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A Review of Lignin Applications and Challenges in Food Safety

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ABSTRACT: Lignin is the second largest natural macromolecular organic substance in nature. Due to its unique chemical structure and biological activity, the application of lignin in the field of food safety has shown significant promise in recent years, although it also faces a series of challenges. This paper reviews the applications of lignin in food packaging, as an antioxidant, in food storage, and as a functional food additive, while analyzing the challenges encountered in the application process. This paper also addresses the challenges associated with inefficient extraction and separation techniques, the effective utilization of active ingredients, and outlines future research directions for lignin applications in food safety. In summary, lignin holds significant potential in the field of food safety, but a thorough and comprehensive evaluation of its functional properties, application effects, and potential risks is urgently needed to facilitate its further development and application in this area.

Keywords: Lignin; Food packaging; Antioxidants; Food additives; Food safety

1. Introduction

In light of the growing global concerns regarding food safety and sustainable development, the quest for green, safe, and effective food additives and preservation materials has emerged as a significant research focus within the food industry^[1-3]. Lignin, a natural complex organic polymer, is abundantly found in plant cell walls and ranks as the second largest biomass resource on Earth, following cellulose^[4-5]. Historically, lignin has been primarily viewed as a waste product of the paper industry, leading to resource wastage and contributing to environmental pressures. However, in recent years, with the growing emphasis on sustainable development, lignin has been reassessed and is increasingly being studied and applied in the field of food safety^[6].

From a food safety perspective, safeguarding food quality, extending shelf life, and ensuring the absence of harmful residues are essential for maintaining consumer health^[7]. Some synthetic chemical substances used in traditional food preservation and additives may pose potential health risks^[8]. For instance, certain preservatives can adversely affect the liver, kidneys, and other organs, while some synthetic pigments may be

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carcinogenic^[9-11]. In contrast, lignin, a natural and biodegradable substance, is expected to mitigate these risks. On one hand, lignin possesses excellent antioxidant properties that effectively eliminate free radicals from food, slow down the oxidative deterioration process, and preserve the color, flavor, and nutrients of food^[12-13]. For instance, in oil and fatty foods, oxidation can lead to rancidity, resulting in unpleasant odors and the formation of harmful substances^[14]. The addition of lignin can inhibit oxidation reactions and extend the shelf life of oils and fats. On the other hand, lignin's antimicrobial properties enable it to suppress the growth and reproduction of microorganisms in food, thereby reducing the risk of spoilage due to microbial contamination^[15]. In foods that are particularly susceptible to microbial contamination, such as meat and dairy products, lignin can serve as a natural antimicrobial agent, helping to mitigate infestations by bacteria, molds, and other microorganisms, thus ensuring food safety^[16].

In terms of food industry development, the application of lignin presents new opportunities and innovative solutions. As consumer demand for healthy and natural foods continues to rise, food companies must seek new raw materials and technologies to meet market needs. The incorporation of lignin can lead to the creation of a range of new functional foods and food packaging materials, thereby facilitating the advancement of the food industry. In the development of functional foods, lignin can be utilized as a source of dietary fiber, which aids in promoting intestinal peristalsis and reducing blood lipids and glucose levels, thereby addressing consumer demand for healthier options^[17-19]. In the realm of food packaging, biodegradable materials derived from lignin can not only mitigate the environmental pollution associated with traditional plastic packaging but also impart antibacterial and antioxidant properties to enhance food freshness. This approach aligns with environmental protection principles while simultaneously boosting the market competitiveness of food enterprises. Lignin can play a critical role in addressing the sustainable development goals (Figure 1)^[20-24].

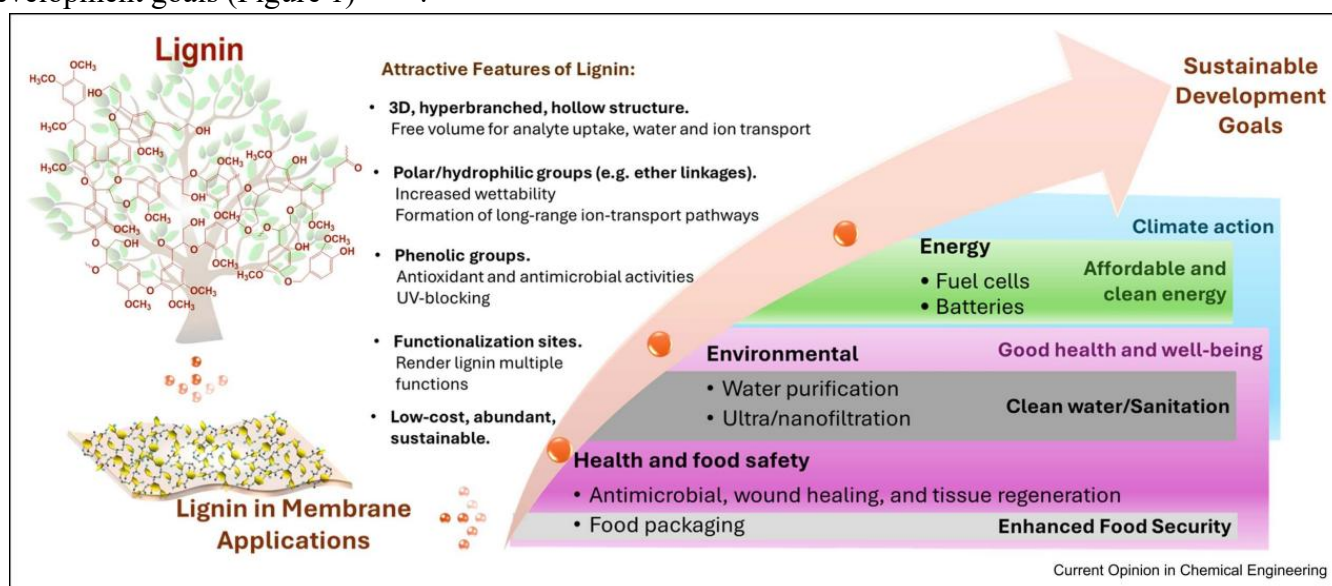


Figure 1. The critical role of lignin in achieving sustainable development goals^[24].

Although the application of lignin in the field of food safety is promising, it still faces several challenges. These challenges primarily include the need for improved extraction and purification techniques, the

exploration of functionalization and modification methods, and further investigation into the synergistic effects with other food ingredients. Therefore, to promote the application of lignin in food safety, ongoing research must focus on continuous innovation to enhance the feasibility and effectiveness of its practical applications.

In light of the above, this paper reviews the applications of lignin in food packaging, antioxidants, food storage, and as functional food additives, while also analyzing the challenges encountered in these applications. In food packaging, lignin has been utilized to develop biodegradable materials due to its antimicrobial and antioxidant properties, which can extend the shelf life of food and reduce environmental pollution^[25-27]. As a natural antioxidant, lignin effectively delays the oxidative deterioration of food during preservation; however, the antioxidant capacity of lignin varies significantly depending on its source. Improving the stability and antioxidant capacity of lignin through modification is currently a prominent area of research. In food storage, the high adsorption capacity of lignin can be utilized to adsorb and remove harmful substances from food, such as heavy metals and pesticide residues^[28-29]. However, challenges remain, including the low purity of lignin extraction and insufficient research on its safety and large-scale applications. Additionally, lignin is emerging as a functional food additive, with promising potential prebiotic properties that may help regulate the intestinal microbial community. Nevertheless, there is a lack of long-term data on its effects on human health^[30-32]. This paper also addresses the challenges associated with inefficient extraction and separation techniques, the effective utilization of active ingredients, and outlines future research directions for lignin applications in food safety. In conclusion, the study of lignin's application in food safety is highly significant for enhancing food safety protection methods and promoting the sustainable development of the food industry. By offering theoretical support and practical guidance for the extensive use of lignin in this field, we anticipate opening new avenues to address food safety challenges and foster the green development of the food sector.

