and developing intelligent and active packaging material which contains plant extracts to enhance the quality and monitor the freshness of the food product especially the product which are perishable (Mor et al., 2021). Further research can be carried out and can be focused on the safety aspects of food inside packaging material and preventing the spoilage or toxicity of the food, which might be due to the reason degrading food product when exposed or when it comes in contact with the external environment (Dilkes-Hoffman et al., 2018). So, there is a scope for developing a stable packaging material. Most of the dumped, discarded natural products consist of bioactive components, it can be an additional income generation to the industries. Food waste from various processing industries can be utilised for its bioactive components to be incorporated as an indicator for microorganisms (Stevens, 2021; Chandrasekar et al., 2021). Different combinations could be assessed by employing various biodegradable polymers with varying pigments. Since most of the studies are focused on high protein foods and milk, there is a scope of research towards fruits and vegetables that are highly perishable and require nontoxic intelligent indicators for visual spoilage monitoring (Sapuan et al. 2021). These packaging films can be optimized further and commercialized to be employed as active and intelligent packaging for visual quality evaluation of fresh food products.

11.CONCLUSION

This review article has addressed the theoretical information of the various sources of availability of raw material, opportunity, properties, and application of the biodegradable packaging material. The scope for developing biodegradable packaging material and its innovations are tremendously increasing, which is greatly influenced by legislative changes, world demand and policy by the constitution. The main drawback for biodegradable packaging materials are its low transparency and higher brittleness, but it can be combated with addition of some of the nanocomposites so as enhance its properties. Studies could be carried out to experiment on interactions between food and packaging material and also the migration, absorption rate are also being matter of interest. It is very important to improve and enhance the poor properties of the biodegradable packaging material so that, it will be a contribution to the environment, research field and to the future generation.

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