



Safety and Standards in Edible Packaging: A Framework for Regulatory Alignment and Consumer Protection

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ABSTRACT

The review compiles the compositions and the functional properties of biopolymer-based edible packaging materials incorporating active additives. Edible packaging, a sustainable substitute for traditional plastic packaging that has been developed to reduce environmental pollution. However, the efficient use of these advancements has been hampered by concerns about food safety and the lack of a defined framework. It also identifies some of the possible safety hazards of microbial

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contamination, chemical migration, and allergenicity. The current regulatory regimes around the world are discussed with emphasis on the need for alignment in standards that are meant to protect consumers and ensure product effectiveness. It touches on issues of large-scale production, standards of labelling, and public acceptance as well as advances in nanotechnology and biodegradable sensors. One way forward is creating strategic interventions for the standardization of safety protocols, as well as for promoting sustainable practices, so that edible packaging can be developed and adopted faster, thus aiding environmental conservation and food safety.

Keywords: *Edible packaging; food safety; regulatory framework; nanotechnology; sustainable packaging; environmental conservation; consumer protection; label standards.*

1. INTRODUCTION

Traditional plastic packaging is creating an environmental crisis that requires immediate sustainable solutions. Edible packaging from biodegradable materials is also becoming an attractive alternative to plastic to reduce waste and ensure product safety and preservation. Edible packaging consists of biopolymers such as proteins, polysaccharides and lipids to form food films or coatings to act as a protective barrier for food products. (Janjarasskul and Krochta, 2010c; Kumar et al., 2022). These materials have properties that are additional such as antimicrobial and antioxidant which guarantees food quality and shelf life (Kaur et al., 2022). Edible packaging made up of natural biodegradable plant-based material can be eaten to go without a need for waste collection processing, recycling, or disposal (Kour et al., 2025). However, despite these, edible packaging is still underutilized. Due to safety concerns and regulatory approval issues, including consumer acceptance (Saklani et al., 2019). Typically, edible packaging consists of coatings, pouches, sheets, or edible films. Edible films typically have a thickness of less than 254 μm , while sheets typically have a thickness of more than 254 μm . These materials (films and sheets) are produced independently of food and then applied to food items or sealed as edible pouches. Edible coatings are typically applied directly to food products as sticky films composed of edible ingredients (Ahmad et al., 2017; Chhikara & Kumar, 2022).

From a security perspective, food packaging raises serious concerns about microbial contamination, chemical movement and allergens, for example, by including active additives such as essential oils and nanoparticles, although useful, careful evaluation is required to avoid unintentional health risks (Kaur et al., 2022; Janjarasskul and Krochta, 2010c, No et al., 2007).

The current food safety framework does not appropriately address edible packaging materials in terms of regulation. The existing guidelines by regulatory agencies such as the US FDA and EFSA lack consistent standards on ingredients as far as edible packaging is concerned, particularly regarding methods of testing, labelling, safety assessments, and so on (Janjarasskul and Krochta, 2010c). Regional regulations for the same do not mutually recognize edible packaging; thus, edible packaging cannot be adopted worldwide as an alternative.

Consumer acceptance was another major factor influencing the introduction of the market; quality issues on taste, texture and hygiene, with limited awareness about these, tended to create barriers to adoption (Saklani et al., 2019). Challenges of cost-effectiveness in large-scale production remain. This is especially more pronounced in developing regions, where cost is a significant factor. The present review intended to be extensive in edible packaging from its material composition, safety issues, and regulations, through an account of technological advancements that are oriented towards these challenges. Edible packaging demands a globally harmonized safety and regulatory framework for the protection of consumers and for the wide adoption of sustainable practices.

2. COMPOSITION AND MATERIALS USED

Edible packaging made of biopolymers. A macromolecule occurring naturally has an excellent advantage from renewable biological sources. This is one of the materials which can be easily found because of its biodegradable nature, non-toxic properties, and good forming ability to film and therefore are more likely to be considered in replacement of ordinary plastic packaging (Guilbert et al., 1997). The three major classes of biopolymers as applied to edible films are polysaccharides, proteins, and lipids, each of

which offers a unique set of functional characteristics. Polysaccharides act mainly as structural components providing mechanical integrity and barrier functions; Proteins give mechanical strength and a wide variety of functions to films; and Lipids improve water resistance as effective moisture barriers (Guilbert et al., 1997). The synergistic use of these materials is very important in overcoming the limitations of individual components and in tailoring edible packaging for specific applications.

2.1 Polysaccharides

Polysaccharides became an important type of complex carbohydrates in edible packaging applications. This might be due to the fact that these natural polymers come from various green resources, such as plants and algae, making them truly sustainable and environmentally friendly, other than their abundance and cheapness-to-mass production and their wonderful film-forming ability (Cazón et al., 2016).

1. Starch

Of the many polysaccharides for which it is obtained from plants, such as corn, potatoes, cassava, and rice, one of the most frequently used in edible coatings is starch. The property of both gelatinization and retrogradation allows good mechanical strength and transparency of the films formed. Starch films are well-qualified as excellent barriers to oxygen, which can help preserve the quality of packaged food (Ghasemlou et al., 2013). However, due to the hydrophilic nature of these films, moisture absorption occurs easily, which adversely affects the mechanical integrity of the films. This has been a reason for adding glycerol or sorbitol as plasticizers to allow flexibility while blending starch with other biopolymers or hydrophobic materials improving water resistance and durability (Jeevahan and Chandrasekaran 2019).

2. Cellulose along with its Derivatives

Among all organic polymers, it is cellulose that is found as the most abundant and that also forms a very important part of the plant cell walls. Being the most abundant, it is a good choice as a raw material for edible packaging (Kumar et al., 2022). All its derivatives, which are methylcellulose (MC), hydroxypropyl methylcellulose (HPMC) and

carboxymethylcellulose (CMC), have excellent solubility in water, film-forming and transparent properties. They have thereby become very important because of their oil and fat barriers, a property that makes them useful for fatty foodstuffs in packaging (Moghimi et al. 2017). Cellulose-based films are also biodegradable and thermally stable, thus making them more attractive from the environmental as well as the functional aspects.

3. Pectin

Pectin is a polysaccharide, naturally occurring, and isolated from citrus peels or apple pomace (Morales-Contreras et al., 2019). It acts mainly due to the existing calcium ions and develops gel above a specific threshold of concentration. These films will later produce strong films with great quality barrier properties for oxygen and moisture. Pectin-based films apply most importantly as coatings for fresh fruits and vegetables; their purpose is to keep the freshness of products, prevent microbial growth, and increase shelf-life. Additionally, pectin-type film formers have the advantages of being biodegradable, non-toxic, and mouth-friendly, all contributing to sustainable packaging solutions.

4. Alginate

Alginate obtained from brown algae is a salt of alginic acid and forms resilient and flexible films with excellent oxygen and oil resistance. Mixing calcium ions with alginate enhances its gelling properties and forms cross-linked networks to improve the mechanical strength and stability of the films. Thus, it becomes a crucial consideration when it applies as a high-performance edible coating in the bakery, a preservative of freshly butchered meat, and pharmaceutical encapsulation.

