

Review

Review of Smart Edible Films and Coatings for Perishable Foods and Future of Smart Packaging

Almas Bibi¹ and Jamil Afzal^{2*} 

¹Department of Applied Chemistry, Government College University Faisalabad, Pakistan;

²International Islamic University, Malaysia

* Corresponding Email: sirjamilafzal@gmail.com (J. Afzal)

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ABSTRACT

The focus of this review article is smart edible films and coatings and also to elaborate the future of smart packaging for perishable foods. The galaxy of smart packaging is expanding in research and concepts at a quick pace. A number of proposals and preliminary solutions to food preservative issues were produced using recently developed technologies and advanced methods, such as molecular biology and nanotechnology. The study highlights several novel sustainable packaging solutions that must take into account the need to minimize environmental effects, reduce losses, and ensure food safety and quality. Food packaging contributes to waste production in addition to being essential for maintaining food during transportation and storage from farm to table. By lowering the need for chemicals and preservatives, current food packaging systems strive to prolong the shelf life of perishable foods while simultaneously preventing quality deterioration. A number of techniques and strategies, such as oxygen scavenging and antimicrobial technologies, are linked to the creation of modified films.

Keywords: Active and Intelligent Packaging; Edible Films; Edible Coatings; Perishable Foods

1. Introduction

By 2050, there will likely be 9.7 billion people on the planet, leading to rapid urbanization and a rise in the need for fresh foods worldwide [1]. A third of all food produced for human consumption, or 1.3 billion tones, is wasted worldwide each year, despite the agro-industry's struggles to meet this rising demand. The majority of losses occur during storage and transportation in the food supply chain (FSC) system, particularly with regard to perishable food items between production and consumption [2]. For example, inadequate storage and transportation circumstances result in damage or uncontrolled natural processes, such as overriding and decreasing shelf-life, wasting 47% of all fruits and vegetables and 12% of meat goods [3]. In addition to these losses, chemical and biological contaminations play a major role. Food preservation is greatly impacted by food packaging, a crucial step in the food manufacturing process [4]. Food packaging serves to keep food isolated from the outside world, preventing microbial contamination and nutrient oxidation brought on by outside influ-

ences [5]. Traditional packaging materials' effects on the environment, especially those of single-use plastics, have sparked worries about pollution, resource depletion, and ecosystem damage [6]. Researchers and industry participants have been looking at substitute materials and technologies that provide more environmentally friendly answers to these problems. Making packaging materials out of biopolymers made from renewable resources is one possible approach [7]. A popular carbohydrate polymer derived from crops like corn, wheat, and potatoes, starch has become a viable option because of its renewable nature, biodegradability, and abundance [8].

The primary functions of films and coatings are essential for extending the shelf life of food items [9]. They must prevent UV rays and the movement of substances between the food and the ambient air; they must also serve as a defense against mechanical harm [10]. Antimicrobials, antioxidants, and nutrients are examples of functional/bioactive substances that can be added to stop the growth of bacteria and fungi; Probiotics and other health-promoting microorganisms can improve their nutritional value. It is also pos-

sible to add tastes and aromatic substances as enhancing agents; the finished product should also use biological ingredients and be biodegradable [11]. In the future, more sophisticated uses of smart edible films and coatings are probably going to be produced by continued research and development in this area. Researchers are investigating the use of increasingly complex sensors, like those that can identify certain spoiling components or track foodborne infections. Moreover, these films are performing better thanks to developments in nanotechnology, which are making them thinner, more effective, and able to transport a wider variety of bioactive compounds [12]. In the future of food packaging, smart edible films and coatings will surely be essential as these technologies develop further, tackling issues of environmental sustainability and food security [13].

