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Crosslinking methods for improving the properties of soy-protein based films for meat packaging: a review

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ABSTRACT

Crosslinking methods have been used to improve the properties of soy protein-based films for various applications, such as meat packaging. Some of the crosslinking methods that have been reported in the literature include boiling soy milk, baking soy protein isolates, adding canola and sorghum proteins, incorporating Plantago major seed mucilage and Anethum graveolens essential oil, adding pine needle extract (PNE), incorporating montmorillonite and citric acid, using xylose as a crosslinker, and crosslinking with glutaraldehyde. The incorporation of additives such as canola and sorghum proteins, Plantago major seed mucilage and Anethum graveolens essential oil, and pine needle extract (PNE) has also been reported to improve the properties of soy protein-based films. In conclusion, soy protein-based films have excellent film-forming properties and many functional characteristics, making them a promising material for food packaging applications. However, their poor moisture barrier properties must be improved to make them more suitable for food packaging applications. Crosslinking methods have been used to improve the properties of soy protein-based films for various applications, such as meat packaging. The incorporation of additives such as canola and sorghum proteins, Plantago major seed mucilage and Anethum graveolens essential oil, and pine needle extract (PNE) has also been reported to improve the properties of soy protein-based films.

Keywords: Soy protein-based films, meat packaging, crosslinking, meat

INTRODUCTION

Packaging materials are widely used in the meat business to safeguard meat products from possible dangers such as infection, spoilage, and oxidation. On the other hand, traditional packaging materials, such as metals, plastics, and glass, have substantial environmental problems, such as poor biodegradability, high carbon emissions, and limited renewability **[1]**, **[2]**. Packaging materials have become a major concern due to their environmental impact. The accumulation of plastic waste in the environment has led to the need for sustainable food packaging. Despite safety concerns, the low cost of materials and functional properties of plastics have led to their continued use in food packaging. There is a need to critically evaluate the various materials used for packaging due to their environmental influence during production and after their end-of-life **[3]**, **[4]**, **[5]**.

Protein-based films and coatings have gained attention recently due to their advantages over synthetic films, including their use as edible packaging materials. Soy protein-derived films have evolved as an eco-friendly option for meat packing in response to these issues. These films, made from soy protein derived from soybeans by extrusion or casting, are renewable, biodegradable, and biocompatible. Soy protein-based films, on the other hand, have challenges with mechanical strength, thermal stability, and moisture resistance, limiting their applicability for meat packing applications. Crosslinking techniques for increasing the properties of soy protein-based films have been developed to overcome these limits **[6]**, **[7]**, **[8]**.

Figure 1 summerizes the scheme of different agent involved in meat packaging.