2. Characterization of lignin and the current status of its application in the field of food safety

2.1 Characterization of lignin

2.2 Chemical structure and composition

Lignin is a complex natural polymer characterized by a distinctive and intricate chemical structure^[33]. It primarily consists of phenylpropyl alkyl units interconnected by ether and carbon-carbon bonds, resulting in a macromolecule with a three-dimensional network. Lignin contains more than ten different types of connections between phenylpropanoid structural units, including β - β' , β -1', 5-5', β -O-4', 4-O-5', β -5'/ α -O-4', β - β' / α -O- γ' , α -O-4'/ β -O-4''/3'-3'', among others. These linkages typically occur at specific sites, particularly at the β -site. This unique structure imparts various special properties and functions to lignin. The structure of lignin, the main monomeric structural units and connections, and the types of functional groups contained are shown in Figure 2^[34-38].

The phenylpropyl alkyl units is the fundamental component of lignin, which can be categorized into three main types based on its structural differences: Syringyl lignin (S-lignin), derived from syringyl

propane structural monomers. It has high methoxy content and loose structure, showing good biocompatibility due to improved solubility in food systems, suitable for edible films and additives; Guaiacyl lignin (G-lignin), formed from guaiacyl propane structural monomers, is rich in free phenolic hydroxyl groups and has a dense aromatic skeleton. It exhibits strong antimicrobial activity by destroying the cell membranes of spoilage microorganisms and inhibiting their growth, as well as excellent antioxidant capacity by scavenging free radicals; and p-hydroxyphenyl lignin (H-lignin), which is polymerized from p-hydroxyphenyl propane structural monomers. It has the simplest structure, with the lowest free phenolic hydroxyl content and no methoxy groups, resulting in weak antimicrobial and antioxidant capacities that are insufficient to independently protect food^[39-40].

The proportions of these three monomers vary significantly among lignins from different plant sources. Gymnosperms predominantly contain guaiacyl lignans (G)^[41], dicotyledons primarily consist of guaiacyl-syringyl lignans (G-S), and monocotyledons are characterized by guaiacyl-syringyl-p-hydroxyphenyl lignans (G-S-H)^[42-43]. The overall composition of lignin lacks regular repeating structural units, and there is no specific ordering among its structural components. This variation in monomer composition directly influences the structure and properties of lignin, which in turn determines its potential applications across various fields.

The structure of lignin contains a variety of reactive groups, including phenolic hydroxyl, alcoholic hydroxyl, carbonyl, and methoxy groups. These reactive groups provide lignin with significant chemical reactivity, allowing it to participate in various chemical reactions, such as oxidation, reduction, esterification, and etherification^[44-48]. The phenolic hydroxyl group exhibits strong reactivity and can undergo condensation reactions with other substances, altering the molecular structure and properties of lignin^[49]. The methoxy group influences the stability and solubility of lignin^[50]. These reactive groups are not only crucial for lignin's biological activity but also serve as an important foundation for its applications in the food industry.

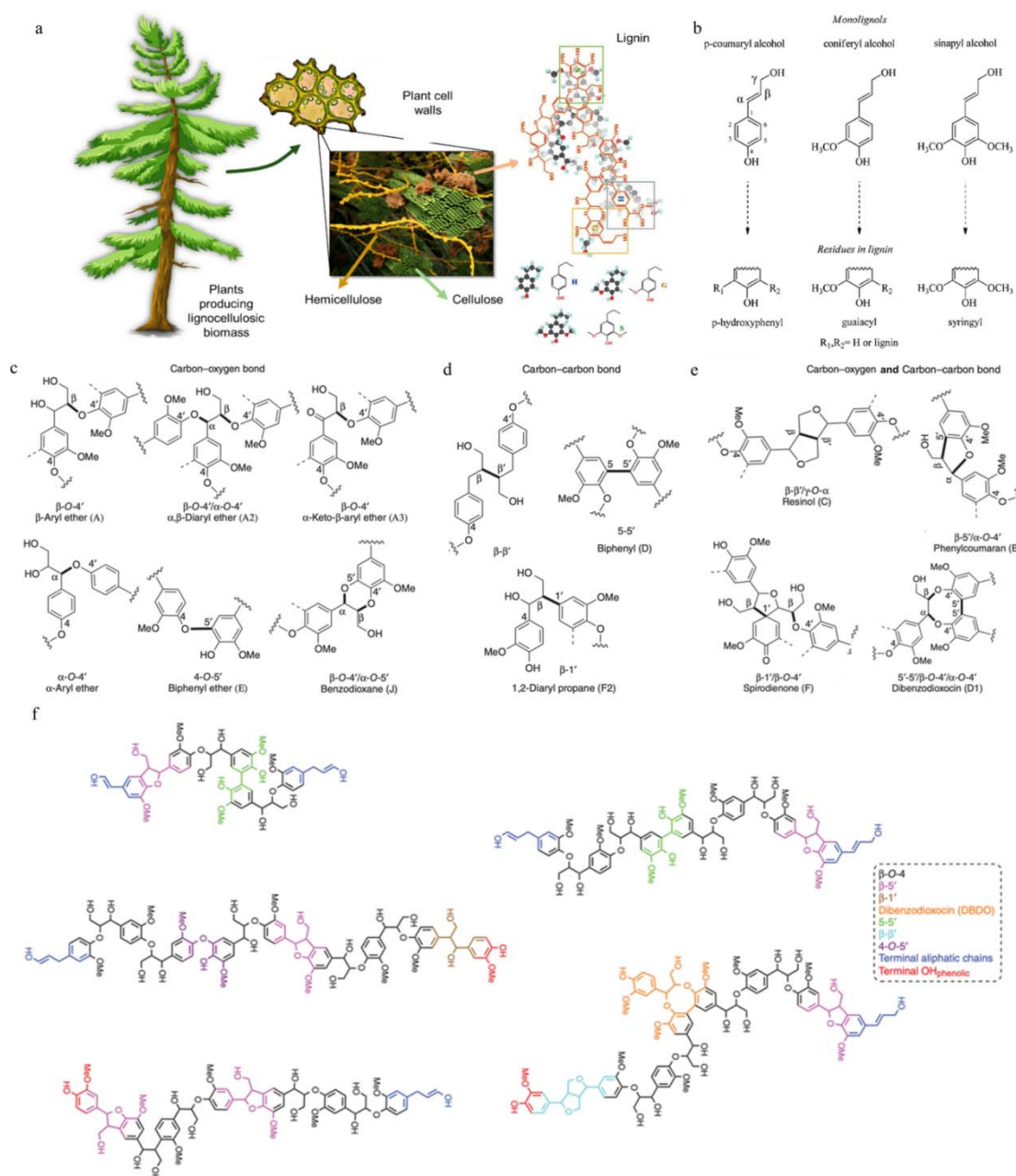


Figure 2. (a) Structure and location of lignin, (b-e) Main monomeric structural units and connections of lignin, (f) Summary of functional group types of lignin^[37].

2.1.2 Impact of the nature of lignin on its application in food safety

2.1.2.1 Stabilization

Lignin is insoluble in water and most organic solvents due to its complex three-dimensional mesh structure and extensive hydrogen bonding. However, its solubility can be enhanced through appropriate chemical modifications or treatments^[51-53]. Alkali lignin remains insoluble in water under acidic and neutral conditions but becomes soluble in solvents with strong hydrogen bonding capabilities, such as sodium hydroxide (NaOH) aqueous solutions (with a pH of 10.5 or higher), dioxane, acetone, methyl fibrinolytic agents, and pyridine. In contrast, sulfonated lignin is soluble in a range of aqueous solutions across various pH levels but remains insoluble in organic solvents. This variation in solubility expands the potential applications of lignin in the food industry, enabling it to interact more effectively with other components of food systems.

Lignin exhibits excellent thermal stability, maintaining its structure and properties within a specific temperature range^[54-55]. However, at excessively high temperatures, lignin undergoes thermal degradation, which compromises its structural integrity and alters its properties^[56-57]. Additionally, lignin is sensitive to environmental factors such as light and oxygen, prolonged exposure to these elements can lead to oxidative reactions that negatively impact its quality and functionality^[58]. In food applications, it is crucial to thoroughly consider the stability of lignin and implement appropriate measures to safeguard its properties, ensuring its effectiveness and safety within food systems.