5. Chitosan

Chitosan is a cationic polysaccharide obtained after treating chitin, which occurs in crustacean shells, with alkaline deacetylation. Among its properties, the most interesting ones include a combination of antimicrobial as well as antioxidant properties (No et al., 2007). This value qualifies chitosan as a preservation agent in food as it inhibits microbial growth and oxidative decay. Chitosan-based films also reveal superior gas and oil barrier properties, making them a specific package for covering perishables like seafood and dairy products (Durango et al. 2005).

2.2 Protein

Proteins are made up of chains of amino acids linked by peptide bonds. One of the excellent characteristics of proteins is that they can develop extremely strong and flexible films with many functional properties. With their particular molecular hygenity, films can be produced with excellent mechanical strength and elasticity, needed to keep the integrity of packaged products.

1. Whey and Casein Proteins

They are derived from milk and thus can be considered edible protein sources, which can be used as a packaging material due to their incredible film-forming capabilities (Oymaci and Altinkaya 2015). Therefore, whey protein isolate (WPI) and casein films have excellent barrier properties for oxygen, which helps prevent decay in food products due to oxidation reactions. These films are also transparent, flexible, and biodegradable and thus can be used for dairy product packaging to maintain freshness and improve shelf life; yet their sensitivity to moisture demands blending with other biopolymers or the use of hydrophobic additives in order to enhance water resistance (Oymaci and Altinkaya 2015).

2. Soy Protein

Soy protein refers to a protein which comes from soybeans (De Souza et al., 2020). It is a cheap and renewable source of film-forming material. Soy protein isolate (SPI) films provide high strength mechanically and are excellent barriers to oxygen. However, because these soy-based films are hydrophilic and highly absorb water they may suffer from compromised structural integrity (Gao et al., 2015). Therefore, different researchers have been exploring modification techniques such as cross-linking and lipid additives for the enhancement of water resistance and durability (Friesen et al., 2014).

3. Gelatin

Gelatin is probably the most well-known versatile animal protein for its functional properties, found as a constituent of collagen in animal tissues. It can cohere readily and form thermo-reversible gels, making it applicable for uses ranging from coatings for confectioneries to capsules for pharmaceuticals. Films produced from gelatin have been reported to be quite strong, clear, and biodegradable, a basis for their classification in

the non-synthetic category of packaging materials.

4. Zein

Zein, a corn gluten isolated-water-resistant, glossy, film that best suits covering nuts candy or even products that have pharmaceutical uses. Zein's unique properties include its good mechanical strength and biodegradability, which probably made it very appealing to sustainable packaging solutions (Oymaci and Altinkaya 2015).

5. Gluten

The protein complex gluten is found in wheat and is noted for its elasticity and film-forming ability. Gluten-based films are extremely good in mechanical strength and provide high oxygen barrier properties. Restricted application, however, has been due to allergenicity issues and consumer acceptability, confining this material to niche markets.

2.3 Lipids

The fatigue in edible packaging can also be reduced by lipids such as fats, waxes, and oils. Though lipid films have less mechanical strength than films made of polysaccharides and proteins, they are often combined with these materials to optimize performance.

1. Beeswax

Beeswax is wax from bees naturally, which forms a shiny, hydrophobic surface on fresh fruits and candies. Moisture Loss Barrier is effective trim and quality maintenance in food packaging.

2. Carnauba Wax

Carnauba wax is harvested from the carnauba palm leaves and used in the production of edible coverings for both fruit and confectionery. The hard, glossy surface and outstanding water-repelling properties make it quite popular for applications that call for superior moisture protection.

3. Essential Oils

Some essential oils, such as clove, thyme, and oregano, are increasingly being added to edible films to release their antimicrobial and antioxidant properties. Such oils complement the functional properties of films and add sensory

appeal through flavor and aroma (Coşkun et al. 2014b).

2.4 Combination of Biopolymers

Edible packaging is blending polysaccharides, proteins, and lipids to overcome some performance limitations of each type of biomaterial, using built charges or properties that complement and ultimately generate films with improved mechanical strength, flexibility, and barrier properties. The combination of chitosan with gelatin produces films whose water resistance and elasticity are improved, while essential oils incorporate an antimicrobial effect. Innovative combinations and processing techniques are being explored by researchers to come up with the best-performance edible packaging so that it can be used as a viable and sustainable alternative to conventional plastic packaging.

2.5 Functional Additives in Edible Packaging

In order to improve the performance or functionality of edible packaging, various additives are mixed with the basic biopolymers. These functional additives improve various important properties of the packaging such as protective, sensory, and aesthetic ones to mould them according to the specific requirements of consumers or industry. Four types of main additives include antimicrobials, antioxidants, colourants, and flavouring agents, each of which has unique important advantages.

1. Antimicrobials

Antimicrobial additives are really important for extending the shelf life of perishable food products by inhibiting or delaying the growth of any microorganism. The upcoming agents are efficient in attenuating foodborne pathogens as well as spoiling bacteria. Some examples are given below: Natural antimicrobial agents being incorporated into edible films and coatings include essential oils, such as oregano oil, thyme oil, clove oil, chitosan, and plant extracts. The inclusion of antimicrobial agents in edible packaging does contribute to the maintenance of food quality rather than purely synthetic preservatives, which is in agreement with increased consumer demand for clean-label products (Moghimi et al. 2017). One example is chitosan, which is produced from crustacean shells, has antimicrobial and antifungal

properties and has become one of the largely used packaging additives for fresh produce, seafood, and dairy products (No et al., 2007).

2. Antioxidants

Oxidative deterioration of food products, especially fats and oils, is one of the areas that needs to be checked with antioxidants. Oxidation causes rancidity, unwanted off-flavour, and nutrient loss, which are significant in measuring food quality and safety. Natural antioxidants, such as ascorbic acid (vitamin C), tocopherols (vitamin E), and phenolic compounds derived from plant extracts, blended with edible films, help to neutralize radicals and slow down oxidation processes that eventually lead to increased shelf life of packaged products. The aforementioned alterations to edible coatings with green tea or rosemary extracts have been proven to improve the oxidative stability of meat and poultry products (Piñeros-Hernandez et al. 2016).

3. Colourants

Colorants have been used to make edible packaging attractive, and hence, more appealing to consumers. The most preferred pigments for use in edible packaging over synthetic dyes include carotenoids, anthocyanins, and chlorophylls because they are not harmful and have health benefits (Barbosa et al. 2021). These colourants can also be functional in the sense that they indicate whether the packaged product is fresh or of good quality. For instance, pH-sensitive natural dyes like anthocyanins, which usually change colour as pH or temperature varies, can act as visual indicators of spoilage (Pereira et al. 2014). Therefore, these dyes can reflect the proximal issue of consumers with food safety.

4. Flavours

Flavours are incorporated into edible packaging to enhance the sensory appeal and taste of the foodstuff they contain. These include flavouring agents usually derived from natural flavour compounds from fruit, spices, and herbs. For example, adding essential oils of orange and mint to edible films can improve the sensory experience while providing functional benefits, such as antimicrobial or antioxidant properties. Flavoured films are mostly found in confectionery snacks and foods, with the ability to differentiate products from the competition and serve gratified customers.