The aim of this review article is to highlight the use of smart edible films and coatings and provide creative solutions that meet the needs of both the environment and modern consumers. This study will cover;

- The difficulties of the food supply chain in the twenty-first century, these technologies are opening the door for safer, more durable, and environmentally friendly packaging choices by fusing sustainability with active and intelligent features.
- To highlight the advances in nanotechnology, and food safety concerns that are driving the rapid development of smart edible films and coatings in active and intelligent packaging.
- To point out the hindrances related to the creation and application of smart edible films and coatings with consumer acceptance, safety, and regulatory compliance.

2. Edible Films and Coatings

Biopolymers, including proteins, polysaccharides, lipids, and resins, are the primary substances that make films; the qualities of the final films and coatings are significantly influenced by the physical and chemical properties of the biopolymers [14]. Although hydrophilic, hydrophobic, or both can be present in film-forming materials, only water or ethanol can be utilized as solvents to preserve edibility [15]. Proteins are frequently utilized as materials to make films; they are macromolecules with particular molecular structures and amino acid sequences [16]. The amphiphilic nature, electrostatic charges, and conformational denaturation of proteins are what set them apart from other film-forming materials [17]. Heat denaturation, pressure, irradiation, mechanical treatment, acids, alkalis, metal ions, salts, chemical hydrolysis, enzymatic treatment, and chemical crosslinking are all simple ways to alter the secondary, tertiary, and quaternary structures of proteins to produce desired film properties. These processes can regulate the mechanical and physical characteristics of produced coatings and films; animal tissues, milk, eggs, grains, and oilseeds are only a few of the various plant and animal sources from which protein film-forming components can be made [18]. The following Figure 1 is the graphical representation of edible films and coating;



Figure 1: Edible Films and Coating adopted from [19]

Fibers, non-starch carbohydrates, and starch are examples of materials that create polysaccharide films; unlike proteins, which have 20 common amino acids, polysaccharides have simple monomers [20]. However, compared to proteins, polysaccharide structures have far greater molecular weights due to their more complex and unpredictable shape. The majority of carbohydrates have a neutral charge, however, in rare instances; certain gums have a negative charge. Since the neutral carbohydrate structure contains a lot of hydroxyl groups or other hydrophilic moieties, hydrogen bonding is the most important factor in the development and properties of films[21].

2.1. Smart Food Packaging

Four broad categories of food packaging can be distinguished: intelligent, smart, passive, and active packaging [22]. The package's basic and fundamental properties are protected, preserve, and present which are served by a variety of methods. The most common type of packaging to date is the most basic one, which is made of inexpensive materials and doesn't come into contact with the food within. Traditional packaging methods for passive packing include the use of covering materials that have built-in insulating, protecting, or handling properties. For sustainability and food safety, the importance of smart edible films and coatings in food preservation is becoming more widely acknowledged. These cutting-edge materials solve environmental issues related to conventional packing techniques while also extending the shelf life of perishable items [23]. Smart edible films offer a biodegradable substitute that helps to cut down on food waste and packaging pollution by using biopolymers and natural ingredients. In a time when customers are demanding safer, healthier products and sustainability advocates are putting increasing pressure on the global food sector, this move toward more environmentally friendly solutions is crucial. Following Figure 2 is the illustration of smart food packaging;

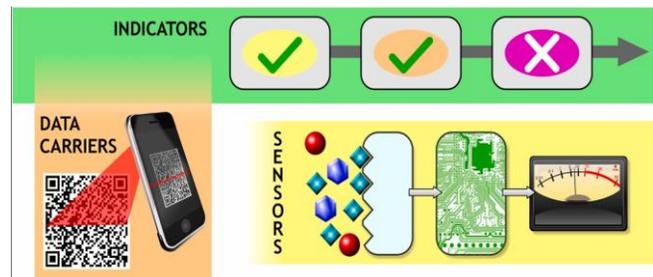


Figure 2: Smart Food Packaging adopted from[24]