2.1.2.2 Biologically relevant properties

Lignin exhibits a range of biological activities that confer significant application value in the field of food safety. One of its key bioactivities is its antioxidant property^[59]. In food systems, oxidation is a primary cause of quality degradation, nutrient loss, and reduced shelf life. Lignin can exert antioxidant effects through various mechanisms; for instance, the phenolic hydroxyl groups in its structure can donate hydrogen atoms to free radicals, effectively scavenging them and inhibiting oxidative reactions in food^[60]. Additionally, lignin can mitigate the catalytic effect of metal ions on oxidation by chelating these ions, further enhancing its antioxidant capabilities^[61]. Incorporating lignin into oil and fat-based foods can significantly delay oxidative rancidity, thereby preserving the quality and flavor of fats and oils^[62].

Antimicrobial activity is a crucial factor in the application of lignin for food safety^[63]. Numerous microorganisms, including bacteria and molds, can lead to food spoilage and pose risks to food safety. Lignin exhibits an inhibitory effect on a wide range of microorganisms, primarily by disrupting their cell membrane structures, interfering with metabolic processes, and inhibiting enzyme activity. Research has demonstrated that lignin significantly inhibits common food contaminants such as *Escherichia coli*, *Staphylococcus aureus*, and *Bacillus subtilis*. Consequently, lignin can be utilized to develop natural antimicrobial agents and preservatives for food products^[64-67].

Lignin also exhibits antiviral activity. Although there are relatively few studies on its antiviral properties in the context of food safety, research has demonstrated that lignin can inhibit certain viruses. Its mechanism of action may involve interference with the adsorption, invasion, and replication processes of these viruses. The antiviral activity of lignin offers new insights and strategies for addressing viral contamination during the processing and storage of various foods, which can pose significant threats to food safety^[68-69].

2.2 Lignin applications in food safety

2.2.1 Demand for lignin applications in the food safety sector

2.2.1.1 The Need for Food Preservation

Freshness and preservation have long posed significant challenges in the production, storage, and transportation of food. The deterioration of food primarily results from microbial contamination and oxidation. Microorganisms, including bacteria, molds, and yeasts, can rapidly multiply and decompose the nutrients in food under favorable environmental conditions, leading to issues such as spoilage, mildew, and

unpleasant odors. According to statistics, approximately one-third of the world's food is lost each year due to microbial contamination, resulting in substantial economic losses and exacerbating the issue of food security^[70]. In the storage of fruits and vegetables, mold growth often leads to fruit rot, diminishing the quality and marketability of agricultural products. Foods high in protein and fat, such as meat and dairy products, also serve as breeding grounds for microorganisms. Microbial contamination can compromise the taste of these foods and even produce harmful substances that pose health risks to consumers^[71-72].

Oxidation is a significant contributor to food spoilage. The oils, vitamins, pigments, and other components in food are highly susceptible to oxidation, leading to changes in color, loss of flavor, and depletion of nutrients. The oxidation of fats and oils generates harmful substances such as peroxides and aldehydes, which can cause rancidity, produce unpleasant odors and bitter tastes, and diminish the overall quality and nutritional value of these fats and oils^[73]. When antioxidant compounds, such as vitamin C found in fruits and vegetables, undergo oxidation, they lose their beneficial effects on the human body, which also negatively impacts the appearance and taste of the food^[74].

There are numerous issues associated with traditional food preservation methods. While chemically synthesized preservatives exhibit strong antibacterial properties, they may pose potential risks to human health. Long-term consumption of benzoic acid and its salts, sorbic acid and its salts, and other commonly used preservatives can burden the liver, kidneys, and other organs^[75-76]. Furthermore, some studies have indicated that certain preservatives may be carcinogenic. Synthetic antioxidants, such as butylated hydroxyanisole (BHA) and dibutyl hydroxytoluene (BHT), also present safety concerns, leading to increasing restrictions on their use. Although some physical preservation methods, such as low-temperature refrigeration and air conditioning, can extend the shelf life of food, their high costs and stringent equipment and storage requirements limit their applicability in certain regions and for specific types of food^[75].

Lignin holds significant potential for extending the shelf life of food due to its antioxidant properties, which effectively scavenge free radicals and inhibit oxidative reactions. When added to fatty foods, lignin can slow the rate of oxidative rancidity in fats and oils, preserving their color and flavor while extending their shelf life. Research indicates that when lignin is incorporated into soybean oil, the peroxide value of the lignin-enriched oil is significantly lower than that of the control group stored under identical conditions. This suggests that lignin effectively inhibits the oxidation of fats and oils. The antimicrobial properties of lignin enable it to inhibit the growth and reproduction of microorganisms in food. For common food contaminants such as *E. coli* and *Staphylococcus aureus*, lignin demonstrates a significant inhibitory effect. Incorporating lignin into meat products can reduce the number of microorganisms, lower the risk of food spoilage, and help maintain the freshness and safety of these products^[25,77-79].

2.2.1.2 Demand for Safety and Environmental Protection

As a barrier between food and the external environment, food packaging materials play a crucial role in ensuring food safety and quality. These materials should possess not only excellent physical properties, such as barrier performance and mechanical strength, to protect food from external factors, but they must also

ensure safety and prevent contamination. Traditional food packaging materials, such as plastic, metal, and glass, have certain advantages in packaging performance; however, they also present numerous challenges^[80-81].

Plastic packaging materials are among the most widely used food packaging options today; however, concerns regarding their safety and environmental impact are becoming increasingly prominent^[80]. Many plastic packaging materials contain harmful substances such as plasticizers and bisphenol A, which can migrate to food during contact, posing risks to human health. Plasticizers can disrupt the human endocrine system, adversely affecting reproductive and developmental functions^[82]. Bisphenol A has been linked to various diseases, including breast and prostate cancer^[83]. Additionally, plastic packaging materials are notoriously difficult to degrade, leading to significant environmental pollution and contributing to what is commonly referred to as According to statistics, the world generates hundreds of millions of tons of plastic waste each year, with a substantial portion entering oceans and soil, resulting in long-term damage to the ecological environment^[83-84].

Although metal packaging materials possess good barrier properties and mechanical strength, they are prone to corrosion and have higher costs, among other drawbacks^[85]. When metal comes into contact with acidic or alkaline substances in food, it can undergo corrosion, leading to the migration of metal ions into the food and adversely affecting its quality and safety. Additionally, some metal packaging materials require high energy consumption during production, which places pressure on the environment. On the other hand, glass packaging materials, while relatively safe and stable, are heavy and fragile, making transportation and usage inconvenient. Furthermore, the production of glass also demands significant energy and resource consumption.

As public awareness of food safety and environmental protection continues to grow, the safety and environmental standards for food packaging materials are becoming increasingly stringent. Lignin, a natural and biodegradable material, offers unique advantages in meeting these demands. It exhibits excellent biodegradability, allowing it to be decomposed by microorganisms in the natural environment and ultimately converted into carbon dioxide and water, thereby preventing long-term environmental pollution^[85-86].

2.2.1.3 Demand for Food Additive Safety and Functional Enhancement

Food additives play a crucial role in the food industry by enhancing the quality, taste, and color of products, as well as extending their shelf life and improving processing performance^[87]. However, there are several issues associated with the use of food additives. The safety of certain additives has come under scrutiny, and some synthetic food additives may pose potential risks to human health. For instance, synthetic pigments such as carmine and sunset yellow can trigger allergic reactions and may adversely affect children's intellectual development^[88]. Similarly, synthetic sweeteners like sodium saccharin, when consumed in large quantities over extended periods, may impact the body's metabolic and nervous systems. Additionally, many food additives serve relatively limited functions, making it challenging to meet the modern food industry's demand for multifunctional and high-performance solutions. During food processing, the necessity to

incorporate various additives to achieve multiple functions not only increases production costs but also introduces potential safety risks^[88-89].

