

degradable and recyclable (Gil & Rudy, 2023). In the meat processing industry, traditional packaging materials such as synthetic foils are commonly used, often in combination with cardboard outer packaging. The most recurrently employed synthetic plastics for meat packaging include polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyester (PET), polyamide (PA), polyvinylidene chloride (PVDC), and ethylene vinyl alcohol (Cenci-Goga *et al.*, 2020). However, the extensive usage of these materials has resulted in serious environmental issues, for instance, natural resource depletion, pollution, and global warming, as they are both non-renewable and non-degradable (Song *et al.*, 2023). As a result, efforts have been focused on developing sustainable packaging materials and methods of production in the food industry (Meherishi *et al.*, 2019). On the other hand, incorporating natural bioactive substances into packaging offers an opportunity to prolong the shelf life of meat products and reduce the need for direct food preservatives. These active components interact with the packaged food or the surrounding environment to extend its shelf life by preserving its quality and safety. Compared to traditional packaging, the use of active compounds further extends the shelf life of food products by reducing harmful effects during storage, such as

oxidation, microbial growth, and moisture loss (Bharti *et al.*, 2022).

Meat forms a significant part of the modern diet across the globe due to its nutritional value (Umaraw *et al.*, 2020; Arya, *et al.*, 2017). It is a rich source of essential amino acids, essential fatty acids, and various vitamins and minerals (Bharti *et al.*, 2020). However, the presence of such nutrients makes meat highly susceptible to deterioration. The deterioration of meat products during processing, distribution, and storage has considerable environmental and economic implications for the industry (Bharti *et al.*, 2011). Changes occurring during meat storage include protein oxidation, lipid oxidation, and an overall increase in metmyoglobin content (Chulayo & Muchenje, 2015). Lipid oxidation in meat is the primary cause of damage and quality loss in meat and meat-related products. Oxidation limits and reduces the storage life of meat products, leading to rancidity, the formation of toxic compounds, and nutritional value losses due to the degradation of fatty acids (Bharti *et al.*, 2017a). Controlling the oxygen concentration in meat packaging is crucial to slow down these damaging reactions and decay. The spoilage of raw meat is caused by specific spoilage organisms that produce metabolites, resulting in unpleasant taste and odor, ultimately decreasing consumer interest in meat products (Pellissery *et al.*, 2020).

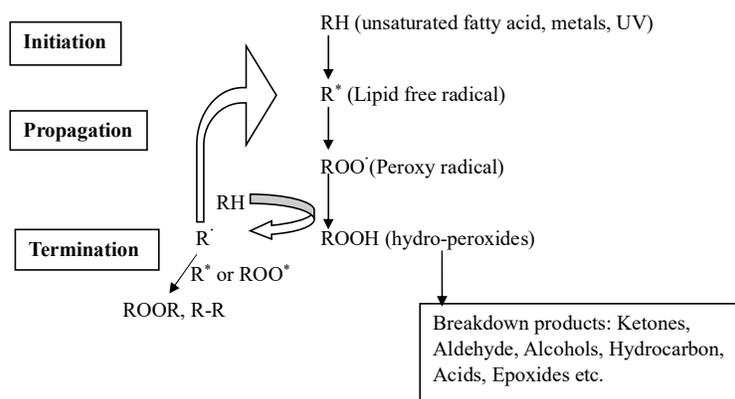


Fig. 1: Auto-oxidation of meat (Bharti *et al.*, 2017a)

Comprehension of edible packaging

The use of natural and renewable biopolymers in packaging is becoming more popular due to their lack of environmental issues compared to petroleum-based plastics. Edible films must contain substances compliant with food regulations and be cost-effective, easy to use, and environmentally friendly. Hydrocolloids (polysaccharides and proteins), lipids, and composites are the three main structural materials used to classify edible

films (Bharti *et al.*, 2020). There is a jeopardy of contamination for edible packaging, which could render them inedible, although they are inherently biodegradable if not consumed. Polymers are favored for food packaging due to their edibility and safety for humans (Gumienna & Górna, 2021).