The functional capacities of edible films may be improved by the addition of intelligent and active features; bioactive substances with antibacterial and antioxidant properties, such as probiotics or essential oils, can be included in these films [25]. This indicates that these coatings actively support preserving the food's safety and nutritional value in addition to preserving food quality by acting as a barrier against outside influences. Films enhanced with natural preservatives, for example, can stop germs from growing, greatly lowering the risk of foodborne diseases [26]. The function of smart edible films in the circular economy is another crucial element; researchers are looking into making these films out of food industry leftovers, which encourages waste reduction and resource efficiency [27]. For instance, materials made from whey protein or fruit peels not only efficiently use trash but also give the films functional and nutritional improvements. This approach

makes the entire food packaging process more ecologically friendly and aligns with sustainable food development goals.

2.2. Characteristics of Smart Packaging

From a literary perspective, packaging is frequently mentioned as a source of containment that keeps items together and encloses them [28]. However, according to the investigation, there is another possible use for packaging that involves the two-way contact between the consumer and the package that is made possible by enabling communication technology. According to the investigation, the experiences that the packaged product offers the customer have a significant impact on consumer–brand connections[29]. Packaging has the potential to improve these experiences and play a significant role in fostering relationships because it is an integral component of the product. Generally speaking, every package has linguistic, structural, and graphic components, including form, size, color, material, brand, and producer. Additional improved qualities of packaging are produced by applying various design and technology-based advancements to such components. Packaging features are the salient or unique attributes of packaging that allow it to perform its intended duties. Distinct packaging types have distinct features because features are heavily influenced by the kind of product the box holds. A feature of packaging functions is a component that enables the performance of a designated task, activity, or particular role, such as protection or communication.

The packaging industry has recently been forced to address environmental challenges and develop, modify, or design new or existing packaging elements due to mounting environmental pressure [30]. One of the key attributes that packaging needs to have is the ability to interact and communicate with consumers. Additionally, packaging interacts with consumers both inside and outside of the retail setting; that is, packaging communicates with consumers at the point of purchase and at the point of product utilization at home.

3. Types of Smart Edible Films

Food packaging was one of the first commercial applications of nanotechnology in the food industry. About 400–500 goods are already packed using nanoparticles, and almost all of them are employed on a commercial scale. It is anticipated that during the following ten years, nanotechnology would account for 25% of all food packaging. Enhancing the barrier function of food packaging materials is the main goal of nano-packaging, which will limit gas and moisture exchange and manage UV radiation exposure, hence extending product shelf life. For instance, the nanotitanium dioxide plastic addition "DuPont light stabilizer 210," which was introduced by Du Pont, helps to lessen UV damage to foods that are stored in clear containers. The purpose of nanopackaging is to prolong shelf life by facilitating the release of flavors, antioxidants, enzymes, antimicrobials, and nutraceuticals. They acknowledged that this discovery, which was based on research from a UK institute, would completely change the way food is packaged in the future. The microbe-resistant nanoparticles are widely acknowledged to be safe, non-toxic, and helpful for wrapping edible items. The researchers report that ZnO and MnO nanoparticles are essential for destroying microorganisms. Ding and Povey created innovative nanofusion, a novel nanocomposite made up of a variety of functionalized nanoparticles with a size of hundreds of micrometers. Additionally, the capacity to break down liquid components into nanoparticles efficiently targets microorganisms, whose bacteriostatic and antibacterial qualities aid in their death. Based on these results, it is simple to predict what packaging will look like in the near future.

3.1. Active Films and Coatings

The purpose of active films is to absorb or release chemicals that enhance food preservation; these coatings actively fight spoiling agents by containing bioactive substances like enzymes, antioxidants, and antimicrobials [31]. For instance, essential oils with antimicrobial qualities, like cinnamon or oregano, can be used in films to stop the growth of fungi or bacteria. Additionally, by preventing oxidation, these coatings help preserve the food's nutritional value and sensory appeal during long storage times.