Lignin presents significant potential as a novel food additive. Its structure comprises various active groups, which confer a range of biological activities, including antioxidant and antibacterial properties. These characteristics make lignin a promising multifunctional food additive^[90]. Incorporating lignin into food can inhibit oxidative deterioration and help preserve nutrients and color by leveraging its antioxidant properties^[91]. For instance, adding lignin to baked goods can delay the oxidation of fats and oils, prevent rancidity, and extend the shelf life of baked goods. The antimicrobial properties of lignin can be utilized to inhibit the growth of microorganisms in food, reduce the reliance on preservatives, and enhance food safety. Incorporating lignin into dairy products can suppress the growth of beneficial bacteria, such as lactic acid bacteria, while also inhibiting the proliferation of harmful bacteria, thereby ensuring the quality and safety of dairy products. Additionally, lignin can be included in food as a source of dietary fiber, which promotes intestinal peristalsis and helps lower blood lipids and glucose levels, addressing consumer demand for healthier food options. Adding lignin to bread not only increases its dietary fiber content but also improves its texture and flavor, enhancing the overall nutritional value. As a natural food additive, lignin is derived from a variety of sources, is relatively low in cost, and exhibits good biocompatibility, aligning with the modern food industry's need for safe, natural, and multifunctional food additives^[91]

2.2.2 Current status of lignin applications in food safety

2.2.2.1 Application of lignin in food packaging

Lignin, a natural polymer, has garnered increasing attention for its applications in food packaging in recent years. Its unique chemical structure and physical properties provide excellent biocompatibility and degradability, making it a significant choice for plant-based materials. The antioxidant properties and UV shielding capabilities of lignin can help extend the shelf life of food products while reducing losses due to oxidation and photodegradation^[91]. Furthermore, lignin exhibits remarkable mechanical strength and toughness, which can effectively enhance the overall performance of packaging materials^[92].

In the preparation process, lignin can be combined with other bio-based polymers (e.g., polylactic acid (PLA), polycaprolactone (PCL), etc.) to enhance its processing performance and functionality. Studies have demonstrated that incorporating lignin at levels between 5% and 30% can significantly improve the mechanical properties of composites. For instance, the tensile strength of the composites increased by approximately 15% when 10% lignin was added. Additionally, the hydrophilic nature of lignin imparts excellent film-forming properties to the composites, making them suitable for packaging various food products^[93-94]. The development of lignin-based packaging materials also involves surface modification techniques. Modifying lignin through chemical or physical methods can enhance its compatibility with other polymers and improve the functionality of the packaging materials. Common modification techniques include graft copolymerization, cross-linking, and solvent impregnation. These methods can significantly enhance the

thermal stability, toughness, and barrier properties of lignin, thereby meeting the diverse requirements of food packaging^[95].

Lignin-based packaging materials have a multifaceted impact on food preservation and quality protection, primarily due to their antioxidant and barrier properties. In terms of antioxidants, the lignin structure contains abundant phenolic hydroxyl groups and other active functional groups. These groups have the ability to donate hydrogen atoms, allowing them to react with free radicals generated during the oxidation process of food, thereby effectively neutralizing these free radicals and inhibiting oxidation reactions^[96]. The lignin-encapsulated anthocyanin nanoparticles exhibited excellent encapsulation efficiency, and strong antioxidant and antibacterial activity against *Staphylococcus aureus*. When used as active ingredients in PVA-PEG-based packaging films, these films maintained the quality of tomatoes for at least 15 days at room temperature, which was significantly longer than the 7-day shelf life of tomatoes packaged with conventional PVA-PEG films and control samples^[97]. In the packaging of fatty foods, oxidation is the primary cause of rancidity, which produces unpleasant odors and harmful substances, ultimately diminishing the quality and safety of the food. Lignin-based packaging materials can slow down the oxidative rancidity process of fats and oils due to their antioxidant properties. Studies have demonstrated that when lignin is added to polylactic acid and other packaging materials for soybean oil, the peroxide value of the oil stored under identical conditions is significantly lower in the lignin-containing packaging compared to the control group without lignin. This indicates that lignin effectively inhibits the oxidation of fats and extends the shelf life of the oil. Lignin can also reduce the catalytic effect of metal ions on the oxidation reaction by chelating metal ions, further enhancing its antioxidant effect. Some metal ions in food, such as iron ions and copper ions, can accelerate the oxidation reaction, lignin can combine with these metal ions to reduce their catalytic activity, thus protecting the food from oxidation. In terms of barrier properties, lignin-based packaging materials provide a significant barrier to oxygen, water vapor, and other substances. Oxygen is a critical factor contributing to the oxidation and deterioration of food, while the presence of water vapor affects the moisture content, which in turn influences the taste, texture, and microbial stability of food. Lignin-based packaging materials impede the transmission of oxygen and water vapor through their molecular structure and physical properties. Some studies have examined lignin-based packaging materials combined with other biopolymers and found that their oxygen transmission rate is significantly lower than that of conventional packaging materials. This characteristic effectively reduces the contact between food and oxygen, thereby delaying the oxidation process. In terms of water vapor barrier properties, lignin-based packaging materials also demonstrate excellent performance, maintaining the stability of the food's moisture content. This helps prevent food from drying out and hardening due to moisture loss, as well as inhibiting microbial growth caused by excessive moisture. When packaging bakery products such as bread, lignin-based packaging materials can effectively block water vapor, helping to maintain the soft texture and freshness of the bread while extending its shelf life. Additionally, lignin-based packaging materials serve as a barrier against certain odoriferous substances, preventing external odors from permeating the food and inhibiting the food itself from emitting odors, thereby

preserving its original flavor. For foods with particularly strong odors, such as durian and stinky tofu, lignin-based packaging materials can prevent these odors from contaminating other products while also maintaining the unique flavors of these items^[98-99].

However, lignin faces several challenges in practical applications. One significant issue is its structural complexity and the instability of its sources, which complicate the consistency and repeatability of its performance^[100]. Additionally, the poor processing characteristics of lignin hinder the application of conventional thermoplastic processing techniques to lignin substrates^[101]. Furthermore, lignin's high moisture absorption capacity can adversely affect the wet-state performance of packaging materials and the freshness of food products. Although lignin has demonstrated numerous advantages in the food packaging sector, market recognition still requires improvement. In-depth research into its functionalization within the industry, along with effective cost control, will be crucial for promoting the future application of lignin. Key areas for advancing the commercialization of lignin in the food packaging industry include the selection of diverse lignin sources, optimization of the extraction process, and modification of material properties. With advancements in material technology and a growing awareness of ecological and environmental protection, the application of lignin in food safety is expected to have increasingly broad prospects.

2.2.2.2 Application of lignin as a food additive

Lignin is an important natural polymer found abundantly in plants, known for its excellent biocompatibility and biodegradability. In the realm of food additives, the application of lignin has garnered increasing attention, particularly for its role as a natural antioxidant and functional ingredient^[102]. The antioxidant properties of lignin primarily stem from its rich phenolic hydroxyl structure, which makes it highly effective in preventing lipid oxidation and extending the shelf life of food products^[103]. Additionally, lignin is utilized to enhance the texture of food and improve its stability. It serves as an emulsifier and thickener, contributing to the consistency and mouthfeel of various food items. Furthermore, lignin exhibits strong emulsifying properties, effectively stabilizing oil-water separation and enhancing the texture of dairy products and condiments^[104]. Lignin offers innovative ideas and methods for optimizing food processing technology and enhancing food quality, and it is anticipated to be more widely utilized in the food industry.

Of course, the application of lignin as a food additive faces several challenges. Its poor solubility in food limits its effective utilization. Additionally, the undesirable odor and color of lignin can negatively impact the sensory properties of food, resulting in lower consumer acceptance. Therefore, it is essential to enhance the extraction and processing methods for lignin^[105-106]. Currently, researchers are exploring chemical modification and enzymatic techniques to improve lignin's applicability as a food additive.