Cellulose, the most abundant biopolymer globally, is a superlative raw material for sustainable packaging. Cellulose ethers, such as methylcellulose, hydroxypropyl cellulose,

hydroxypropyl methylcellulose, and carboxymethyl cellulose, are suitable for producing packaging films. Cellulose is derived from various natural sources like wood, cotton, food waste, agricultural waste, cereal bran, and fruit peels. Its widespread availability, biodegradability, eco-friendliness, and affordability make cellulose a preferred material for packaging. In addition to being edible and biodegradable, cellulose's sensory properties are advantageous, making it suitable for encapsulating bioactive substances.

Starch is a crucial biodegradable polymer due to its abundance, cost-effectiveness, biodegradability, and renewability. Starch-based films have been widely utilized in food packaging and preservation due to their excellent film-forming ability, and unique gelatinization properties, and

are odorless, tasteless, and colorless. Despite their good organoleptic and gas barrier properties, starch-based materials are brittle and hydrophilic, restricting their processing and use.

Chitosan, a biopolymer derived from chitin, is an alternative option. Chitosan films have demonstrated effective antibacterial and antioxidant properties in meat food packaging. The structure of chitosan, with its amino and hydroxyl groups, influences its antimicrobial activity against both gram-positive and gram-negative bacteria. Chitosan-based films offer a strong gas barrier, but their brittleness eliminates the need for plasticizers. Gelatin, a water-soluble natural polymer, is a biodegradable, biocompatible, commercially available protein.

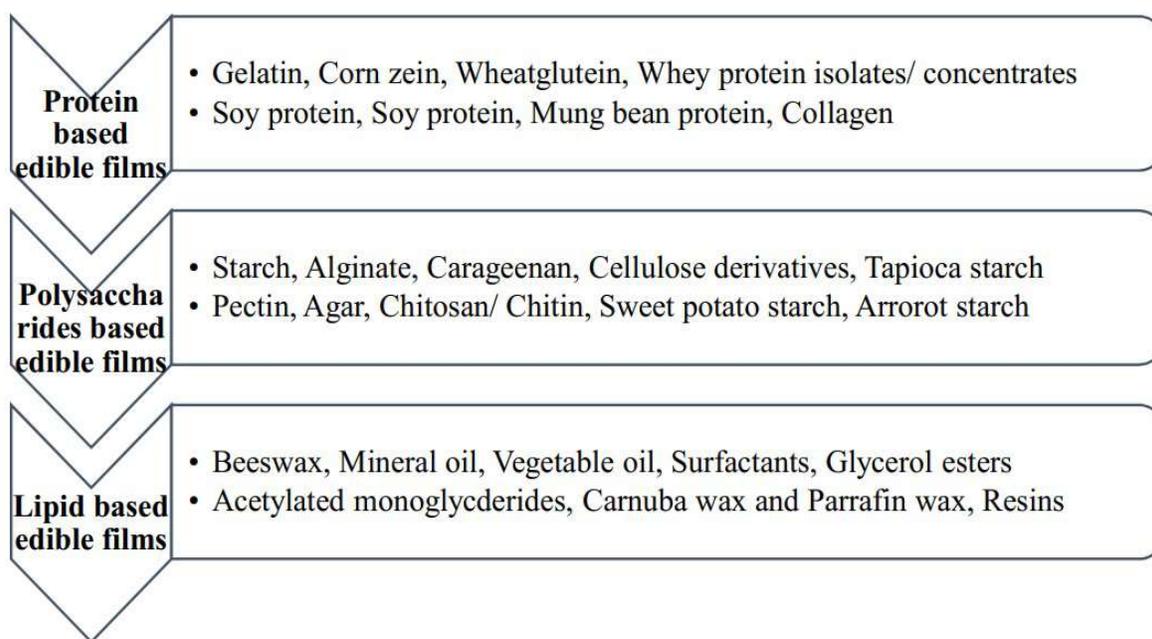


Fig. 2: Classification of edible packaging material

Composite films

An updated approach to edible and biodegradable film technology involves creating composite films by blending various polysaccharides, proteins, and lipids to enhance their functionality (Shaikh *et al.*, 2021). These composite films can be tailored to produce a combined effect of the individual properties of the pure components. However, similar to synthetic polymers, the mechanical and barrier characteristics of composite biofilms heavily rely on the attributes of the constituent polymers and their compatibility (Bharti *et al.*, 2021).