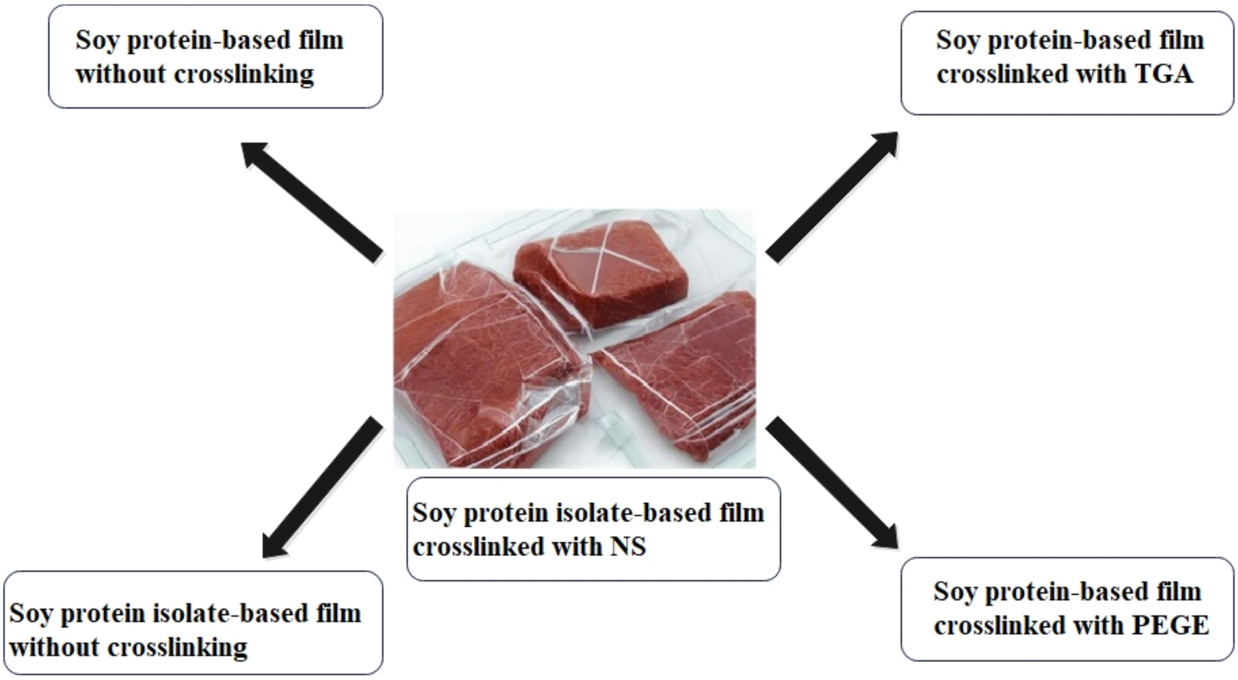

Figure 1 Scheme of different types of crosslinking agent (TGA – triglycidylamine; NS – nanosilica; PEGE – Pentaerythritol Glycidyl Ether).

Several methods have been adopted to enhance the strength of soy protein-based films, with crosslinking being one of the most commonly employed techniques. Crosslinking is widely recognized as an effective approach to improving the mechanical properties of these films. Crosslinking can reinforce the film structure and enhance its overall strength by creating chemical or physical bonds between soy protein molecules. Various chemical crosslinking techniques have been extensively investigated to enhance the performance of films derived from soy protein. Glutaraldehyde, a frequently employed crosslinking agent, is known for forming stable covalent bonds with the amino groups present in soy protein molecules. The process of crosslinking serves to improve the mechanical robustness, water resistance, and barrier characteristics of the films. Formaldehyde has been utilized as a crosslinking agent in various applications. However, its utilization is constrained owing to its potential safety and environmental risks. Genipin, obtained from the gardenia fruit, exhibits potential as a natural crosslinking agent, enhancing the film characteristics and reducing environmental impact. Polyfunctional acids, including citric acid and succinic acid, have been employed as crosslinking agents in order to develop a network structure that improves the mechanical and 7barrier characteristics of films **[7]**, **[8]**, **[9]**.

Physical crosslinking approaches present as a plausible method for enhancing the quality of films composed of soy protein. The application of heat treatment has been demonstrated to result in protein denaturation, facilitating subsequent reassembly, ultimately conferring enhanced film properties, including augmented tensile strength and attenuated water vapor permeability. The solvent evaporation process entails using volatile solvents for dissolving the protein and forming a film, which solidifies through the solvent's dissipation. This technique has the potential to enhance the mechanical robustness and hydrophobic properties of the film. The phenomenon of freeze-thaw cycles plays a crucial role in the development of physical crosslinks among protein molecules, thus leading to enhanced mechanical properties of the film. This process involves subjecting the film to multiple instances of freezing and subsequent thawing **[9]**, **[10]**, **[11]**.

This comprehensive overview provides a detailed analysis of the various crosslinking techniques used to improve the properties of soy protein-based films for meat packaging. The review evaluates the impact of these techniques on mechanical strength, thermal stability, water resistance and barrier properties. In addition, the potential industrial applications and regulatory considerations related to using soy protein-based crosslinked films in the meat packaging industry are explored. A thorough understanding of the strengths and limitations of different crosslinking methods aims to facilitate the development of sustainable and high-performance packaging materials that meet the stringent requirements of the meat industry while minimizing the impact on the environment.

Importance of packaging in the meat industry

Packaging plays a crucial role in extending the shelf life of meat products. Vacuum packaging and modified atmosphere packaging (MAP) are two techniques used to achieve this goal. Vacuum packaging removes air from the package, which slows down the growth of bacteria and other microorganisms that cause spoilage. MAP involves replacing the air inside the package with a mixture of gases that inhibit the growth of bacteria and extend the product's shelf life. In addition to extending shelf life, packaging also provides important information to consumers about the meat product they are purchasing. Labels on meat packaging provide information about the product's nutritional value, ingredients, and cooking instructions. However, it is important to note that meat industry packaging can also negatively impact the environment. The use of non-biodegradable materials, such as plastic, can contribute to pollution and waste. Therefore, the industry needs to explore and adopt sustainable packaging solutions that minimize their environmental impact. Some studies have explored the use of biodegradable packaging materials, such as xanthan-based films, which have positive effects on sensory, physicochemical, and microbiological parameters, as well as on ecological safety of the raw materials **[12]**.