Overall, lignin holds significant potential as a food additive, and its application in enhancing food quality and extending shelf life is promising. With ongoing research and technological advancements, the efficiency of lignin utilization and its market acceptance are expected to improve, creating new opportunities for the food industry. However, challenges related to the sensory properties and processing adaptability of lignin must still be addressed to facilitate a broader range of applications.

2.2.2.3 Application of lignin in food testing and safety assurance

Lignin, owing to its unique structure and properties, demonstrates significant potential in the development of innovative food detection technologies. The principle primarily relies on the specific interactions between lignin and target detectors, as well as the alterations in the optical and electrical properties of lignin itself to facilitate detection^[107-108]. In practical applications, lignin has been utilized to identify harmful substance residues in food and to monitor changes in food quality.

In the detection of harmful substances in food, a technology utilizing lignin has been developed to accurately measure pesticide residue levels. This ensures that pesticide residues in food remain within safe limits, thereby protecting consumer health. By combining lignin with various sensor technologies—such as modifying the surface of electrochemical sensors with lignin—researchers can leverage the interactions between lignin and microorganisms. These interactions lead to changes in the sensor's electrical signals, enabling rapid detection of microbial counts in food. For instance, when microorganisms like *E. coli* are present, their interaction with the active groups on the surface of lignin alters the sensor's electrical signals, such as resistance or current. By monitoring these signal changes, it is possible to assess the extent of microbial contamination in food^[109-110].

In monitoring the freshness and quality changes of food, the antioxidant properties of lignin can serve as an effective indicator for assessing the degree of oxidation in easily oxidized foods, such as fats, oils, and nuts. By detecting changes in the antioxidant activity of lignin within the food system, we can indirectly reflect the oxidized state of the food, thereby determining its freshness and quality. Additionally, lignin can be utilized to monitor food processing. During the processing of baked goods, the impact of lignin on α -amylase activity can be employed as a monitoring index. If the activity of α -amylase exhibits abnormal changes during processing, it may indicate issues with the processing technology, such as unsuitable temperature or time parameters. Timely adjustments to these parameters can help ensure the stability and quality of the baked products^[111-113].

Lignin holds significant promise and considerable development potential in the field of food testing. As public demands for food safety and quality continue to rise, there is an increasing need for food testing technologies that are accurate, rapid, and convenient. Lignin, a natural, abundant, and distinctive material with unique properties, offers innovative ideas and approaches for advancing food testing technology. In the future, lignin may be further utilized to develop more sensitive and rapid food detection methods. When combined with nanotechnology, lignin can be transformed into nanomaterials, such as lignin nanoparticles^[114]. Its high specific surface area, along with its unique optical and electrical properties, can be harnessed to create new types of nanosensors for detecting trace amounts of hazardous substances, biotoxins, and other contaminants in food^[115-116]. Additionally, lignin may be integrated with biorecognition technologies, such as immunoassay and nucleic acid aptamer technologies, to develop highly specific food detection methods that enhance accuracy and selectivity. With ongoing technological advancements and in-depth research, the application of lignin in the field of food testing will continue to expand, further unlocking its developmental potential^[117].

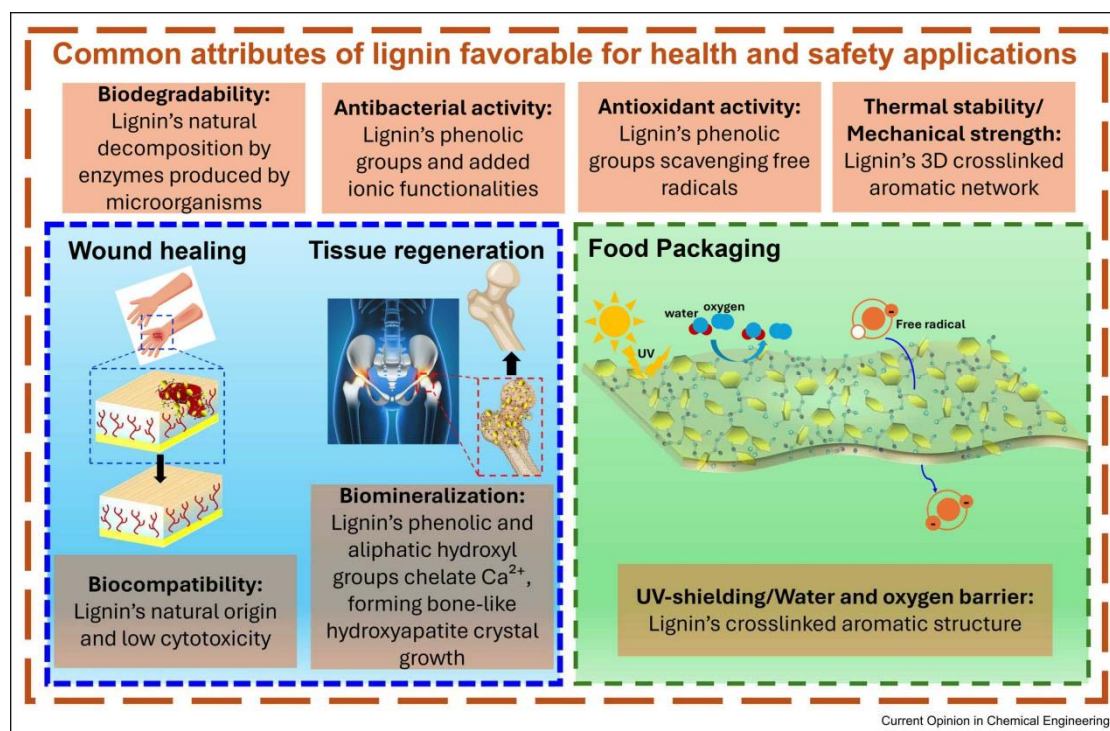


Figure 3. The appeal of lignin in applications such as food safety^[24].

3. Types of lignin-based materials used in food safety applications

3.1 Films and Coatings

The use of lignin-based films and coatings in food safety is increasingly attracting attention, as these materials are not only biocompatible but also demonstrate excellent gas barrier properties and mechanical strength. Lignin, a natural polymer, contains a wealth of functional groups, including hydroxyl and methoxy groups. These characteristics allow lignin to impart favorable film-forming and functional properties to the films^[118-120].

For one thing, treatments that modify lignin can further enhance the performance of the film. For example, lignin can be compounded with polylactic acid (PLA) or polyvinyl alcohol (PVA) to create a composite film that improves mechanical strength and elasticity, while also enhancing water vapor and oxygen barrier properties. Research has shown that the tensile strength of the film can be increased to 35 MPa, with an elongation of 250%, through such modifications^[121].

Second, lignin-based coatings play a crucial role in food safety. By applying lignin to the surface of food packaging, the freshness of food can be effectively extended, and the oxidation process can be slowed^[122]. For instance, when the lignin content in the coating is maintained between 2% and 5%, it can significantly reduce the oxygen levels inside the package, thereby mitigating the risk of oxidative deterioration of food. Additionally, the antimicrobial properties of lignin offer further protection for food safety^[123], with studies demonstrating significant inhibition of *E. coli* and *S. aureus*.

Third, although lignin-based films and coatings demonstrate good performance, several challenges persist. First, lignin's poor solubility can impact the homogeneity of the films and coatings, as well as complicate the coating process^[124]. Second, the variability among lignin sources results in differences in their

physicochemical properties, which can influence their effectiveness in various applications^[125]. Therefore, establishing standardized lignin extraction and modification processes is essential for further enhancing performance. Additionally, research into the long-term stability and degradability of lignin is gradually increasing to ensure safety and environmental sustainability during application.

In conclusion, lignin-based films and coatings demonstrate significant potential in the field of food safety. However, further research and optimization are necessary to enhance material properties and improve process feasibility.