Nanocomposite films

The incorporation of nanomaterials such as inorganic nano compounds, nanofibers, and nanotubes into biopolymer-based edible films and coatings has a notable impact on enhancing their physicochemical, mechanical, barrier, and thermal properties (Zibaei *et al.*, 2023). Nanoscale fillers, including laponite, montmorillonite, sepiolite, palygorskite, nano-SiO_{2-x}, nano-ZnO, nano-oxide, and nano-TiO₂, exhibit characteristics such as reduced size, large surface area, high aspect ratio, and heightened surface energy (Dash, Ali, Das, &

Mohanta, 2019). Similarly, nanocrystals, nanofibers, starch, chitin, and cellulose-based whiskers possess properties akin to nanoscale fillers. The addition of nanomaterials to biopolymers like proteins and polysaccharides enables their dispersion into the polymeric chains, leading to the enhancement of their physicochemical properties and mechanical strength.

Edible film production

The process of producing edible films can be categorized as dry or wet. During the dry process, edible films are made using methods such as heat pressing, extrusion, and molten casting without the use of liquid solvents like water or alcohol. In this method, heat is used to raise the temperature of the biodegradable materials above their melting point

to shape them. Therefore, it's essential to know the thermoplastic properties of the raw materials to design the manufacturing process for edible films. On the other hand, the wet process of edible film production involves using solvents to dissolve the raw materials. After that, the solvent is removed through drying to create the edible film structure. The choice of solvent is crucial in this process due to the film's intended human consumption, and only water, ethanol, or their mixtures are employed as solvents. Initially, all the components of the edible film-forming materials are dissolved or evenly dispersed in the solvents to create raw material solutions. Subsequently, these solutions are applied to flat surfaces using a dipping roller, spreader, or sprayer, and then dried to eliminate the solvent, resulting in the formation of a film structure (Bharti *et al.*, 2022).