Soy protein-based films as a sustainable alternative to traditional packaging materials

In the meat industry, films made of soy protein have been identified as a sustainable substitute for conventional packaging materials. These films offer several environmental advantages over traditional packaging materials like plastics, metals, and glass because they are renewable, biodegradable, and biocompatible. Soy protein can be extracted from soybeans and used to create soy protein-based films through casting or extrusion procedures. Films made of soy protein using renewable and biodegradable materials have a lower carbon footprint than traditional packaging materials. This means that they can be disposed of in an environmentally friendly manner and do not contribute to the accumulation of non-destructive wastes in landfills. Marine Soy protein films require less energy some than conventional packaging materials, significantly reducing the environmental footprint **[13]**.

However, one of the challenges associated with soy protein-based films is that they often exhibit high mechanical strength, water resistance, and thermal instability, which limits their use in meat packaging limits. To overcome these challenges, crosslinking methods have been proposed for soy-protein-based films to improve their mechanical properties, barrier properties and thermal stability **[14]**, **[15]**, **[16]**, **[17]**.

Film-forming methods for soy protein

Various film-forming methods have been reported for soy protein, including heating, extruding, spinning, casting, and thermally compacting. Heating has been used to form soy protein-lipid films in ancient China, where a creamy yellow film formed after the soy milk heating to near boiling was removed and dried, and there finally formed the soy protein film. Soy protein films can also be produced by extruding soy protein isolates with polyethylene oxide (PEO) and low-density polyethylene (LDPE). Spinning is another method for film-forming of soy protein, producing soy protein fibres by spinning a soy protein solution. Casting is the most popular method for film-forming soy protein, where a thin layer of soy protein solution is cast onto a flat surface and dried to form a film **[18]**, **[19]**, **[20]**.

Thermally compacting is another method for film-forming soy protein, where soy protein powder is compacted at high temperature and pressure to form a film. The processing conditions, such as temperature, pH, and concentration of the protein solution influence the film-forming properties of soy protein. The film-forming properties of soy protein can also be improved by adding plasticizers, crosslinking agents, and other additives **[20]**, **[21]**.

Soy protein-based films have been produced using various film-forming methods such as heating, extruding, spinning, casting, and thermally compacting. Heating is a common method used to produce soy protein-based films, where soy milk is boiled in a thin pot until the film is formed. Another method for obtaining soy protein film is based on baking soy protein isolates on pans for 1 h at a temperature of 100 °C. In a study, canola and sorghum proteins were added to soy proteins to improve adhesion. In another study, a coating based on Plantago major seed mucilage enriched with Anethum graveolens essential oil inhibited bacterial growth **[16]**.

Pine needle extract (PNE) has also been incorporated into soy protein-based films to improve their properties. Incorporating montmorillonite and citric acid into whey protein isolate films has been shown to preserve fresh-cut apples by reducing enzymatic browning and loss of apple quality and increasing shelf-life. Soy protein-based films have also been functionalized by incorporating antioxidants, antimicrobial agents, and other bioactive compounds to improve their functionality **[16]**, **[21]**, **[22]**.

Crosslinking Methods

Boiling Soy Milk Boiling soy milk was investigated as a crosslinking method for soy protein-based films. Soy milk was heated to a boiling temperature, and the films were immersed in the boiling soy milk for a specific duration. The heat treatment was expected to induce denaturation and aggregation of soy proteins, leading to crosslinking within the film matrix. The crosslinked films exhibited improved mechanical properties compared to the untreated films, attributed to the formation of intermolecular bonds between protein chains **[8]**, **[16]**, **[23]**.

Baking Soy Protein Isolates Baking soy protein isolates was explored as an alternative crosslinking method. The soy protein isolates were dispersed in a suitable solvent and then subjected to a baking process at a specific temperature and time. The heat-induced reactions during baking promoted the formation of covalent bonds between protein molecules, resulting in enhanced film properties. Baked soy protein films exhibited increased tensile strength and reduced water vapor permeability compared to the control films **[16]**, **[24]**.

Adding Canola and Sorghum Proteins Incorporating canola and sorghum proteins into soy protein-based films was investigated as a means of crosslinking. To optimise the crosslinking effect, canola and sorghum proteins were mixed with soy proteins in varying ratios. The presence of these additional proteins provided reactive functional groups that could participate in crosslinking reactions with soy proteins. The resulting films showed improved mechanical properties and reduced water uptake, suggesting successful crosslinking between different protein sources **[25]**, **[26]**.