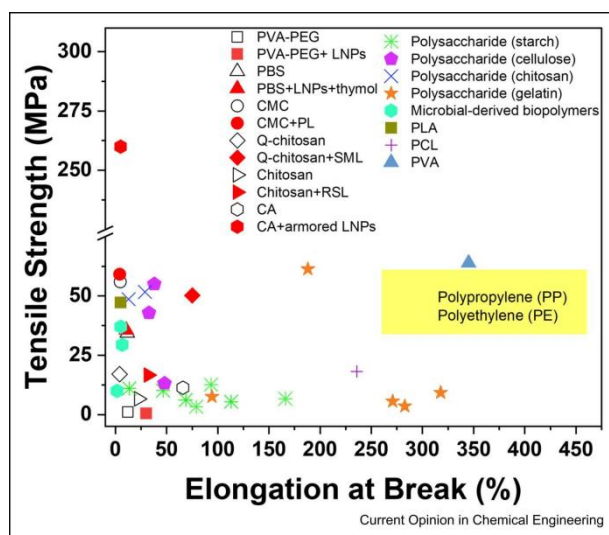


Figure 4. Mechanical performance of membranes for food packaging applications^[24].

3.2 Composite material

The application of lignin-based composites in the field of food safety has garnered significant attention. As natural polymers with excellent biocompatibility and biodegradability, lignin-based composites possess low cost, good processability, and excellent mechanical properties, making them suitable for mass production of food packaging materials; thus, lignin serves as an ideal component for such materials^[126-127].

The incorporation of lignin not only enhances the mechanical properties of the composite but also improves its barrier properties and UV resistance. Research has demonstrated that the tensile and flexural strengths of the composites are significantly increased with lignin concentrations ranging from 10% to 30%^[128]. For instance, when the lignin content is at 20%, the tensile strength can be enhanced by over 20%. Furthermore, lignin exhibits remarkable shielding capabilities for volatile substances, particularly in food preservation, thereby extending the shelf life of food products^[129].

In the preparation process, lignin and polymer composite methods primarily include melt mixing, solution casting, and copolymerization. Among these, the melt mixing method is widely favored due to its ease of operation and low cost. The temperature is maintained within the range of 160°C to 180°C, which facilitates the complete melting of lignin and promotes effective interaction with the matrix polymer. Additionally, the incorporation of suitable cross-linking agents, such as melamine-formaldehyde resin, can significantly enhance the thermal stability and mechanical strength of the composites^[130].

However, the food safety of lignin-based composites warrants careful consideration. Their decomposition products may release hazardous substances at elevated temperatures, necessitating an evaluation of the materials' pyrolytic behavior to ensure safety in food contact conditions^[131]. The volatile components of these composites can be effectively analyzed using gas chromatography-mass spectrometry (GC-MS), and migration tests can be conducted to assess their potential impact on food quality, if required.

Nevertheless, there are several challenges associated with lignin-based composites. First, the water solubility of lignin and compatibility issues with other polymeric materials limit its application in specific food packaging. Second, while lignin enhances the mechanical properties of materials, the processing characteristics still require optimization, particularly in large-scale industrial production processes. Additionally, the source of lignin and the cost of purification are critical factors that impact its large-scale application. Therefore, future research should concentrate on efficient extraction and modification techniques for lignin to reduce production costs and enhance its functional properties. Overall, lignin-based composites present significant potential for application and scientific research value in the field of food safety.

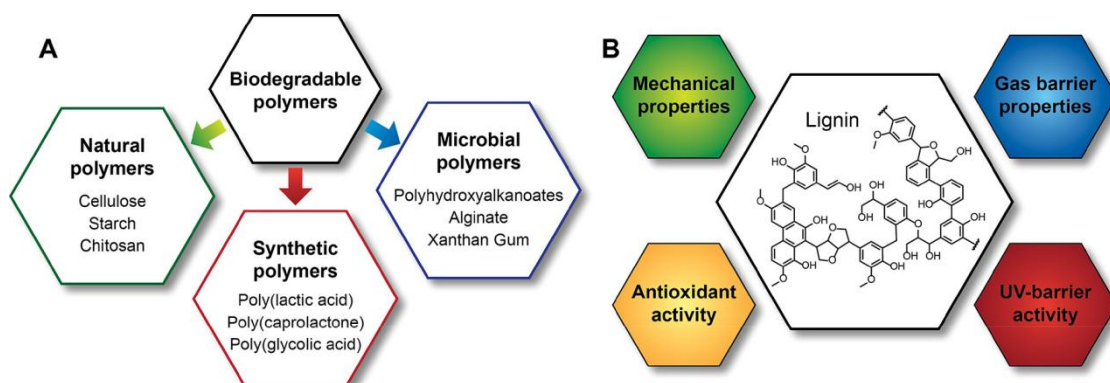


Figure 5. Biodegradable polymers utilized in food packaging^[68].

3.3 Nanoparticles

Lignin nanoparticles, with a typical particle size of 10–200 nm and tailorable shape via various preparation conditions, are a highly promising class of biomaterials increasingly utilized in food safety applications due to their exceptional biocompatibility and environmental friendliness^[132]. The preparation of these nanoparticles typically involves lignin as the primary raw material, which is modified through chemical or physical methods to create nanocomposites with specific functionalities. Notably, the preparation methods for lignin-based nanoparticles include solution polymerization, ultrasonic-assisted techniques, and sol-gel processes. These methods effectively control the morphology and size of the particles, endowing them with remarkable properties at the nanoscale^[133–135]. Research has demonstrated that smaller particle sizes correspond to larger specific surface areas, which can enhance the nanoparticles' ability to interact with target molecules. And the good dispersibility, strong functional activity, which can effectively exert antimicrobial and antioxidant effects in food packaging and additives. For instance, studies have shown that modified lignin-based nanoparticles can inhibit certain pathogenic bacteria by over 85%, exhibiting strong antimicrobial properties^[136–137].

In food safety monitoring, lignin-based nanoparticles are extensively utilized for the detection and removal of heavy metal ions, pesticide residues, and other pollutants. Research indicates that lignin-derived nanoparticles, when used as adsorbents, can achieve removal rates of heavy metal ions such as lead and cadmium exceeding 90%, demonstrating excellent adsorption capacity. Furthermore, these nanoparticles exhibit remarkable stability across various pH conditions and can adapt to a wide range of food environments^[138-139].

Although lignin-based nanoparticles offer significant advantages in the field of food safety, their application still encounters several challenges, primarily related to production costs and the feasibility of large-scale manufacturing. The source of lignin and its extraction process can influence the quality and performance of the nanoparticles, necessitating further optimization to reduce costs. Additionally, the migration behavior of lignin-based nanoparticles in food, as well as their long-term safety, requires urgent evaluation through more comprehensive studies to ensure their safety and effectiveness in practical applications.

Overall, lignin-based nanoparticles are emerging as significant materials in the field of food safety due to their renewable and environmentally friendly properties. However, addressing the technical and scientific challenges associated with their application remains a crucial focus for future research.