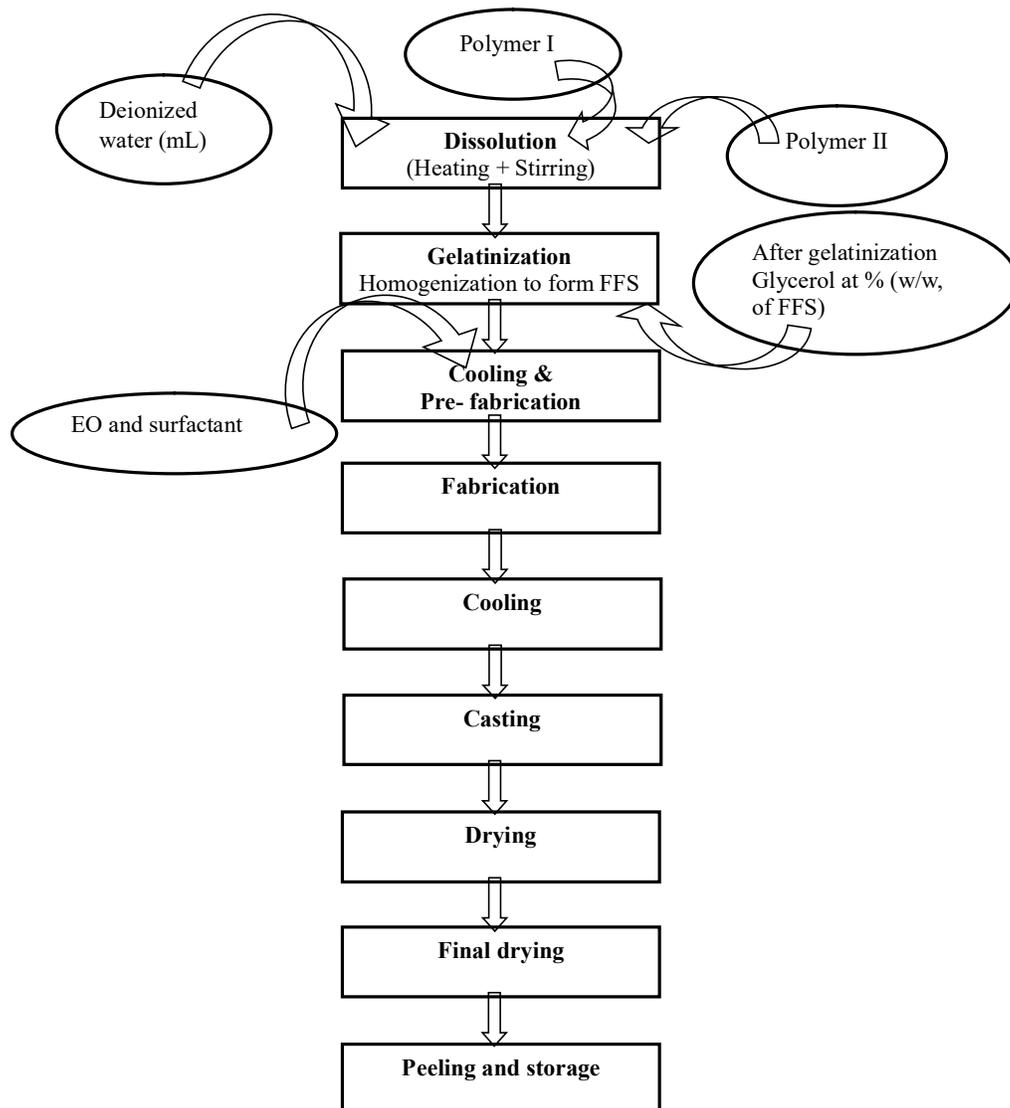


Fig. 3: Flow diagram of active edible film preparation

Essential oil

In recent times, there has been a growing demand for natural antimicrobial and preservative-free food packaging driven by concerns for food safety and health (Arya *et al.*, 2019). Essential oils (EOs) are vital natural products known for their antimicrobial, antioxidant, and antifungal properties due to their phenolic and bioactive components. They have been deemed safe for human consumption and approved by the United States Food and Drug Administration (US FDA) for use as additives and flavor agents in food and food products. EOs are commonly utilized in the food packaging industry to create antimicrobial packaging to combat various types of foodborne pathogens. Recent research has extensively explored the effects of EOs such as Clove, Anise, caraway (Bharti *et al.*, 2022b) tea tree, oregano, rosemary, garlic, thyme, lemon grass, sage, *Origanum vulgare L.*, lime, *Zatariumultiflora*, citral, clove, sunflower, Curcuma oil, basil oil, and orange peel on enhancing the physical, mechanical, and barrier properties of composite films by addressing identified weaknesses. Incorporating EOs into edible packaging allows for a controlled release of bioactive ingredients, aiding in the reduction of oxidation and masking objectionable aromas (Arya, *et al.*, 2017). Furthermore, EOs are used to develop antifungal coatings, particularly for fruits and vegetables, to minimize green and blue molds in highly perishable horticultural commodities. Additionally, integrating EOs as potential natural antimicrobial additives aims to enhance the properties of edible films/coatings and various food products including beverages, fruits, vegetables, milk, and dairy-based products (Bharti *et al.*, 2017b).