Incorporating Plantago Major Seed Mucilage and Anethum Graveolens Essential Oil The incorporation of Plantago major seed mucilage and Anethum graveolens essential oil was studied as a crosslinking method for soy protein-based films. Plantago major seed mucilage acted as a film-forming agent, while Anethum graveolens essential oil provided antimicrobial properties. The mucilage formed a gel-like matrix, and the essential oil acted as a crosslinking agent within the film structure. The crosslinked films exhibited improved mechanical strength, enhanced water resistance, and antimicrobial activity **[27]**, **[28]**.

Adding Pine Needle Extract (PNE) The addition of pine needle extract (PNE) was explored as a crosslinking method for soy protein-based films. PNE contains natural polyphenolic compounds that can undergo crosslinking reactions with soy proteins. The PNE was incorporated into the film-forming solution, and the films were subsequently dried to form a crosslinked structure. The resulting films demonstrated increased tensile strength and reduced water vapor permeability, indicating successful crosslinking between PNE and soy proteins **[29]**.

Using Xylose as a Crosslinker Xylose, a monosaccharide, was explored as a crosslinker for soy protein-based films. Through condensation reactions, Xylose has reactive hydroxyl groups that can form crosslinking bonds with soy proteins. The xylose solution was mixed with the film-forming solution, and the films were cast and dried. The resulting films exhibited enhanced mechanical properties and reduced water vapor **[14]**.

Properties of Soy Protein-Based Films for Meat Packaging

Mechanical properties

It is crucial to evaluate their mechanical properties to ensure the strength and durability of soy protein-based films used for meat packaging. The mechanical properties that are typically assessed include tensile strength, elongation at break, and puncture resistance. These properties are essential in determining the film's ability to withstand stretching, deformation, and puncture. By evaluating these mechanical properties, it is possible to ensure that the soy protein-based films provide adequate protection and preservation of the meat product. The term "tensile strength" denotes the upper limit of stress that a given material can endure prior to its failure in a state of tension. The mechanical property of resistance to deformation or tearing during handling and transportation is important for packaging materials. Soy protein-based films often manifest reduced tensile strength compared to conventional packaging materials. Nevertheless, the application of crosslinking techniques has the potential to enhance their mechanical properties **[30]**, **[31]**, **[32]**.

The elongation at break measures the extent of deformation that a substance can sustain prior to rupture when subjected to tensile forces. The attribute mentioned above holds significant pertinence in the realm of packaging materials, owing to its inherent capacity to depict the film's proficiency in terms of elastic deformation and energy retention, sans any rupture or fissure formation. Soy protein-derived films have demonstrated elevated elongation at break when compared to conventional packaging materials.However, this characteristic can be enhanced by implementing crosslinking techniques **[32]**.

Puncture resistance is the film's resistance to puncture or penetration by sharp objects. This is an important property for packaging materials as it indicates the film's ability to protect the product from damage during handling and transportation. Soy protein-based films are typically less puncture-resistant than conventional packaging materials, but cross-linking can also improve this property **[33]**.

In addition, Soy protein-based films have emerged as a promising alternative to petroleum-based films for meat packaging applications. However, to be effective, these films require additional mechanical properties beyond those mentioned earlier. Two crucial properties that soy protein-based films must possess are flexibility and foldability. These properties are essential for films that need to conform to the irregular shapes of meat products. The ability of the film to flex and fold allows it to conform to the product's shape, providing complete coverage and protection. Soy protein-based films can be formulated to possess excellent flexibility and foldability, making them ideal for various meat packaging applications. Another critical mechanical property of meat wrap films is tearing strength. This property refers to the film's ability to resist the propagation of tears that have already started. Films with good tear strength are less likely to develop minor tears or punctures during handling and transportation, which can compromise the package's integrity and lead to spoilage and contamination. Cross-linking technology can be used to enhance the tear strength of soy protein-based films. This technology improves the tear strength of the films, making them more suitable for meat packaging applications. I need references related to these paragraphs **[34]**, **[35]**.