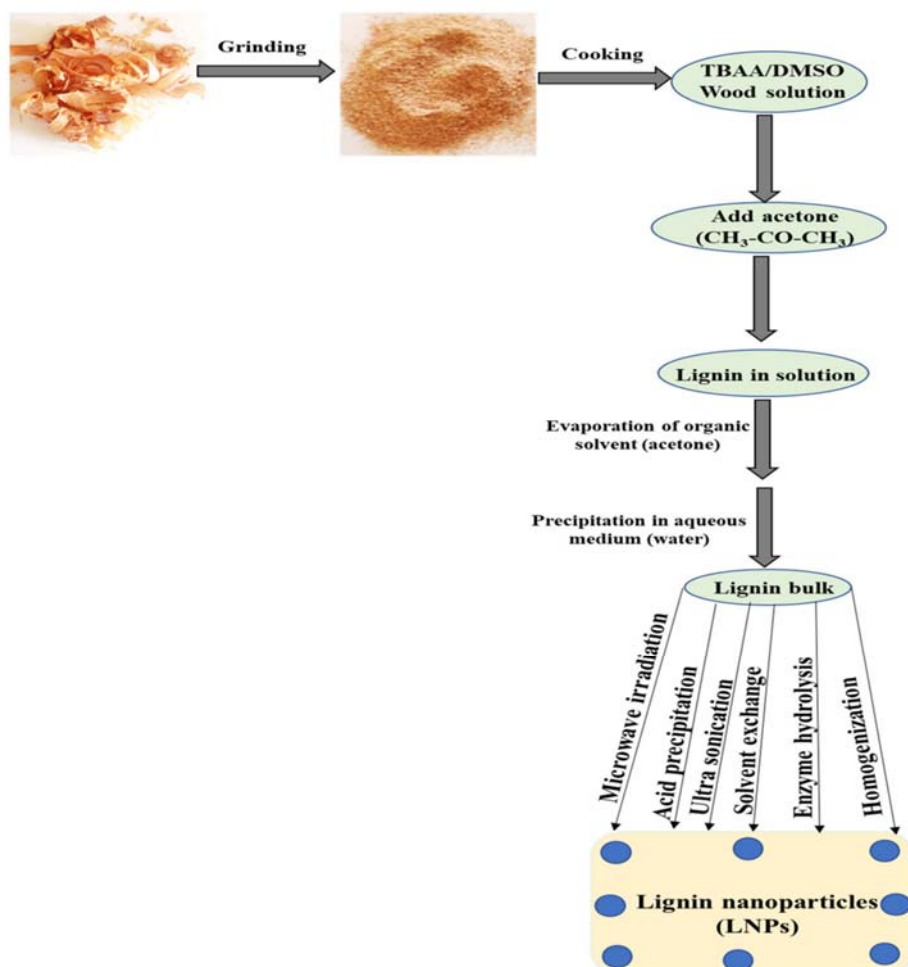


Figure 6. Schematic diagram of lignin nanoparticle synthesis methods^[140].

Table 1. Information from some of the latest reports on the synthesis of hollow nanoparticles/nanocapsules of lignin^[141].

Type of Lignin Used and Structure Formed	Method Used	Mechanism suggested
Ultrasonic Assisted synthesis		
Dioxane soluble fragment of alkali lignin, hollow colloid	Ultrasonic spray-freezing	Peripheral precipitation
Kraft lignin, microcapsules	Ultrasound driven self-association	Ultrasound-mediated cross-linking
Kraft lignin, nanocapsules	Ultrasonication of microemulsion	Ultrasound-induced self-assembly and complexation
Kraft lignin, hollow nanospheres	Ultrasonication assisted solubilization, anti-solvent addition	Self-assembly at two different phases
Wheatgrass lignin and Sarkanda grass lignin	Ultrasonication of aqueous suspension	Side chain cleavage/depolymerization and oxidative coupling/polymerization
Homogenization assisted synthesis		
Organosolv lignin residue, submicron spheres	Homogenization enhanced nucleation	Hydrophilic-lipophilic aggregation
Change of pH and/or solvent		
Enzymatic hydrolytic lignin, single hole nanospheres	Solvent-anti-solvent precipitation method	Layer by layer self-assembly outside to inside
Kraft lignin, nanocapsules	Solvent-anti-solvent precipitation method	Spontaneous distribution of hydrophilic-lipophilic sequences
Softwood Kraft lignin, lignin Nanoparticles	Anti-solvent addition using dialysis bag	Chemical precipitation
lignin nanocontainer	Interfacial polyaddition	Polyaddition reaction at interface
Enzymatic hydrolytic lignin, solid nanospheres	Solvent-anti-solvent precipitation method	Layer by layer self-assembly inside to outside
Kraft lignin, nanospheres	Solvent-anti-solvent precipitation method	Chemical precipitation
Low sulfonated lignin (indulin AT)	Solvent-anti-solvent and base-acid precipitator	Chemical precipitation
Kraft lignin	DMF (solvent)-compressed CO ₂ (anti-solvent)	Expansion by anti-solvent

4. Safety Evaluation of Lignin

4.1 Toxicological studies on lignin

Lignin is a naturally occurring polyphenolic compound that is widely found in the cell walls of plants^[142]. In recent years, an increasing number of studies have focused on its toxicological properties, primarily due to safety concerns associated with the widespread use of lignin in the food industry. Laboratory toxicological studies have demonstrated that lignin and its derivatives exhibit varying cytotoxic responses in both in vitro and in vivo experiments. Research has shown that lignin, at certain concentrations, can induce the generation of intracellular reactive oxygen species (ROS), disrupting the redox balance of cells and leading to apoptosis. This effect is particularly pronounced in specific types of hepatocytes and renal cells^[143]. Additionally, a 90-day subchronic oral toxicity study on Sprague-Dawley rats fed calcium lignosulphonate at a dose of 2000 mg/kg bw/day showed no significant adverse effects on body weight, organ indices, blood biochemical indicators, or histopathological changes of major organs^[144]. Moreover, lignin-loaded chlorogenic acid particles alleviated patulin-induced liver and colon damage in mice, reversing colon length

shortening and abnormal serum biochemical indicators, further supporting lignin's *in vivo* safety and protective potential^[145].

The chemical structure of lignans from various sources varies, which directly influences their toxicological behavior. For instance, terpene-type and phenolic-type lignans exhibit significant differences in toxicity across cell lines; the former demonstrates a stronger toxic effect on human hepatocellular carcinoma cells, while the latter has a milder effect on skin cells^[146]. Furthermore, the high molecular weight of lignin is positively correlated with its biocompatibility; however, excessively high molecular weights may trigger immune responses in certain biological environments. In the study, lignins of different molecular weight ranges (e.g., 1000-5000 Da and 5000-10000 Da) exhibited dose-dependent acute toxicity in mice^[147].

The effects of lignin on the liver and kidneys have been extensively studied in animal experiments. Mice treated with lignin exhibited significantly elevated levels of liver enzymes, such as ALT and AST, particularly in the high-dose group, indicating a potential risk of liver injury. Additionally, there is concern regarding the accelerated absorption of certain heavy metals facilitated by lignin as it passes through the digestive tract. This phenomenon was confirmed in *in vitro* experiments, especially in the presence of cadmium and lead, where lignin was shown to enhance their toxicity^[148].

To understand the mechanisms behind lignin's toxicity, researchers have investigated its capacity to bind to cell membrane receptors and its influence on the regulation of transcription factors. For instance, lignin can modulate the immune response by inhibiting the NF- κ B signaling pathway, which results in reduced immunity in organisms that are chronically exposed to lignin^[149].

The reproducibility and applicability of various studies in toxicological assessment still require further validation. Despite the significant toxicological data provided by existing research, the chronic toxic effects and potential environmental safety of lignin intake remain highly controversial. Therefore, future studies should focus on elucidating the toxicological mechanisms of lignin, and comprehensive evaluations should be conducted to ensure its safe application in the food sector while fully understanding the potential risks it may pose^[150].

4.2 Biocompatibility of lignin-based materials

Lignin-based materials are increasingly being recognized for their potential in food safety applications, particularly due to their biocompatibility, which stems from their unique chemical structure and biological properties. Lignin is a significant natural polyphenolic polymer characterized by its phenylpropene derivative composition. This material demonstrates low toxicity and promotes good cell adhesion and proliferation when in contact with living organisms.

Studies have demonstrated that lignin and its derivatives exhibit excellent compatibility with a diverse array of cell types, including fibroblasts, endothelial cells, and muscle cells. Cytocompatibility tests were conducted on various lignin-based materials using the MTT assay and fluorescent staining techniques to evaluate cell proliferation and survival. The results indicated that the cell survival rate for lignin-based materials typically exceeded 80% and displayed favorable nutrient release characteristics^[151-152].

In terms of antimicrobial properties, lignin-based materials exhibit inhibitory effects against a broad spectrum of bacteria and fungi. These antimicrobial properties primarily stem from the aromatic structure and phenolic hydroxyl groups present in lignin, which are biologically active. It has been observed that lignin additives can significantly reduce microbial growth in food packaging materials, positively impacting the shelf life of food^[153].