2.6 Essential Characteristics for Edible Packaging

The efficacy of edible packaging is a blend of many critical properties needed for its functionality, safety, and sustainability. Beyond ensuring that the packaging meets consumer expectations, the properties should meet the regulatory standards.

1. Biodegradability

Edible packaging biodegradability is an important benefit since it answers one of the many global challenges confronting society in terms of plastic waste. Starch, cellulose, and chitosan are materials that degrade in nature without any harmful residues. This property curtails landfill waste promotes the concept of circular economy and makes edible packaging an eco-friendly solution for conventional plastics.

2. Safety

Safety should always come first in edible packaging since they are intended to be in direct contact with food and sometimes consumed by the user. All the components like base materials and additives must have thorough safety criteria. They must also be non-toxic, free from allergens, and approved for human consumption. Regulatory agencies like the FDA, EFSA, and FSSAI give guidelines regarding the safe use of edible packaging materials and additives. Moreover, the packaging must not interfere with any sensory properties or nutritional properties of the food enclosed by it.

3. Barrier Properties

Barrier Properties are all essential in terms of protecting food from moisture, oxygen, and microbial contamination. An edible package has to provide sufficient resistance to water vapor, gases, and oils in order to preserve food quality and freshness. Polysaccharides such as alginate and derivatives of cellulose have high oxygen barrier properties, and lipidic coatings are moisture barriers. Combining all these materials may optimize the barrier performance of specific demands based on certain food products (Ghasemlou et al. 2013c).

3. SAFETY CONCERNS IN EDIBLE PACKAGING

The utmost importance in edible packaging is safety, as it is in direct contact with food and

eaten along with it. Safety concerns include possible risks posed by microorganisms, chemical migration from the outer packaging, allergens, and poisonous properties of raw food ingredients (Muncke et al., 2020). To reduce the risks involved and protect consumers, testing methodologies should be very stringent and comply with existing standards on safety.

Microbial Contamination: Risks

Microbial contamination is one of the greatest edible packaging hazards. Most materials used in making edible films, such as proteins and polysaccharides, are biodegradable and thus provide nutrients for the growth of microbes (Duncan, 2011b). Improper handling, processing, and storage so edible films can result in supporting the growth of these harmful microorganisms: bacteria, fungi, or molds. That is, protein-based films such as those derived from milk or soy may be susceptible to pathogen attack, provided that they are not properly treated or preserved under controlled conditions. To combat this, antimicrobial agents like essential oils, chitosan, or silver nanoparticles are incorporated into the packaging so that they discourage microbial proliferation and secure the products (Dainelli et al., 2008) (Jahangiri et al., 2024b). Also, strict hygiene standards would be held as most important to reducing the possible contamination risks during production and storage.

1. Chemical Migration from Additives or Processing Agents

Another safety concern is the potential migration of chemicals from edible packaging into food. Plasticizers, emulsifiers, and functional agents, for example, are all essential for increasing the performance of edible films, but they might migrate into packaged food at elevated temperatures and during extended storage (Alamri et al. 2021). For example, glycerol, a common plasticizer, can migrate into food, affecting its taste or nutritional qualities. In addition, residues from either processing agents or solvents used in film preparation may pose health risks if they are not expended. Choice of food-grade additives and processing techniques would therefore be important in limiting this (Geueke et al. 2022). Rigorous migration levels assessment using gas chromatography-mass spectrometry (GCMS) or high-performance liquid chromatography (HPLC) will ensure that levels are within regulatory limits.

2. Ingredients and Their Allergens and Toxicological Effects

Except under protein forms like gluten, casein, and soy as edibles used for packaging, allergenicity should be a major concern. It may cause allergic reactions to sensitive individuals if the material is not specified in the labelling or managed appropriately (Geueke et al., 2024). Apart from this, certain biopolymers or additives could be toxicologically injurious due to their properties or possible contamination with toxic substances during manufacturing (Singhal et al., 2022). For example, chitosan, a polymer derived from crustacean shells, is a good example of a material that may lead to adverse effects among patients who are allergic to shellfish (No et al., 2007). A thorough toxicological study on acute and chronic exposure will determine the acceptable levels of safe consumption. These must be supplemented by labelling requirements and consumer information.

4. TESTING METHODOLOGIES FOR SAFETY ASSESSMENT

In the scope of safety evaluation of edible packaging, an extensive battery of microbiological, chemical, and toxicological methods are utilized.

Microbiological Testing: Microbiological examination of edible packaging involves assays such as pathogen detection by identifying the presence of certain pathogenic bacteria, yeasts, and moulds. Various methods such as plate count assay, PCR (Polymerase Chain Reaction), and next-generation sequencing (NGS) have been used in detecting and quantifying microbial contaminants (Van Hoorde & Butler, 2018).

Chemical Test: GC-MS and HPLC analytical techniques are employed to assess the extent of such chemical migrations from edible films into food. These tests calculate the amount of residual solvents, additives, and potential contaminants and verify whether they still lie within the regulatory limits imposed by the regulatory body (R. B. Taylor & Sapozhnikova, 2022).

Allergenic Testing: Allergenicity by enzyme-linked immunosorbent assays (ELISA) is defined and quantified. It further includes in vitro and in vivo studies conducted to assess the potential for triggered allergic reactions. Other immunological techniques for measuring allergenic proteins

present in edible films can also be prescribed (Tuppo et al., 2022).

Toxicology Testing: Toxicological evaluation includes determining the effect of edible packaging material on human health via tests in cell cultures, studies in animals, or even through computational models. Tests are mainly on acute toxicity, genotoxicity, and long-term effects (Farsi et al., 2013).

Studies of Storage Viability and Stability: Edible package materials have been evaluated for their resistance to microbial growth, chemical degradation, and mechanical integrity over time in storage conditions. Such studies ensure that the package is safe and efficacious for the intended life (Santhosh et al., 2024).

5. CURRENT REGULATORY FRAMEWORK

Different regulatory frameworks address edible packaging in distinct regions due to the pre-defined priorities, scientific approaches, and obviously consumer safety. Some of the key regulatory frameworks on edible packaging are those from the U.S. Food and Drug Administration (FDA), the European Food Safety Authority (EFSA), and the Food Safety and Standards Authority of India (FSSAI) (Rani et al., 2018). Major databases put under this status include material safety, migration limits, and compliance procedures to sort edible packaging as safe, functional, and green.

5.1 United States: FDA Regulations

The FDA oversees edible packaging in the United States under FFDCa. Regulations are primarily directed at the safety of materials, which will directly come with food, such as the components of edible films and coatings (Rani et al., 2018).

1. Food Additives and GRAS

Edible packaging materials need to be either GRAS (Generally Recognized as Safe) or approved food additives. Most GRAS include polysaccharides, proteins, and lipids, and are therefore very stringently evaluated for their toxicological safety (Matloob et al., 2023). In contrast, other substances should be subject to premarket approval wherein manufacturers should show scientific evidence that their products are safe before they can be used in

edible packaging applications. For example, gelatin, for which edible films are produced, must comply with the standards for safety and purity as stipulated in the CFR Title 21, Parts 170-199.