Thermal properties

Packaging materials used in the meat industry must have good thermal properties as they may be exposed to varying temperatures during storage, transportation, and cooking. However, soy protein-based films have been found to have poor thermal stability compared to commonly used packaging materials like polyethylene and polypropylene. Various methods can be employed to address this issue to improve the thermal properties of soy protein-based films. One approach is to add plasticizers to the films. Plasticizers are substances that enhance the flexibility and processing properties of polymers. By adding plasticizers to soy protein-based films, their glass transition temperature can be lowered, making them more flexible even at low temperatures. Another way to enhance the thermal qualities of soy protein-based films is to add antioxidants. Antioxidants scavenge free radicals and reduce the oxidation rate, preventing film breakdown at high temperatures. For example, vitamin E has been used as an antioxidant to increase the thermal stability of soy protein-based films. Crosslinking is another method that can improve the thermal properties of soy protein-based films. Crosslinking increases the temperature at which film degradation begins and improves overall thermal stability. Formaldehyde has been used as a crosslinking agent in soy protein-based films, improving thermal stability **[36]**, **[37]**, **[38]**, **[39]**.

Optical properties

Visual qualities such as clarity and color are also important packaging considerations in the meat industry. Transparency is important because it allows consumers to inspect the product and determine its quality. In addition, some packaging, such as vacuum packs, rely on transparent materials to monitor for signs of deterioration. Color can also be important for aesthetic reasons, as it can enhance a product’s appearance and help set it apart from competing products. soy protein-based films have poor optical properties compared to common packaging materials like polyethylene and polypropylene. Various methods can be used to improve the transparency of soy protein films, such as adding additives like glycerol or sorbitol. These additives can increase the thickness of the film, reduce light scattering, and increase its refractive index. However, they can also reduce the mechanical strength of the film **[32]**, **[40]**, **[41]**.

Crosslinking Methods for Soy Protein-Based Films

Chemical crosslinking agents

Glutaraldehyde

Glutaraldehyde is commonly used as a crosslinking agent in producing soy protein films. It reacts with amine groups on soy protein molecules to form covalent cross-links that improve the mechanical and barrier properties of the membrane. Glutaraldehyde has been shown to produce films with high tensile strength and good water resistance. However, the use of glutaraldehyde has certain disadvantages. It is a volatile and toxic substance that poses a risk to workers and the environment. Additionally, residual glutaraldehyde in the film can migrate into food products, raising concerns about potential health risks. Therefore, alternative crosslinking agents are sought to be safer and more environmentally friendly **[42]**, **[43]**, **[44]**.

Genipin

Genipin is a natural cross-linking agent that has been investigated for use in soy protein-based membranes. It is derived from the fruit of the gardenia plant and is considered a safer and more environmentally friendly alternative to chemical crosslinking agents. Genipin reacts with amino groups on soy protein molecules, forming cross-linkers that improve the film's mechanical properties and barrier properties. Studies have shown that genipin can effectively improve soybean protein-based films' tensile strength, water resistance, and thermal stability. In addition, genipin has been shown to have antimicrobial properties, which may be beneficial in meat packaging applications to reduce the risk of contamination. However, using genipin as a crosslinking agent also has certain limitations. It has been found to have a slower curing rate than chemical curing agents, which can lead to longer production times. In addition, the use of genipin may discolor the film, which may affect the appearance and marketability of the film **[45]**, **[46]**, **[47]**.

Epichlorohydrin

Epichlorohydrin is a pass-linking agent used in the production of soy protein-primarily based movies. This compound reacts with amino and hydroxyl groups on soy protein molecules, forming covalent go-links that improve the mechanical and barrier residences of the membrane. The use of epichlorohydrin as a crosslinking agent has been proven to provide movies with appropriate tensile power, water resistance and thermal balance. However, there are a few concerns regarding the usage of epichlorohydrin in food packaging packages. This compound is understood to be carcinogenic and can pose a health hazard to people and customers. Additionally, epichlorohydrin left in the movie can migrate into food products, leading to capability health problems. Therefore, there may be a growing interest in locating safer and more environmentally pleasant alternatives to epichlorohydrin for meal packaging **[48]**.

Formaldehyde

Formaldehyde is a chemical move-linking agent used in the manufacture of diverse materials, including movies crafted from soy protein. It reacts with amine agencies on soy protein molecules, forming covalent move-hyperlinks that enhance the mechanical and barrier houses of the membrane. However, formaldehyde has been determined to have sure hazards as a cross-linking agent. It is a poisonous substance that could motive fitness problems, which includes breathing infection and most cancers. In addition, formaldehyde can release risky organic compounds (VOCs), contributing to indoor air pollution. Therefore, there may be increasing hobby in finding opportunities crosslinking agents that are safer and more environmentally pleasant **[45]**, **[49]**, **[50]**, **[51]**.