3.2. Intelligent Films and Coatings

By including sensors or indicators that identify alterations in the food's surroundings, intelligent films provide real-time food quality monitoring [32]. These films can track variables like microbial activity, gas emissions, and pH levels; they frequently display color changes that signify spoiling; for example, the presence of volatile chemicals created during food spoiling may cause some films to change hue. This lowers waste and enhances food safety by enabling retailers and consumers to visually evaluate the freshness of food.

3.3. Bio-based Films

Polysaccharides, proteins, and lipids are examples of natural, renewable materials used to make bio-based smart edible films; because of these components, the films are biodegradable and provide a sustainable substitute for conventional plastics [33]. These films are frequently made from polysaccharides, such as cellulose and starch, because of their strong moisture and oxygen barriers. Because bio-based films preserve food quality while lowering their environmental impact, they frequently support sustainable packaging objectives.

3.4. Composite Films and Coatings

Composite films improve mechanical strength and barrier qualities by combining several natural or synthetic elements; these films provide better defense against gases and moisture by combining polymers like proteins, polysaccharides, and nanoparticles [34]. Composite films are perfect for packing goods like fresh fruits and vegetables because nanoparticles, such as zinc oxide or silver, are frequently added to increase their antibacterial effectiveness.

3.5. Nanostructured Films and Coatings

Nanotechnology is used in nanostructured films to improve their mechanical and barrier qualities; these coatings' strength, thermal stability, and resistance to moisture and gasses can all be greatly increased by including nanoparticles [35]. Additionally, these coatings have antioxidant and antibacterial properties that enhance food preservation and safety. For even more accurate food quality monitoring, nanostructured coatings can be made to identify rotting indications at the nanoscale level.

3.6. Smart Edible Films

Unlike conventional solutions, intelligent packaging uses natural polysaccharides, which are non-toxic, biocompatible, and biodegradable, to improve functionality [36]. The development and uses of polysaccharide-based intelligent packaging are highlighted in this review, which also covers a variety of sensing techniques for keeping an eye on food attributes like temperature and microbial contamination [32]. In addition to examining present issues and potential future paths, the study highlights the potential of these materials in the food sector. To give consumers information on the quality of food as it is being stored and transported; intelligent food packaging can detect changes in the environment. Because colorimetric pH indicators are inexpensive and easy to use, they have

been used specifically in food-intelligent packaging. Although polysaccharide-based intelligent packaging materials have advanced significantly in recent years, issues including limited mechanical characteristics and moisture sensitivity still exist. These materials require a thorough examination. With an emphasis on polysaccharide-based intelligent packaging systems, different food quality sensing methods and new developments in food packaging, this study examines the most recent research. The opportunities and difficulties these materials face in the market are also covered. Intelligent films used in food packaging:

- pH-Sensitive Films
- Temperature-Responsive Films
- Oxygen Scavenger Films
- Moisture-Responsive Films
- Active Packaging Films

3.7. Antimicrobial films

There are two types of packaging: biodegradable and non-biodegradable; non-biodegradable plastics, such as PET, LDPE, and PP, are widely used because of their strength, affordability, and barrier qualities, but they also present health and environmental hazards [37],[38]. Biodegradable materials are now the main emphasis in order to lessen the environmental impact of packaging due to the increased demand for sustainable packaging. When antimicrobial (AM) agents are included in the polymer film, AM packaging effectively inhibits bacteria. It works better than adding preservatives directly for two reasons: (1) AM agents are released from the film gradually, and (2) there is less chance of inactivation by food ingredients, which can happen when preservatives are introduced directly. Food quality can also be lowered by direct addition, which can alter texture and flavor. Thus, without sacrificing quality, AM packaging extends food safety and shelf life.