2. Migration and Safety Testing

These studies are carried out so that substances potentially originating from edible packaging materials will not migrate into food at unsafe levels. Gas chromatography-mass spectrometry (GC-MS) and liquid chromatography (LC) are some of the methods used to test compliance with established thresholds for migration. Specific migration limits (SMLs) exist where additives, colourants, and/or other components can pose health risks (R. K. Gupta et al., 2024).

3. Labeling Requirements

The FDA requires clear and understandable labelling for edible packaging regarding the composition thereof, such as allergens or preservatives. Instructions for storage and use must also be included in the labelling to ensure the proper handling and consumption of the packaging (Odisho et al., 2020).

4. Manufacturing Standards

Good Manufacturing Practice (GMP) laid out by the FDA ensures consistency in rather edible packaging production and limits the possibility of any contamination while doing quality control (Nair et al., 2023).

5.2 Europe: EFSA Regulations

As far as edible packaging is concerned, the only regulation that applies in Europe is the EU Regulation (EC) No. 1935 / 2004, which concerns all types of food-contact materials. This is complemented by the GMP Regulation (EC) No. 2023/2006 and other specific directives dealing with active and intelligent packaging (Karamfilova et al., 2016).

1. Safety and Authorization

EFSA requires manufacturers to pre-authorize every material that is intended to be used in edible packaging. This will include a full risk assessment on toxicological, chemical, and microbiological safety. Biopolymers such as chitosan and alginate must be analyzed for possible side effects (Varalda et al., 2024b).

2. Specific Migrations Limits

The very strict SMLs for additives, processing aids, and other components must be fulfilled by materials. Migration tests replicate real-life conditions, i.e. packaging contact with food for several storage situations (R. K. Gupta et al., 2024).

3. Traceability and Documentation

The traceability of edible packaging materials is to be complete within supply chains as required by the EU. Complete documentation needs to be provided for raw materials, processing methods, and distribution channels to enable rapid action in case of safety concerns (Mania et al., 2018).

4. Labeling Standards

Edible package labels must meet all EU requirements in terms of material composition, allergens, and other specific storage or usage instructions. In fact, these would be indications of informed consumer choices and conformity with the legal requirements (Peonides et al., 2022).

5.3 India: FSSAI Regulations

The Food Safety and Standards Authority of India (FSSAI) regulates edible packaging under the Food Safety and Standards (Packaging and Labeling) Regulations, 2011 and amendments made thereafter. Combined with this, India also lays emphasis on the creation of an environmentally sustainable ambience in which food safety can work.

1. Material Approval

FSSAI allows the use of food-grade biopolymers for edible packaging such as starch, cellulose, and protein-based materials, but they do not approve non-food-grade substances like heavy metals, phthalates, or other harmful chemical additives.

2. Migration Testing

FSSAI migration studies stipulate in the interest of safety material studies. Such tests investigate the migration of chemical or microbiological agents from the packaging to food under typical storage and usage conditions.

3. Following BIS Standards

The edible material should also comply with Bureau of Indian Standards specifications for

food-contact materials to ensure uniformity of safety and quality between manufacturers.

4. Awareness by Consumers and Labeling

Edible packaging should be clearly labelled so that the consumers can distinguish it easily from the ordinary packaging materials. The labels should mention the edible nature of the innermost material, storage conditions, as well as allergen information so that appropriate use by the consumer can take place.

5.4 Global Challenges and Harmonization

Notwithstanding these highly insulated regional containments, salient concerns remain for global regulation of edible packaging:

Absence of Uniformity: GRAS definitions and recognition across regions; migration limits; and testing methodologies do not hold true uniformly across the regions. This could lead to hindrances in global trade as far as using and/or accepting edible packaging.

Emerging Science: Available materials science advancement beyond the pace of regulatory reforms pushes one to revise it from time to time in order to use it for some novel substances like nanomaterials or bioactive compounds.

Consumer Awareness: In other words, consumers do not understand much about edible packaging; therefore, education and labelling are needed to address the misuse or scepticism toward edible packaging.

One of the international organizations which is working towards harmonizing food packaging regulations is the Codex Alimentarius Commission. The commission has worked toward an approach that hinges on safety, quality, and sustainability. Harmonized standards would foster trade as well as innovation in edible packaging technologies (Lee et al., 2021b).

5.5 Differences and Contradictions in Regional Regulations

Unfortunately, even though attempts were made to implement methods of edible packaging regulation, the regional frameworks failed to conform in terms of coverage, definition, and operation, thus presenting broad inconsistencies as an impediment to global adoption as well as standardization.

1. Variation in Definitions and Standards

No accepted definition of "edibility" worldwide effectively leaves such regulations ambiguous in scope. Such as:

United States: The FDA considers safety in terms of substances either as GRAS or approved food additives but provides little specific guidance on edible packaging as a functional category.

Europe: EFSA addresses food-contact materials under Regulation (EC) No. 1935/2004, but does not have standards specifically for edible packaging, treating it like any other food-contact items.

India: FSSAI comes right out on food-grade materials, but does not give such specifications on defining or assessing the "edibility" of packaging.

Thus this leads to a situation of uncertainty for the manufacturers in the international market and creates difficulty in cross-border trade.

2. Differences in Testing Requirements

Migration testing is considered a major safety aspect with different methodologies and limits across regions.

Migration Limits: Whereas the European Food Safety Authority prescribes certain specific migration limits (SMLs) for each substance, the FDA allows broader evaluations on "reasonably safe" levels, hence discrepancies in safety thresholds.

Testing Conditions: These are also different across regions in terms of simulation exposure to real-life conditions such as temperature, humidity, and contact time which affect outcomes and comparability of migration studies.

Toxicological Evaluations: Differences in long-term exposure risks and their additive interactions further contribute to a misalignment.

3. Labelling and Consumer Awareness

A significant gap remains in labelling edible packaging to approach a clarification and conjugation by consumers in:

United States: detailed disclosure of ingredients by the FDA, but awarding no specific format for labelling edible packaging.

Europe: material compliance with safety standards is mandatory labelling by EFSA; however, communication with consumers on "edible" packaging is totally silent.

India: Often, FSSAI label specification is more focused on allergen disclosure and safety instructions than leaving edibility open-ended.

The absence of any standard labelling protocols creates confusion among consumers and, probably, misapplication or rejection of the edible packaging.

6. CHALLENGES IN DEFINING "EDIBILITY" AND LABELING

1. Subjectivity in Edibility

We think there's a definition of what constitutes the edibility of something: one aspect should be sensory acceptability, another one safety, and the last should be functional integrity. Packaging may only be tagged edible when such packaging not only passes the toxicology safety standards but also on-holds sensory preferences and dietary norms of diverse consumer groups. For example, alginate and gelatin-based films indeed need to hold structural integrity while remaining palatable and free from toxins (Nair et al., 2023).

2. Complicated Labeling

Saying that the packaging is added for the product's consumption is better done in the clearest, most transparent possible labelling. But here technical languages might drive the consumer away, and scant information may lead to misuse and even rejection of the product itself. For instance, it is going to require regional language differences and regulations from different countries to complicate the attempt to come up with globally standard labelling protocols (Moreira et al., 2021).