Transglutaminase

Transglutaminase is an enzyme discovered obviously in some of meals, along with meat, fish, and dairy merchandise. It catalyzes the formation of covalent bonds among proteins, improving meals' feel and balance. Transglutaminase has also been used as a move-linking agent in manufacturing soy protein movies. The use of transglutaminase as a crosslinking agent has been proven to enhance the mechanical homes and barrier houses of soybean protein-based totally membranes. It forms covalent bonds among membrane protein molecules, creating a more stable and durable cloth. In addition, transglutaminase is non-poisonous and non-volatile, making it a safer alternative to numerous move-linking sellers. Transglutaminase can inadvertently move-link proteins, main to the formation of allergens or other unwanted compounds. Therefore, it's important to cautiously examine the protection and effectiveness of transglutaminase and different crosslinking agents before using them in meals packaging or different applications **[52]**, **[53]**, **[54]**, **[55]**.

Physical crosslinking methods

Heat treatment

The heat treatment process represents a physical crosslinking technique that can be effectively utilized to induce modifications in the properties of films based on soy protein. During heat treatment, denaturation of soy protein molecules occurs, resulting in the loss of their original structure and the establishment of fresh bonds with adjacent molecules. The consequence of this phenomenon manifests in the creation of physical intermolecular connections among the protein entities, which subsequently enhances the film's mechanical and barrier characteristics. The degree of crosslinking susceptibility observed during thermal processing is contingent upon a range of variables, predominantly including temperature, duration, and moisture levels. Elevated temperatures and prolonged heating durations may contribute to an overabundance of crosslinking, eventually inducing a decrease in film pliability and an elevation in fragility. Conversely, the induction of significant crosslinking may not be accomplished by low temperatures or brief heating durations **[56]**, **[57]**, **[58]**.

UV irradiation

Radiation crosslinking is a method used to improve the properties of soy-protein based films for meat packaging. This method involves exposing the films to high-energy radiation, such as gamma rays or electron beams, which causes the polymer chains to crosslink and form a three-dimensional network. This network improves the mechanical properties of the films, such as their tensile strength and elongation at break, as well as their barrier properties, such as their water vapor permeability and oxygen transmission rate. Radiation crosslinking can also improve the films' thermal stability and antimicrobial properties. However, the process can be expensive and requires specialized equipment, and there are concerns about the safety of using radiation on food packaging materials. Therefore, further research is needed to optimize the process and ensure its safety and effectiveness **[40]**.

Enzymatic crosslinking

Enzyme crosslinking is a method of crosslinking proteins that involves the use of enzymes to catalyze the formation of covalent bonds between protein molecules. One enzyme commonly used for this purpose is transglutaminase (TGase). TGase catalyzes the formation of covalent bonds between the side chains of glutamine and lysine in proteins, leading to cross-links between protein molecules. Enzyme crosslinking is a gentle and environmentally friendly method of protein crosslinking that does not require the use of harsh chemicals or high temperatures. It also provides precise control over the degree of crosslinking, tunable by varying enzyme concentration and reaction time. Enzymatic crosslinking has been used to improve the mechanical and barrier properties of soy protein films, making them more suitable for applications such as food packaging. In one study, soybean protein isolate films were crosslinked using TGase, resulting in improved tensile strength and water resistance. The use of TGase also resulted in membranes with improved oxygen and carbon dioxide-blocking properties **[24]**.

Applications of Crosslinked Soy Protein-Based Films in Meat Packaging

Preservation of meat quality

Using cross-linked soy protein films in meat packaging can help preserve meat quality. The film provides a barrier to oxygen, moisture, and other gases that can cause meat to spoil or spoil. In addition, these films can prevent the loss of moisture in the meat, leading to the meat's shrinking and hardening. Films made from cross-linked soy protein can also help extend the shelf life of meat products. Food wrap can slow the growth of bacteria and other spoilage microorganisms by reducing the amount of oxygen that comes into contact with meat. This can help maintain meat freshness and quality for longer. In addition, using films made from cross-linked soy proteins can help reduce the packaging material required for meat products. Because these films are strong and durable, they can be used in thinner layers than traditional packaging materials, such as plastic or paper. This can help reduce waste and reduce the environmental impact of meat packaging **[16]**, **[18]**, **[20]**. Table 1 presents a comprehensive overview of the properties of crosslinked soy protein-based films developed explicitly for meat packaging. It provides essential information on characteristics such as tensile strength, water vapor permeability, oxygen permeability, barrier properties, mechanical properties, transparency, and shelf life. This valuable resource serves as a reference for researchers and industry professionals seeking to explore sustainable alternatives in meat packaging.