3.8. Antioxidant films

Antioxidants, including synthetic kinds like BHT and BHA, are frequently added to polymers to increase food stability and prevent thermal degradation [39]. Problems over the migration of artificial antioxidants into food, however, bring both legal and health problems. Natural antioxidants including tocopherol, plant extracts, and essential oils from plants are being studied as safer substitutes. These natural antioxidants are a promising option for food packaging since they not only stop oxidation but may also enhance the nutritional content of food while it is being stored.

4. Enhancing Food Preservations

Numerous polymers have the ability to create films and are non-toxic, biodegradable, antibacterial, and antioxidant. These characteristics enable their extensive application in the creation of edible films, coatings, and nano-emulsions. However, a number of variables, including the degree of deacetylation, molecular weight, pH, concentration, and origin, affect the biopolymers' functional ability [40]. It is commonly known that the degree of deacetylation and its concentration boost a polymer's antibacterial efficacy. For example, chitosan containing soluble amine groups is created when chitin is deacetylated. The degree of solubility of chitosan is determined by the presence of these soluble amine groups, and it rises as the degree of deacetylation increases. In reaction to stress, plants create secondary metabolites called phenols; they stop oxidation and damage to cells. Polyphenolic substances, including anthocyanin, flavonoids, and phenolic acids, are found in plant extracts. Phenolic and its derivatives are present in these extracts and act as potent antibacterial and antioxidant agents. Because of their ability to scavenge radicals, phenolic compounds function as antioxidants by preventing oxidative chain reactions [41]. When added to coat-

ing compositions, the different phenolic elements work in concert to increase the coatings' overall antibacterial and antioxidant capabilities. Phenolics primarily cause membrane instability in microorganisms, which allows them to enter cells and obstruct protein synthesis, ultimately leading to cell death. According to a study, phenolic extracts' antibacterial effectiveness depends on both their concentration and the length of time they are exposed to the test microbe. The following Figure 3 is the example of food preservations mechanism;

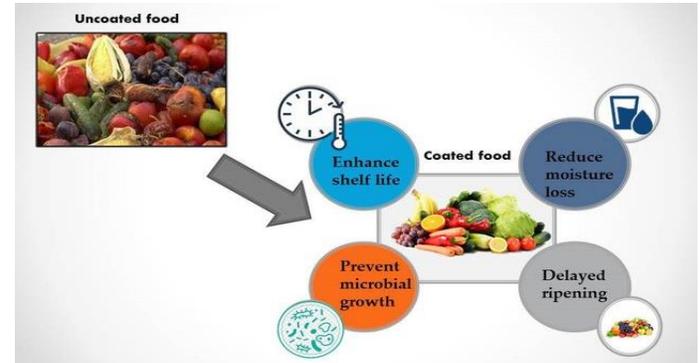


Figure 3: Food Preservations Mechanism adopted from [42]

4.1. Moisture and Gas Control

In order to help regulate the humidity in packaging, moisture absorbers are materials that draw in and hold onto water molecules. These absorbers fall into two categories: moisture removers, which absorb liquids from food, and RH controllers, which control moisture in the packaging headspace (such as desiccants) [43]. Fresh vegetables and meat are frequently covered with moisture removers, which are frequently in the shape of pads or sheets. Although desiccants are frequently employed, superabsorbent composite materials have recently drawn attention because they improve moisture control in food packaging. As a hygroscopic substance, fructose takes in and holds onto moisture for extended periods of time, beginning at 55% relative humidity. It was added to Fruitpad strawberry packaging to improve moisture absorption and decrease weight loss. By regulating in-package humidity, sorbitol, another FDA-approved moisture absorber, increases the shelf life of vegetables like tomatoes and mushrooms. Although they have difficulties breaking down, cellulose derivatives such as carboxymethylcellulose (CMC) are very good at absorbing moisture. Because of their superior moisture-absorbing ability and non-toxic nature, inorganic absorbers such as calcium oxide and silica gel are increasingly frequently utilized [44]. Moisture control films used for food packaging:

- Low-Density Polyethylene (LDPE)
- Polypropylene (PP)
- Polyvinylidene Chloride (PVDC) Coated Films
- Silica Gel or Desiccant Films
- Carboxymethylcellulose (CMC)-Based Films
- Polyamide (Nylon) Films

4.2. Smart films and coatings for fruits

After harvesting, fruits and vegetables continue to be physiologically active, which can cause problems like respiration and water loss and ultimately lower their quality? By decreasing evaporation and respiration, packing materials can have their shelf life increased by reducing moisture and oxygen permeability [45]. It has been demonstrated that edible films work well as barriers, preventing water loss and postponing ripening. These films' capacity to maintain freshness is further improved by the addition of active ingredients like phenolic or essential oils. Because of its ability to

form films and act as antimicrobials, chitosan is frequently used in edible packaging for fresh fruits and vegetables. For example, chitosan films containing 8% galangal oil have been shown to prolong the shelf life of mangoes by 9 days at room temperature while preserving their firmness by slowing respiration and metabolic activity. Furthermore, protein-based films, such as whey protein, are effective barriers against gas diffusion and moisture. Whey protein films containing 0.5% lemongrass essential oil helped preserve polyphenol levels in fresh-cut pears while preserving their firmness during storage [46]. However, the addition of essential oils can affect the fruit's acceptability, indicating that more research is needed to maximize their use.

4.3. Smart films for meat and sea food

During preparation and storage, meat products are susceptible to enzymatic autolysis, lipid oxidation, and microbiological spoiling. Vacuum or nitrogen packaging is frequently employed to address these problems, and edible coatings can be enhanced with natural antioxidants to prevent oxidation [47]. Studies indicate that chitosan films containing essential oils can considerably increase the shelf life of meats. Polysaccharide-based films, especially chitosan, are beneficial because of their antibacterial qualities. Although their significant moisture permeability can be reduced by adding hydrophobic materials, protein-based coatings can enhance mechanical qualities and act as gas barriers. By lowering microbial counts and enhancing barrier qualities, lipid-based films—which are frequently mixed with proteins or polysaccharides—also improve meat quality and shelf life. Recent studies highlight how essential oils, such as garlic oil, can effectively preserve meat products by drastically lowering the number of germs that cause spoiling. Despite being high in proteins and minerals, seafood products—such as fish, shrimp, and shellfish—are extremely susceptible to lipid oxidation and microbial contamination while being stored. Active edible films can be used to decrease lipid oxidation, moisture loss, and microbiological development, improving their quality and prolonging shelf life [48]. For this aim, polysaccharides such as chitosan and alginate have been thoroughly investigated; chitosan has been shown to possess both antibacterial and antioxidant qualities. Research shows that chitosan-based films can suppress contaminants like *Listeria monocytogenes* on cold-smoked salmon and that adding more antimicrobial agents can increase their effectiveness. For instance, resveratrol-loaded alginate films have been demonstrated to be more effective than standard alginate films at preventing the growth of spoilage microorganisms in rainbow trout that have been stored.

4.4. Smart films for dairy and bakery products

Although dairy products like milk, cheese, and yogurt are rich in nutrients, they are also quite vulnerable to chemical and microbiological deterioration. Active edible films have been created to prevent microbial development and off-flavors, improving their quality and shelf life. Adding antioxidants and antimicrobials, like essential oils, to these films can increase their efficacy [47],[48],[49]. For instance, chitosan-based films containing thyme essential oil can greatly increase the shelf life of Karish cheese by lowering bacterial counts for more than four weeks, while essential oil-loaded alginate films have been demonstrated to shield cheese from microbial contamination and water loss. Products from bakeries rank among the most essential staple meals that people around the world eat on a regular basis. Global sales of bread and other bakery goods will reach approximately \$1172.65 billion by 2021, with China alone accounting for over \$250.203 billion of the total. By 2027, the global market for bakery products was expected to grow to \$457.4 billion; bakery products are among the most important basic foods consumed daily by people throughout the world