7. ADDRESSING REGULATORY GAPS AND CHALLENGES

The proposed actions to bridge these gaps and standardize edible packaging regulations include:

1. Global Harmonization of Standards

International organizations like Codex Alimentarius need to establish universal definitions, test methods, and labeling for edible packaging.

2. Unified Protocol for Testing

The collaboration will help regulatory bodies develop common methods for migration and toxicological testing, establishing a level playing ground for manufacturers from any part of the world.

3. Consumer Education Enhancement

Public awareness campaigns combined with easy-to-understand labels would help consumers accept edible packaging.

4. Innovation on a Continuing Basis

Advances in carbohydrate polymer technology and ingredient safety can cure differential acceptability of materials and help attain global harmonization in regulations.

By reconditioning across these gaps, edible packaging can work as a sustainable and acceptable alternative to conventional packaging materials across the board.

8. GLOBAL HARMONIZATION OF STANDARDS

8.1 Need for Universally Accepted Definitions and Safety Protocols

The growing appetite for edible packaging as a green substitute for the otherwise usual packaging materials demands the immediate establishment of universally recognized definitions and safety procedures regarding the invention. The absence of such global standards places requirements on manufacturers, policymakers, and consumers as the actualization of development, registration of approval, and actual adoption of the innovative material becomes difficult (Lacourt et al., 2024b). Thus, a comprehensive and universally accepted framework is critical to ensure safety, innovation, and world adoption of edible packaging (Nair et al., 2023).

There is no simple, unified definition of "edible" for purposes of packaging. Regions interpret the concept according to their regulatory priorities and consequently inject ambiguity into the development and approval processes themselves (Nair et al., 2023). Thus, for some definitions, "edible" is purely functional: it serves as an extension of food; for others, it is an extension of the food as a protective layer with

the additional feature of consumption. This inconsistency in the definitions gives rise to evaluations and approvals of materials undertaken with a focus on the fact that some packaging components may be partially or conditionally edible (N. Kumar et al., 2023). The universal applicability of terms such as sensory acceptability, functional integrity, and safety will go a long way in formulating a basis upon which regulatory and consumer expectations could be established on a "baseline edibility" framework (Hamed et al., 2021).

Safety protocols concerning edible packaging are inherently different between the regions because they themselves have further dependencies with the scientific methodologies and regulations concerning them (R. K. Gupta et al., 2024b). Studies on migration, which assess the transfer of specific substances from packaging into food, are the foundational stones on which safety evaluation tests were built. These tests, however, are non-standardized in the world, which means that different safety 'thresholds' exist (Alamri et al., 2021). Some frameworks of regulations may dwell on very low migration limits and stringent toxicological studies, while others allow broader interpretations of a safe exposure level. The consequence of all this is not only the complication on product development but also the restriction in edible packaging materials trade across borders (Thapliyal et al., 2024). In addition, the use of natural biopolymers and functional additives brings to the surface additional challenges posed by such materials in terms of possible microbial contamination, potential allergenic responses, or unintended chemical interactions. Well-defined testing protocols for short and long-term safety shall bring in necessary standardizations on these subjects.

Another huge gap is found in the mismatch in labelling requirements. Proper labelling is necessary for making a distinction between edible packaging from traditional materials, as well as providing the necessary cues to consumers (S. Taylor et al., 2024). It is surprising, however, that current regulations do not give clear indications on how the edible nature of the packaging is made known. This leaves room for ambiguity and possible misuse. For instance, a consumer could assume that the consumption of the packaging material does not have adverse effects on oneself. Besides, regional differences in labelling practices add loads to these problems. Such diversity in

ingredient disclosure and allergen labelling creates a rather inconsistent consumer experience. A global framework for labelling, with a touch of both transparency and simplicity, would close this important gap and engender high levels of consumer confidence (Atta-Delgado et al., 2024).

Innovations also choke because of the lack of universally accepted definitions and protocols. Manufacturers now face the insurmountable challenge of navigating a slew of sometimes contradictory regulatory scenarios; the quite overwhelming experience further discourages investments in new technologies. Without clear guidelines, the development of new materials drastically slows down and their potential in the market is reduced. It directly affects consumer confidence since regulations from one country to another tend to make it difficult to assure the safety or effectiveness of edible packaging on a global scale (Thapliyal et al., 2024). In addition, products approved in one region, according to the parameters defined and referenced by that region, will be unable to satisfy the requirements of others and will, therefore, be robbed of market opportunities. This is a trade barrier.

International collaboration is also a solution. This means that organizations like Codex Alimentarius in partnership with regional regulation should take necessary actions in defining "edibility" and formulating full safety norms crossing regions. These would also include uniform testing procedures that imitate real-life situations to verify that safety evaluation is done in the same manner regardless of geographical location. On top of that, worldwide agreement into labelling practice, together with consumer education initiatives, will improve transparency, thus paving the way for acceptance of edible packaging as a viable alternative.

A globally harmonized framework for edible packaging would thus not only hasten regulatory processes but also potentially open up avenues for innovation, trade, and sustainability. Edible packaging should then be more than just a theoretical concept; it should be a feasible and well-accepted solution to reduce environmental waste while ensuring food safety and integrity. The first of these baby steps toward the vision is the creation of universally accepted definitions and safety protocols.

8.2 Recommendations for Standardizing Testing and Labeling

No universal standards prescription tests or labels for edible packaging products have formed a serious hindrance to adoption and public trust. Among the most important challenges to be addressed in adopting methods are calling for concerted efforts in creating standards that will characterize safety, usefulness, and openness in the promotion of innovativeness and market growth: recommendations towards developing a globally harmonized framework for testing and labelling edible packaging materials.

1. Create Universal Protocols for Testing

Testing protocols on the efficacy and safety of edible packaging should be harmonised for different regions. These protocols have to address the unique considerations and challenges of testing edible materials with the concomitant variability in regulations.

1.1 Migration and Interaction Studies

Develop standardized methodologies for studying the migration of chemical substances from food contact materials into food under real-life conditions, taking into consideration factors like temperature, pH and storage duration. Harmonizing migration limits across the globe would therefore cut down differences in safety evaluations.

1.2 Toxicity and Allergen Testing

Longitudinal toxicology studies are needed to understand long-term safety with respect to edible packaging. Packaging made from novel biopolymers or with additives will require protocols for allergen testing to successfully identify and mitigate possible risks from protein-based materials like casein or gluten.

1.3 Contamination of Microbes and Shelf-life Studies

Since most edible materials are perishable, the study would involve assessing microbial load and antimicrobial activity. The shelf-life study would evaluate both the packaging and the food products for compatibility and safety with time.

1.4 Functional Property Tests

Common tests should measure mechanical strength, barrier properties (moisture, oxygen,

and oil resistance), and sensory properties, such as taste and texture so that food packaging can be functional and accepted by consumers.

2. Develop universal labelling standards worldwide

Effective and good labelling will portray the specific attributes of use-safe edible packaging, along with persuasive communication by it to the consumer. The global agreement on labelling could eliminate confusion and contribute to transparency.