Active edible packaging on meat

In the construction of active packaging systems, significant advancements have been made through the use of various methods such as dip coating, layer-by-layer assembly, electrospinning, solvent casting, extrusion, and homogeneous emulsification. These technologies can utilize synthetic or natural materials and may incorporate active ingredients like antioxidants, antimicrobials, vitamins, flavors, and dyes (Nieto *et al.*, 2023). Functionalized packaging systems are a departure from traditional food packaging, as they are designed to incorporate various bioactive compounds into matrix materials. This can result in diverse biological effects such as antibacterial and antioxidant properties, providing protection from environmental factors for food products (Bharti *et al.*, 2022a). Active packages are created by integrating plant-based bioactive

materials into polymers, and essential oils have garnered attention as active ingredients due to their antimicrobial and antioxidant properties (Bharti *et al.*, 2022b). Additionally, antimicrobial solutions are integrated into edible films within active packages and are gradually released onto food surfaces in a controlled manner. This approach offers a potential alternative to directly applying antibacterials onto food surfaces, preventing slow permeation into the inner parts of the food (Amanatidou *et al.*, 1999). The effectiveness of these active packaging combinations in meat products has been observed in inhibiting the growth and activities of pathogenic microorganisms such as *L. monocytogenes*, *S. aureus*, and pathogenic *E. coli*. They have also shown promise in inhibiting food spoilage microorganisms in various meat and meat products as well as in fish and its products. Furthermore, the use of additional combined antimicrobial inclusions in food packaging is being explored due to their broad spectrum of activities against spoilage and pathogenic microorganisms (Becerril *et al.*, 2019). The use of antimicrobial packaging for solid foods continues to gain traction, despite various limitations to its commercial use in preserving liquid foods against microorganisms. These limitations include concerns related to food safety regulations, the lack of suitable antimicrobials for liquid foods, and certain compatibility issues with novel polymer materials used for packaging (Jin & Zhang, 2008).

Extract natural ingredients on active packaging

Various natural compounds with antioxidant properties have been extensively studied for their potential use as food preservatives. These compounds include flavonoids, phenolic acids, organic acids, and carotenoids, all of which can effectively inhibit lipid oxidation by scavenging free radicals, chelating metal ions, or quenching oxygen radicals. The application of various natural extracts in active packaging applied to meat has shown positive results. This approach has proven effective in reducing lipid oxidation in cooked turkey meat during storage and preserving its sensory characteristics. The improvement in tenderness observed in the meat samples packed with active packaging may be attributed to the reduction in lipid oxidation and the resulting changes in muscle structure due to the lower pH value. Extracts derived from mustard seeds, rambutan, garlic, and *Origanum vulgare* flowers have been demonstrated to prolong the shelf life of meat (Gharby *et al.*, 2022). The use of natural extracts as ingredients can serve as an alternative to chemical preservatives, especially in the preservation of meat products.

Antioxidant active packaging

The packaging agent with antioxidant properties is created by integrating a variety of active compounds into the structure of the polymer matrix or onto the surface layer of the polymer film. Active compounds commonly used include tocopherols, essential oils, and plant extracts derived from various plants. These compounds function by either absorbing oxygen from the storage space or releasing antioxidant content into the food or its surrounding environment. When producing active packaging materials with antioxidant properties, the antioxidant composition can be combined with polymer packaging materials through three methods: coating technology, extrusion technology, or immobilization. Studies have demonstrated that natural ingredients containing antioxidant compounds, such as green tea, rambutan, rosemary, garlic, ginger, and turmeric (Muthusamy *et al.*, 2024), have a beneficial effect on packaged meat samples, such as extending the meat's shelf life.

CONCLUSION

The incorporation of a variety of active compounds into the polymer matrix or onto the surface layer of the polymer film creates a packaging agent with antioxidant properties. Commonly used active compounds include tocopherols, essential oils, and plant extracts. These compounds work by either absorbing oxygen from the storage space or releasing antioxidant content into the food or its surrounding environment. Active packaging materials with antioxidant properties can be produced by combining the antioxidant composition with polymer packaging materials using coating technology, extrusion technology, or immobilization. Research has shown that natural ingredients containing antioxidant compounds over meat products are promising concepts and can be scaled up at the industrial level. However, identifying the microbes inhibited by different natural extracts used in active packaging is the main challenge in research on active packaging for meat.

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