[50]. By 2021, bread and other bakery products have accumulated about \$1172.65 billion in revenue globally, and in China alone, about \$250.203 billion had been generated; it was predicted that the global bakery products market would reach \$457.4 billion by 2027 [50]. Without preservatives, bakery goods like bread and cakes usually have a short shelf life of three to five days. During this time, their quality is impacted by physical, chemical, and microbiological changes. The industry may suffer financial losses as a result of off-flavors and health hazards brought on by microbial spoiling from bacteria and mold. Although chemical preservatives like calcium propionate and physical preservation techniques like UV radiation and microwaves are employed, they have drawbacks and consumer demand for organic products is growing. To improve food safety, quality, and shelf life, new active and intelligent packaging technologies are being developed; the market for these products is anticipated to expand rapidly [51]. Since consumers may incur additional expenditures, consumer acceptability is critical to the success of innovative packaging methods. Consumer perceptions of active packaging have been the subject of recent research. For instance, consumers' unfamiliarity with antimicrobial packaging led to distrust, although oxygen absorbers were widely accepted in products like bread and pizza.

5. Consumer perception and acceptance

Approximately one-third of the food produced globally each year is wasted. Microbial and oxidative spoilage are the main factors that contribute to food loss and waste, which have significant economic, environmental, and social consequences. Petroleum is the primary source of most food packaging materials due to its affordability, high barrier qualities, and ease of usage. These polymers, however, are not biodegradable and have already given rise to significant environmental concerns. Thus, switching from non-renewable to renewable materials is the current trend in the packaging sector. In the last phase of the supply chain, packaging is a crucial component of a food product that draws customers and affects their decisions to buy. As a result, it is crucial to educate customers about the advantages of new food packaging, support their use in place of traditional ones, and highlight the packaging cost as part of the product's overall cost.

Prior studies have looked into how food packaging affects the product's ultimate cost. Prior studies have examined food packaging from the viewpoints of producers, businesses, consumers, or technicians. The choice and devotion of consumers to biopolymer films—packaging materials that preserve food because of their useful qualities—is, nevertheless, the subject of relatively little consumer-oriented research. Additionally, biopolymer films are cost-effective for customers and are creative, active, eco-friendly, and sustainable, respectively. The sensory and hedonistic qualities of products are frequently inferred by consumers from their packaging. Additionally, customers frequently get familiar with a product's brand by associating it with its packaging. In this sense, one external factor that is closely linked to brand awareness is container color. Color's impact on customer behavior and product perception is a complex phenomenon with strong roots in consumer research and sensory psychology. Color is a basic emotional reaction generator that has a big impact on customer behavior and purchasing choices. A key element of brand identity that aids in consumer recognition and recall is color. Consumers' sensory experiences and preferences are greatly influenced by a number of elements, including font style, label design, brand name, and contextual appeal.

6. Regulations for smart coatings

Excellent sensory qualities, high barrier qualities, high mechanical strength, high microbiological stability, lack of toxins, safety for human health, ease of production, non-polluting, and affordability are all necessary for a successful edible film. Edible film production is still being done on a lab basis. The commercial success of edible films still faces numerous obstacles.

Edible films have a number of drawbacks over synthetic plastics, including weak mechanical strength (particularly bad elongation), poor gas and liquid resistance, a lack of edibility and biodegradability testing, challenges with processing scale-up, etc. To make the edible films economically successful, it is imperative that these challenges be overcome. The majority of the time, the package is made using traditional methods like extrusion, injection molding, injection stretch blow molding, casting, blown film, thermoforming, foaming, blending, and compounding. This is true even when considering manufacturing techniques for innovative packaging production.