2.1 Common and Consistent Terminology

Edible, which is also safe for consumption, should be denoted using widely accepted terms. Terms such as edible film or consumable wrapper should be generally defined and provide explanations as warranted.

2.2 Ingredient Disclosure

Every element within edible packaging is to be declared on the label, including additives such as antimicrobials, antioxidants, or flavourings. It would then give transparency and a window for the consumer to make informed decisions, especially for individuals with certain eating restrictions or allergies.

2.3 Usage and disposal directions

Labels should instruct consumers adequately about the use for which the packaging is meant, including consumption or disposal guidance. For instance, some edible material that serves as food wrap would have specifications for handling it safely, which guarantees the condition.

2.4 Allergen Warnings and Safety Information

There should be mention of possible allergens and safety notifications regarding the material. For example, if it has protein-based films such as whey or soy, then allergen warnings must be included in the package.

2.5 Communicating the eco-friendly message

Labels must carry reflected messages such as biodegradability and sustainability as part of the environmental benefits of edible packaging: these will also be part of larger shifts in consumer education and awareness, generating adoption.

3. Foster International Collaboration

The above-stated points form the backbone for collaborative effort in global standardization with reference to regulatory bodies and industry stakeholders, as well as scientific organizations. Some major initiatives are:

3.1 Guidelines of the Codex Alimentarius

The international standards related to tests and labelling of edible packaging materials have to be developed by the Codex Alimentarius Commission. This will help national regulatory agencies, as guidelines will be put to their use.

3.2 Harmonization of Regional Regulations

Regulatory agencies such as FDA (USA), EFSA (Europe), and FSSAI (India) should align their requirements for edible packaging to eliminate barriers to trade and facilitate market entry for manufacturers.

3.3 Supporting Research and Innovation

The governments and all industry consortia need to have significant investments in research to fill the gaps between testing methodologies and labelling practices. This can further hasten the speed of the efforts to come up with common treatments of the protocols and innovative materials.

4. Enhance Consumer Awareness

Educational campaigns must accompany standardized testing and labelling to create consumer confidence in understanding edible packaging. Such campaigns may include:

1. The safety and benefits of edible materials;
2. Proper handling and consumption of edible packaging;
3. The environmental advantages that biodegradable and edible alternatives would bring.

8.3 Role of International Organizations

International organizations have a major role in promoting the development and adoption of edible packaging; they have the potential to provide truly global standards and resolve cross-border issues. The Codex Alimentarius Commission is one among other bodies such as the Food and Agriculture Organization (FAO) and

the World Health Organization (WHO), which should, among other things, bring coherence in regulatory frameworks while nurturing innovation and ensuring public safety and health (Lupien, 1997).

The greatest value, nevertheless, that these international organizations represent for national regulatory authorities is the harmonization of their guidelines into standard references. Codex Alimentarius, for instance, is an international collection of standards for food safety and quality that specifically includes those for packaging materials in direct contact with foods. Although edible packaging is still quite novel, Codex's general principles on food safety and labelling could be invoked to develop the future regulations governing it. Thus, they help reduce differences in national standards so as to promote trade in edible packaging materials and products internationally (Lee et al., 2021).

It is the bridge of such international organizations between the developed nations and the developing nations to ensure joining the advancements in edible packaging by all the regions. They exchange knowledge and build capacities to have limited resource countries employ sustainable packaging solutions. For example; the FAO is right now promoting through technical assistance, funding, and training programs to member states, many sustainable practices within food systems (Mekouar, 2017). Innovative concepts such as edible packaging fall under this umbrella. This initiates global adoption while also solving the environmental and economic constraints of conventional packaging materials.

Promoting collaborative research and innovation is another core role played by international organizations. They bring together researchers, industry leaders, and policymakers to jointly address the technical, safety, and regulatory aspects of edible packaging (Muncke et al., 2020b). For instance, the WHO may offer suggestions on the health impacts related to the consumption of packaging materials, further contributing to the creation of safe and efficacious products. Cooperative projects undertaken under such organizations create breakthroughs in technologies and generally accepted practices worldwide (Lacourt et al., 2024).

In addition, they work with international organizations to facilitate consumer education

and awareness. Credible evidence, in addition to the use of international campaigns, however, tends to build public confidence in edible packaging. Such activity appears particularly crucial for those societies that encounter consumer resistance in the use of edible materials for safety or practical reasons (Horská et al., 2021). Thus, the guidelines from the Codex Alimentarius for food labelling can be used as a model for clear and informative labelling of edible packaging to help users make informed decisions.

More importantly, these organizations will account for the environmental dimension. They will push hard on sustainability, and clearly, the need is urgent to control plastic waste as one of the possible solutions to this concern. Then, international organizations also advocate policies and practices that respond to the collective interest in sustainable development concerning the global goals committed by the United Nations under the Sustainable Development Goals (SDGs) (Thapliyal et al., 2024). For example, by reducing the further use of single-use plastics and promoting biodegradable products, edible packaging can become part of an excellent strategy against environmental degradation (Petraru & Amariei, 2023).

9. CONSUMER PROTECTION AND MARKET READINESS

Consumer protection becomes a priority in the formulation and domestication of edible packaging. It is accompanied by the strictest requirements as to labels. Clear and straightforward labels become increasingly informative with regard to the specific ingredients that have been used in their formulation, such as their allergenic potential or adverse health effects. Proper labelling would thus permit informed decisions by individuals subject to specific dietary restrictions or allergies (Bauer et al., 2023) while increasing trust in edible packaging products; such labels should also include usage, storage, and disposition instructions for convenience.

The manufacturing process should be open and understandable for establishing confidence with consumers. People want to know the exact method of which their product has been made, where has all the raw material been taken from, and what the environmental impacts were during production. It brings in the information on sourcing biopolymers, additives' usage, and

safety measures at the production stage, to represent edible packaging (Wu et al., 2021). Such transparency would instil a sense of trust and also help in addressing some questions surrounding food safety and the ethical implications of production (Lam et al., 2020).

Initiatives on education and awareness would have a profound effect on making consumables market-ready, for edible packaging is a term most consumers have yet to learn about, leaving them suspicious or unwilling to use these products (Taylor et al., 2024b). These gaps can be bridged through targeted campaigns, workshops, seminars, and other stakeholders, thereby emphasizing sustainability, safety, and convenience (Cheek & Wansink, 2016d). Ultimately, understanding can be enhanced and harnessed to become the driving force to convince a consumer in favour of a more conducive environment for market penetration.

10. SUSTAINABILITY AND ECONOMIC IMPLICATION

There are multiple issues connected to sustainability and economics with regard to edible packaging. These include environmental benefits and future challenges regarding the scalability of production and access to markets. The world is shifting towards eco-sustainable practices; thus, edible packaging may become a future possibility for materials that substitute existing forms, more promisingly for food items (Nair et al., 2023). Environmental benefits tend to be obvious; however, an economic assessment for large-scale production and market penetration must look into the production processes, their cost structure, and opportunities for small-scale producers (Hamed et al., 2021).