Table 1. Properties of Crosslinked Soy Protein-Based Films for Meat Packaging

Application	Description	References
Oxygen Barrier	Crosslinked soy protein-based films possess excellent oxygen barrier properties, reducing oxygen permeability. This minimizes oxidative reactions, such as lipid oxidation, which can lead to off-flavours and spoilage.	**[58]**, **[59]**, **[60]**
Moisture Retention	Crosslinked soy protein-based films can retain moisture within the meat, preventing excessive drying. This helps to maintain the meat's juiciness, tenderness, and overall quality.	**[33]**, **[58]**
Antimicrobial Activity	Crosslinked soy protein-based films possess antimicrobial properties, inhibiting the growth of spoilage and pathogenic microorganisms. This extends the shelf life of meat products and reduces the risk of foodborne illnesses.	**[14]**, **[60]**, **[61]**
Mechanical Strength	Crosslinked soy protein-based films exhibit good mechanical strength and flexibility, protecting against physical damage during handling and distribution. They help preserve the integrity and appearance of the meat.	**[14]**, **[33]**, **[58]**, **[60]**, **[61]**

Extension of shelf life

By acting as a barrier against gases like oxygen, moisture, and others that might hasten deterioration, films formed of soy protein can help increase the shelf life of meat products. These membranes' barrier qualities and their capacity to stop meat products from degrading can be further improved by using cross-linking chemicals like glutaraldehyde. Soy protein films can be created to release antimicrobial substances like bacteriocins or essential oils that may help stop the growth of germs and fungus on the surface of meat products and act as a physical barrier to the outside environment. This can increase the product's shelf life and lower the chance of contracting a foodborne disease. The moisture level of meat products may be maintained using soy protein-based films, which is crucial for their quality and safety. Consumers may find dry, chewy meat less appetizing as a result of moisture loss. Additionally, it may raise the possibility of microbial development and deterioration. By creating a barrier against moisture loss, soy protein films can help maintain the quality and safety of meat products for longer periods **[23]**, **[62]**.

Enhancement of food safety

Crosslinked soy protein-based films can decorate food protection in several approaches. Firstly, by improving the movie's barrier homes, the movies can save you the migration of harmful contaminants such as bacteria, fungi, and viruses into the packaged meat. This can help reduce the risk of foodborne ailments from contamination throughout dealing with, transportation, and storage. In addition, crosslinked soy protein-based films can also reduce the risk of oxidation and spoilage of packaged meat. Films can act as a barrier to oxygen and other reactive species, which can cause meat quality degradation and shorten its shelf life. This may be particularly important for meat products susceptible to oxidative rancidity, such as ground meat and meat products that contain high amounts of unsaturated fatty acids . Furthermore, soy protein-based films can be used as an alternative to synthetic polymer-based packaging materials, which are non-biodegradable and can accumulate in the environment, and cause contamination and harm to wildlife Soy films made from soy protein, on the other hand, are bio - they are biodegradable, can be disposed of safely, and reduce the environmental impact of meat packaging on the snow **[24]**, **[63]**, **[64]**.

Improving packaging efficiency and reducing waste

Soy protein-based films can improve the barrier and mechanical properties of packaging materials in the meat industry, leading to enhanced packaging efficiency and reduced waste. The use of such packaging materials with excellent barrier properties can reduce the need for additional layers or packing materials, resulting in cost savings and a reduced environmental impact. Additionally, improved packaging can extend the shelf life of meat products, reducing food waste. By retaining moisture and oxygen effectively, the growth of bacteria and other microorganisms that cause spoilage can be slowed down, resulting in a longer shelf life of meat products and a lower likelihood of product rejection due to spoilage. Furthermore, improved packaging can enhance food safety by reducing the risk of contamination during transportation and handling. The use of tear-resistant and perforation-resistant packaging materials can minimize the potential for contamination.