Alternatively, sachets and pads can be placed inside the package, or the active ingredient can be directly integrated into the polymer-based package matrix and/or film. Instead, the primary or secondary packaging can incorporate the intelligent component. To keep up with the advancements in packaging composition and structure, polymer packaging production technologies are also intriguing. The market position of active and intelligent packaging in Europe lags well behind that of other countries, especially the USA, Australia, and Japan, where these items are extensively marketed. Edible sensors for food degradation detection are one kind of sensor that is anticipated to be very successful in the field of intelligent food packaging. These sensors are built entirely of natural and biodegradable materials and do not pose any long-term risks to human health. For instance, a sensor that uses a red cabbage extract as a colorimetric indicator and a pectin matrix has been created. The food industry uses pectin, a naturally occurring polysaccharide that is commercially produced from apples and citrus fruits, to enhance the gelation of food items. An important amount of anthocyanins, specifically cyanidin glycoside derivatives, are present in the red cabbage extract. Anthocyanins are well-known pigments that can detect the presence of amines and change color in response to pH variations.

7. Challenges and Future Trends

The creation and application of smart edible films and coatings are fraught with difficulties related to consumer acceptance, safety, and regulatory compliance. Because these materials come into direct touch with food and may potentially be consumed, it is crucial to ensure their safety. To assess their toxicity, allergen city, and long-term impacts on human health, extensive testing is necessary. For the approval of products that come into contact with food, regulatory agencies enforce strict criteria that can be expensive and time-consuming for businesses to follow. Additionally, businesses looking to market their goods internationally face obstacles due to the diversity of international legislation, which makes compliance more difficult. Another significant obstacle is consumer acceptability. Many customers are cautious of new food technologies, especially those that incorporate edible ingredients, even if creative and sustainable packaging solutions are becoming more and more popular. Widespread adoption may be hampered by worries about the safety of bioactive substances or the possibility that they could change the flavor and texture of food. To increase customer trust and allay worries, education initiatives, and clear labeling are crucial. The commercialization of smart edible films and coatings is hindered by the need for companies to overcome perception and safety concerns in order to gain market acceptability and regulatory approval. Advances in materials science, nanotechnology, and food

safety concerns are driving the rapid development of smart edible films and coatings in active and intelligent packaging. The use of nanomaterials, such as nanocellulose, nanoparticles, and nanoemulsions, is one significant development. These materials improve the mechanical and barrier qualities of edible films, increasing their ability to prolong the shelf life of perishable foods. Food preservation is further enhanced by these materials' improved oxygen, moisture, and light barrier qualities. Additionally, nanotechnology makes it possible to create smart coatings that are more sensitive and have improved bioactive qualities, such as antioxidant and antibacterial capabilities, providing a stronger defense against contamination and spoiling. The incorporation of sensor technologies into edible films to create packaging that can continuously check the quality of food is another exciting avenue. In order to improve customer safety and decrease food waste, future research is probably going to concentrate on creating edible films coated with temperature- or pH-sensitive chemicals that can indicate spoiling through color changes. The creation of economical and sustainable biopolymers will also be a top research priority. To create films that are both environmentally benign and practical, scientists are investigating plant-based materials including seaweed, agricultural waste, and other renewable resources. By creating materials that satisfy international safety standards and increasing customer acceptance through open communication and education, research activities will also concentrate on resolving regulatory and safety issues.

8. Conclusion

Smart edible films and coatings are a revolutionary development in the field of intelligent and active packaging for perishable foods. They are a good substitute for conventional packaging techniques because of their capacity to increase food safety, prolong shelf life, and lessen environmental effects. The effectiveness of these packaging options will be further enhanced as research advances by utilizing cutting-edge materials and technologies like sensor integration and nanotechnology. For them to be widely adopted, it is still imperative to overcome issues with consumer acceptance, safety, and regulatory compliance. By emphasizing sustainable practices and informing consumers about the advantages of intelligent edible packaging, the food sector may set the stage for a time when environmental sustainability and food quality are given equal weight.

Declaration

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