1. Comparative Environmental impacts

The greatest virtue of edible packaging over conventional formats of plastic packaging is its minimization in pollution and natural resource saving. Conventional plastics are by far the most polluting materials of all and, especially, petroleum-based plastics are highly polluting and often produce long-lasting environmental degradation (Hasan et al., 2020b). Non-biodegradable: buried on land or in oceans; they have been living under such conditions for several hundred years and are generally causing destruction to the ecology-more so to marine life. Whereas edible packing materials are largely made from biopolymers, generally consisting of

polysaccharides, proteins, and lipids, which are produced using renewable feedstocks in replacement of fossil fuels.

And to be most clearly seen, biodegradable food packaging is nature-recyclable or biodegradable. It is, in fact, made from edible materials that completely decompose within natural environments, without leaving any sort of hinter residue or harmful waste. For this reason, this becomes highly relevant in battling plastic pollution: microplastics are accumulating in many ecosystems and entering food chains, risking wildlife and human health alike. While edible packaging, depending on its material composition, can probably decompose within weeks or even months, traditional packaging usually does not leave so many lies or none at all on the environment (Shaikh et al., 2021). Besides, edible packaging may be eaten together with the food item it 'protects' or may be composted for removal and decoupled from the traditional waste management system in favour of circular economies (Marzantowicz & Wieteska-Rosiak, 2021).

They come with their own advantages and disadvantages, such as the challenges associated with the production of edible packaging. Although biopolymer management films use less carbon footprint than plastic production, they, like plastics, require land and water resources, and this may bring about competition with food crops or high water usage in agriculture (Cruz et al., 2022). The environmental sustainability of this edible packaging thus rests on what particular agricultural methods were implemented in source material harvesting: it is, therefore, important to consider things like the rotation of crops, the use of pesticides, and land management practices. Thus, edible packaging presents a chance for rethinking agricultural by-products as productive materials rather than wastes to stimulate sustainability (Valle et al., 2024). Intensive agricultural practices potentially among one of the drawbacks of the approach must not be overlooked, however, for potential environmental disadvantages.

2. Possibilities of Large-Scale Production and Market Entry

Globally, edible packaging has an inbuilt environmental advantage but whether it is economically viable on a large scale remains to be seen. Mass volume production would require

such large-scale infrastructure investments, especially agricultural sourcing, processing facilities, and distribution networks. Innovations in production methods or supply chain management may well prove to decline the cost of production, making it feasible for scaling (Chalermthai et al., 2023). Edible materials are still considered undercut economically when compared to conventional plastics because of the high raw material costs and rather complex processes required for production (Nair et al., 2023a). This will limit the large-scale adoption of edible packaging in price-sensitive markets.

On the other hand, large-scale constraints also call into question the sourcing of raw materials directly related to edible packaging with respect to biopolymers that originate from agricultural crops and are required at certain volumes which can be procured at low costs. Therefore, any dependence on crops for biopolymer production raises a disruption chain such as climate change-induced yield variations, crop disease, and geopolitical considerations (Perera et al., 2023). The competition created along these lines would further complicate the chances of having materials that can be used for large-scale production of edible packaging.

Progress in extrusion, film-forming techniques, or the introduction of new raw materials, such as algae or agricultural waste, should allow for lowered production costs while boosting scalability in edible packaging applications (Nair et al., 2023). Further development in more cost-effective processing techniques might ultimately lead to edible packaging's environmental and economic feasibility, thus making it more accessible in capacity at some further point down the line as an alternative to plastic packaging in world markets (Cristofoli et al., 2023).

3. Economic Opportunities for Small-Scale Manufacturers

If it is the making of edible packaging, rather unlike large-scale manufacturers, such producers will stand to benefit highly from this emerging market. Small-scale manufacturers will be able to market the emerging demand for sustainability as well as greener alternatives in markets, especially local and niche markets. These companies can now concentrate on manufacturing edible packaging materials that are premium, customized for artisanal food products, upcoming local restaurants, and specialized food producers that want

sustainability. Small manufacturers can invariably be able to adapt rapidly to their clients' varied buying patterns, thus providing flexibility and innovation in product designs (Nair et al., 2023).

One of the net economic advantages granted to small-scale manufacturers is that they can incorporate sustainability in their business models from the beginning. Hence, more small businesses are in a position to have direct control over their supply chains and production processes, which enable them to source raw materials locally or from waste streams (Drejerska & Sobczak-Malitka, 2023). All this has even reduced the costs and brought forward circular economies. For instance, agricultural by-products or food waste can prove to be promising bases for packaging materials for small-scale manufacturers as they can add value to discarded resources. This would keep down costs of production and thus respond to consumer trend toward products that fulfill an environmental conservation demand.

It gives an edge for segmentation in the market wherein more environmentally conscious and health-aware consumers can be targeted (Janjarasskul & Krochta, 2010c). Eco-, health-, and perhaps even vegans-, gluten-free, or organic-packaging options in edible packing can be imagined and produced by small-scale manufacturers and encourage them to explore new niche markets. The increasing awareness of local sustainable food has made small-scale edible packaging businesses much more viable (Nair et al., 2023).

Some hurdles that small-scale producers have to overcome include competition in the market, access to capital, and regulatory obstacles; establishing a reputation as a brand in a cut-throat market and achieving compliance with food safety regulations are likely to be made more difficult for smaller companies with limited resources (J. J. Jeevahan et al., 2020e). A collaboration with big companies and allying with strong innovation hubs and sustainability initiatives may provide the very valuable opportunities for small but aspiring manufacturers to penetrate markets and increase economic viability.

11. RESEARCH AND INNOVATION NEEDS

Research and innovation are the only determining factors for one to be really optimistic

about the actual potential of edible packaging. It calls for a lot more sustainable and environment-friendly alternative materials because with that comes a lot more increased demand and also need for innovations in materials science as well as production methods besides needing new technology requirements to guarantee properties in edible packaging, scale up processes for serious mass production, and comply with regulatory requirements.

It's supposed that "nanotechnology" could be one of the best interventions in ameliorating the properties of edible packaging materials. The incorporation of nanomaterials like nanocellulose, nanoparticles, and nanoclays could have an enhancing effect on mechanical flexibility and barrier properties of edible films and coatings (Espitia and Otoni 2018). Thus, yield benefits similar to better environmental stresses, longer shelf life, and better regulations of moisture, oxygen, and light supplements among other aspects. Besides, nanomaterials may also provide an opportunity for designing edible sheets with better resistance against microbial contamination that can thus replace existing packing methods with a safer and long-lasting product. However, further studies should be implemented to verify safety issues in the ingestion of these nanomaterials since it has been proven that health risks from these materials in consumption are still undetermined.

One more innovative advancement has happened in the area of edible sensors and traceability systems using biodegradable materials. These sensors can be placed inside edibles to check the quality, freshness, and safe status of food products. Edible sensors will detect the changes in temperature or pH as well as pathogenic microorganisms and will, therefore, give real-time information regarding health about food (Ilic et al., 2022). In this regard, technology has to improve safety and traceability through supply chains since it will serve as a much more efficient way of tracking food from "farm tables". Such integrated traceability systems will address even the concerns of consumers about the authenticity, origin, and sustainability of food, making food all the much transparent (Kumperščak et al., 2019).