Moreover, using packaging materials that do not release harmful chemicals or compounds into foods can ensure the safety of meat products for consumption. Several studies have been conducted on the use of soy protein-based films for meat preservation, and the incorporation of antimicrobial agents such as cinnamaldehyde or tea polyphenols has been found to be effective in maintaining the quality and safety of meat products. Edible films made from natural compounds such as polysaccharides, proteins, and lipids have also been studied for their antioxidant and antibacterial activities in meat and meat products and have shown potential as eco-friendly alternatives to petrochemical-based plastic packaging. The incorporation of essential oils from oregano or thyme into soy-based edible films is effective in retarding oxidative changes in meats and can be used as an antioxidant-active packaging. Proteins are excellent materials used for obtaining edible or non-edible coatings and films, and different vegetable and animal protein sources have been studied for their mechanical properties, thickness, moisture content, water vapor permeability, sensorial properties, and suitability for the environment **[15]**, **[23]**, **[65]**.

Industrial Considerations for Soy Protein-Based Films in Meat Packaging

Manufacturing and processing challenges

Soy protein-based films for meat packaging applications can present several challenges. These challenges include achieving consistent film properties, ensuring the safety and quality of the final product, and logistical challenges associated with production and distribution. Factors such as film composition, treatment conditions, and curing methods must be carefully controlled during large-scale production to achieve consistent film properties. It is also important to ensure that the membrane meets regulatory requirements by performing rigorous testing. Residual crosslinkers or other additives in the film can potentially migrate into the meat product, causing health and safety problems. Therefore, careful control of the manufacturing process is essential. In addition, logistical challenges may be associated with the production and distribution of soy protein films, such as transportation and storage requirements as well as cost and scalability considerations. Despite these challenges, soy protein-based films have become widely used for a variety of different products and different food categories such as meat products, vegetables, or dairy products. Proteins are excellent materials used for obtaining edible or non-edible coatings and films, and different vegetable and animal protein sources have been studied. Soy protein-based films have been used to preserve meat analogues, and the incorporation of antimicrobial agents such as cinnamaldehyde has been shown to be effective in retarding the growth of bacteria **[15]**, **[16]**, **[66]**.

Future Directions and Opportunities

The utilization of soy protein-derived films in meat packaging has garnered considerable interest in contemporary times, owing to their eco-friendliness, replenishability, and prospective capacity to enhance meat preservation, food security, and longevity. Notwithstanding, multiple obstacles and prospects exist pertaining to the subsequent investigation and advancement in this area. Possible academic rewrite: One promising avenue for enhancing the mechanical and barrier properties of soy protein-based films is the exploration of innovative crosslinking methods and utilising diverse additives like nanoparticles, biopolymers, and antimicrobial substances. The implementation of this technique has the potential to yield films displaying heightened robustness, suppleness, and antimicrobial properties, thus amplifying the efficacy of such materials as meat packaging. A promising avenue for further research lies in investigating the potential application of soy protein-based films in conjunction with other types of biodegradable packaging materials, such as cellulose and chitosan. The creation of multi-layered films through such intermixing has the potential to yield enhanced functional properties. Cost efficiency and market feasibility are key considerations in introducing and implementing soy protein-based films in meat packaging applications. The manufacturing cost of soy protein-based films can be higher than traditional petroleum-based packaging materials due to higher raw material and processing costs. However, the use of soy protein-based films has the potential to reduce overall packaging costs by improving packaging efficiency and reducing food waste. Marketability is also important as consumer acceptance and demand for sustainable and environmentally friendly packaging materials increase. The introduction of soy protein-based films could meet the growing consumer trend for environmentally friendly and sustainable packaging options and could provide a competitive advantage for companies in the meat industry.

Moreover, advancing sustainable and economically efficient manufacturing techniques for soy protein-derived films could augment their market viability. The use of biodegradable and sustainable packaging materials has gained considerable attention as a viable solution to address the mounting environmental concerns. The utilization of films derived from soy protein within the realm of meat packaging is consistent with the objectives mentioned above, subsequently presenting an avenue for waste reduction and augmenting the sustainability of the food sector.

CONCLUSION

In summary, soy protein-based films have great potential as sustainable and biodegradable alternatives to conventional meat packaging. Crosslinking techniques have been investigated to improve the mechanical barrier properties of soy protein-based films, making them more suitable for use in meat packaging. Various cross-linking agents have been studied, to improve performance and safety Promising results have been obtained. However, there are still challenges to overcome regarding product development and manufacturing, cost efficiency and market power. However, the increasing demand for sustainable and environmentally friendly packaging solutions will create opportunities for the production and commercialization of soy protein-based films in meat products packaging industry Further R&D efforts are needed to overcome these challenges and to better realize the potential of soy protein films in meat packaging.

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