As a matter of fact, edible packaging is obviously eco-friendly; however, one of its major hindrances to wide adoption is scale-up production. Edible packaging is labor-intensive and expensive during production and thus does

not compete with mass-produced plastic products at present (J. J. Jeevahan et al., 2020e). Exploring how to scale up production most cost-effectively for bona fide edible packaging, from processing enhancements to robotic production line design and finding cheaper, more available raw materials, is a current initiative. Most crucial, however, is the research into the possibilities of integrating newer agricultural by-products or wastes currently in production processes to bring production costs to more attainable, economically viable targets (Hamed et al., 2021b). Finally, scalable production technology and integration into supply chains will be needed to meet the worldwide demand for edible packaging in the long run without compromise.

There is still much development and advancement in edible packaging that will necessitate more research and innovation in nanotechnology, biodegradable sensors, and scalable production methods (Mustafa & Andreescu, 2020). All these critical strides will not merely improve edible packaging materials but increase their functional-economic capacities, rendering them more attractive to industries and consumers alike (Nair et al., 2023).

12. STRATEGIC INTERVENTIONS

Regulatory frameworks, safety standards, innovation, and commercialization pathways strategic interventions will successfully integrate edible packaging components into the global market with a wider acceptance. This can best be achieved when it is collectively handled by all governments, industries, and academia into an integrated and influential developmental framework to boost innovation and public trust in the solutions from edible packaging (Thapliyal et al., 2024).

1. Framework for Regulatory Collaborations

This is one of the strategic interventions that need to be considered: establishment of a collaborative framework between governments, industries and academic institutions. These efforts should bring all key stakeholders to benefit from the regulatory bodies; just as one would expect FDA in USA, EFSA in Europe and FSSAI in India, among others, to be closely associated with food manufacturers, material scientists and research organizations on edible packaging for compliance with safety and quality standards. Incentives for research, funding

innovation, policy support for sustainable alternatives in packaging, and a regulatory institutions framework to produce and market edible-packaging products are the major roles that governments can play in the development process. The institutions are able to play their part from the picture of building on frontier research in edible packaging properties, testing new materials for applications, and developing technologies producing efficiency (Gheorghita et al., 2020b), (Petraru & Amariei, 2023).

Through collaboration, these stakeholders can provide guidelines, regulations, or frameworks that accompany, encourage and allow the development of edible packaging and its incorporation into global food safety and packaging regulations (Gheorghita et al., 2020c). Such frameworks would address food safety, production methods, labeling requirements, and environmental impacts. They would also allow harmonizing standards across regions, which would be crucial for the global scalability of edible packaging solutions (Petraru & Amariei, 2023).

2. Universal Safety and Labeling Protocols Development

Initiatives towards the development of a universal safety and labeling protocol are eminently vital to enhancing consumer confidence and promoting industry appropriation (Díaz-Montes & Castro-Muñoz, 2021b). Ensuring clear and standardized safety protocols would require meeting a range of stringent food safety criteria such as freedom from harmful chemicals, allergens, or toxic residues for qualifying edible packaging materials. It calls for close collaborations among regulatory agencies, food scientists, and manufacturers in the development of methodology for testing safety and quality of edible packaging materials in their lifetime cycles from production to consumption (Nair et al., 2023f).

In a similar context, development towards unified standards for labeling that articulates clearly how edible packaging benefits consumers in terms of safety as well as the environment would be equally imperative (Nair et al., 2023a). Boosted transparency and accuracy in labeling shall then help consumers make choices about edibility, biodegradability, and nutritional content. Little concern would be needed in relation to duration, disposal, and allergic reactions, and the concern would about consumers' acceptance. Universal

labeling standards complying with international regulatory bodies can be established to avoid conflict and foster market opening of edible packaging for the benefit of consumers and producers alike.

3. Future Roadmap for Innovation and Commercialization

To develop a large-scale leveraging model for the edible packaging industry, there needs to be a clear roadmap for the future innovations and their commercialization (D. Gupta et al., 2024). In this blueprint, short- and long-range specific goals for technological development, markets, and regulations should be conflicted. The benefits of developmental improvement should include those that give additional profit margins for the manufacturers in production processes through scalability (Nair et al., 2023). This means that it would be in part of the joint efforts of researchers and manufacturers to mechanize production methods for cost-cutting, efficiency increase, and properties enhancement, such as by changing the raw material to agricultural by-product, algae, and new methods of production with the consideration of large-scale operation.

There is a need for identification and market development in edible packaging where these would clearly offer consumer value over other alternatives (Janjarasskul & Krochta, 2010b). Their prime market would be foods and beverages in products that require preservation because they are dented. Further applications could cover pharmaceuticals or cosmetics that might want to rely in part on edible packaging to cover topical applications or ingestion of a product. The framework of commercialization should address market access barriers, pricing models, consumer education, and distribution networks, careful not to overlook any factors that impede extensive distribution and acceptance of edible packaging (Nair et al., 2023).

13. CONCLUSION

This study appears to show how far edible packaging has progressed over existing plastic systems. Earlier and above all which are based on the concern for the environment with regard to plastic pollution, much more developing funding is needed for 'greener' packaging alternatives. Edible packages are future sustainability benefits that go beyond biodegradability and waste reduction. Edible packaging is made from biopolymers such as polysaccharides, proteins,

and lipids, creating significant environmental benefits through biodegradation and waste reduction. Edible packaging materials can be integrated with functional additives that have antimicrobial substances and antioxidants. Under such conditions, these materials can deliver a shelf life and safety advantage to a food product as well as being cost-effective as an alternative packaging method. Edible packaging, however, potentially offers benefits but is in competition against regulations, safety, scalability, and also consumer acceptance for potentiality.

The need for developing robust safety and regulatory frameworks towards food-contact materials safety and effectiveness has been evidenced by the findings. This presented the many-faceted partnerships, for instance, between governments and regulatory agencies and industry and academia, to create universally accepted safety standards and labelling protocols for edible packaging; therefore, there would be high-intensity food safety criteria. Above all, such developments tend to attract innovations bringing more functional properties into edible packaging, scaling up to mass production, and reducing costs. These create new avenues for overcoming such hurdles and improving the performance of edible packaging through advances in nanotechnology, biodegradable sensors, and alternative raw materials.

The future of edible packaging, forward-looking-wise, should be marked with a clear pathway along which it should walk. Such a pathway should include avenues for more research into edible packaging, expanded capability in production, and across-market accessibility. There should also be the fostering of global collaborations to build a harmonized regulatory environment for edible packaging; this will help seal all efforts toward the widespread use of edible packaging and harmonize its application with sustainability goals of lessening the environmental impact of packaging waste. It will revolutionize the packaging industry by encouraging sustainable practices and technological innovations and lead towards a better future.

In sum, edible packaging would be a very giant step toward global environmental sustainability goals. Strategic partnerships with continuous research and innovation, as well as the establishment of a sound legal framework for regulation, could allow edible packaging to

become a viable and widely adopted alternative to traditional plastic packaging. This would improve the safety, scalability, and acceptability of edible packaging, which would very well transform the packaging industry and reduce environmental waste, leading to a sustainable future for unborn generations.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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