At the same time, lignin-based materials offer significant advantages in terms of biodegradability^[154]. Unlike traditional plastics, lignin-based materials are rapidly decomposed by microorganisms in soil and water, thereby reducing environmental impact. Research has demonstrated that the degradation cycle of polylactic acid (PLA) composites enhanced with lignin can be shortened to just a few months, ensuring excellent ecological compatibility^[155].

Although lignin-based materials offer numerous advantages in terms of biocompatibility, they still encounter several challenges. The structural complexity and diversity of lignin sources result in a wide range of physicochemical properties, which impose greater demands on their processing and performance stability. To address these challenges, future research will primarily focus on modifying lignin to improve its potential for food safety applications. By employing chemical modification or copolymerization techniques, the mechanical properties and thermal stability of lignin-based composites can be enhanced, thereby expanding their range of applications.

Taken together, the biocompatibility of lignin-based materials in the field of food safety establishes a solid foundation for their large-scale application. However, future research and development must concentrate on enhancing the material properties and reducing production costs to facilitate their widespread use in the food industry.

4.3 Health effects of long-term lignin consumption

The health effects of long-term lignin consumption have increasingly attracted the attention of researchers. As a crucial component of plant cell walls, lignin exhibits excellent biocompatibility and biodegradability, leading to its widespread use in the food industry in recent years. Its primary functions include increasing the fiber content of foods, promoting intestinal health, and enhancing the antioxidant capacity of various food products.

Studies have shown that lignin intake promotes intestinal microbial diversity, with a recommended daily intake of 2 to 6 grams to maintain optimal digestive function. In the gut, lignans serve as prebiotic factors that stimulate the growth of beneficial bacterial strains, such as bifidobacteria and lactobacilli. This stimulation helps improve intestinal permeability and reduce inflammatory responses. According to a 2020 study, regular consumption of lignin-rich foods can decrease the incidence of intestinal diseases by approximately 35%^[156]. Furthermore, the antioxidant properties of lignans help mitigate cellular damage caused by free radicals, significantly lowering the risk of cardiovascular disease^[157].

Individual differences in the metabolism and effects of lignin should not be overlooked. Research has shown that variations in genetic background and gut microbiome can influence how individuals respond to

lignin, with some people experiencing different effects based on their gut microbial composition. Consequently, it is essential to conduct further research to establish safe intake levels for diverse populations. More clinical trials and epidemiological studies are urgently needed to clarify the specific effects and potential risks associated with long-term consumption of lignin on human health.

4.4 Detection and assessment of lignin residues

Detection and assessment of lignin residues are crucial in the field of food safety. Lignin, a significant component of plant cell walls, can pose potential risks to food quality and safety. In recent years, various methods have been employed for the detection and assessment of lignin residues, primarily including chemical analysis, physical analysis, and bioassays.

Among the various chemical analytical methods, liquid chromatography (HPLC) and gas chromatography (GC) are the most commonly employed detection techniques. HPLC is particularly effective in separating lignin components with high sensitivity and specificity, making it suitable for analysis in complex food matrices^[158]. Research has demonstrated that HPLC equipped with a UV detector can achieve a detection limit as low as 0.1 mg/L. Conversely, the GC method is ideal for analyzing volatile lignin components, and when coupled with mass spectrometry (MS), it enables more accurate qualitative and quantitative analyses. Relevant studies indicate that the results of lignin residue determination using GC-MS reveal that residues can be effectively identified within the range of 1-100 mg/kg^[159].

Physical analytical methods primarily include Fourier Transform Infrared Spectroscopy (FT-IR) and Near Infrared Spectroscopy (NIR) techniques. The FT-IR method facilitates rapid screening and quantitative analysis of constituents by identifying the characteristic absorption peaks of lignin. The results indicate that FT-IR can effectively identify lignin at a concentration of 100 mg/kg. NIR technology has been employed for online monitoring of lignin content, leveraging its rapid and non-destructive characteristics^[160-161]. However, current technology still requires improvements in accuracy and reproducibility to meet the standards of the food industry.

Bioassay methods primarily encompass enzymatic and biosensor technologies. The enzymatic method employs specific enzymes to degrade lignin and assess the conversion rate of the reaction it influences. This approach offers high sensitivity and selectivity. Furthermore, biosensor technology has demonstrated promising applications in monitoring lignin residues. By integrating specific recognition of lignin with transduction materials, real-time monitoring can be achieved, with a detection limit as low as 0.05 mg/L^[162].

The methods for detecting and assessing lignin residues are diverse, and effectively combining different technologies can enhance the overall quality of food safety monitoring. With ongoing technological advancements and innovations, the monitoring of lignin in the realm of food safety will become increasingly refined in the future, ensuring the quality and safety of food.

5. Challenges and Strategies in Application

5.1 Technical Challenges in Extraction and Purification

5.1.1 Limitations of Existing Extraction Methods

Currently, the methods for extracting lignin primarily include chemical, biological, and physical extraction techniques. However, each of these methods has significant limitations.

The chemical extraction method is one of the most commonly used techniques for lignin extraction, which primarily includes the acid method, alkali method, and organic solvent method. Acid extraction of lignin typically employs either dilute or concentrated acids to hydrolyze plant fiber materials, thereby separating lignin from cellulose. However, this method generates a significant amount of acidic waste, leading to serious environmental pollution. Additionally, the extraction process often involves high temperatures and strong acidic conditions, which can compromise the structural integrity of lignin and reduce its biological activity^[163].

Bio-extraction is a relatively environmentally friendly method that primarily involves enzyme digestion and microbial fermentation. The enzymatic method utilizes specific enzymes, such as lignin peroxidase and laccase, to hydrolyze plant fibers and separate lignin. This approach is mild, preserves the structure of lignin, and exhibits high selectivity^[164-165]. However, the high cost of enzymes, relatively low extraction efficiency, and extended extraction time pose challenges for large-scale production. In contrast, the microbial fermentation method employs microorganisms to ferment plant fibers, thereby separating lignin from cellulose. While this method is also environmentally friendly, the fermentation process is significantly influenced by microbial species, culture conditions, and other factors. Additionally, the long fermentation cycle and unstable yield further limit its industrial application^[166].

Physical extraction methods include mechanical, ultrasonic, and microwave techniques. The mechanical method separates lignin from plant fibers using mechanical forces, such as ball milling and grinding. While this method is straightforward, it has low extraction efficiency, high energy consumption, and results in low lignin purity. The ultrasonic method employs ultrasonic cavitation and mechanical vibrations to enhance the mixing of lignin and solvent, thereby improving extraction efficiency^[167-169]. However, the high cost of ultrasonic equipment and stringent equipment requirements make large-scale application challenging. The microwave method leverages both thermal and non-thermal effects of microwaves to facilitate the release of lignin from wood. Nonetheless, lignin may undergo thermal degradation during microwave extraction, which can negatively impact its quality and performance, and the equipment costs are also relatively high.

5.1.2 Factors Affecting Lignin Purity and Quality

The purity and quality of lignin are influenced by several factors, with the source of raw materials and the extraction process being two of the most significant.

Different sources of raw materials lead to variations in the structure and composition of lignin, which in turn affect its purity and quality. Factors such as plant species, growing environment, and geographical location all influence lignin characteristics^[170]. The proportions of the three primary lignin monomers—coniferyl alcohol (guaiacyl), sinapyl alcohol (syringyl), and p-hydroxyphenylpropane—vary among different plant species, resulting in differences in the chemical structure and physical properties of

lignin^[171]. Lignin extracted from hardwoods predominantly contains guaiacyl-syringyl lignin (G-S), while lignin extracted from softwoods primarily consists of guaiacyl lignin (G). Additionally, plants growing in diverse environments may exhibit variations in lignin content and structure. For instance, plants at high altitudes may possess a relatively higher lignin content and a more complex structure due to harsher environmental conditions. Furthermore, lignin content and structure can differ across various parts of the plant, such as the bark, trunk, and branches. Typically, the lignin content in the bark is higher than that in the trunk, and its structure may be more compact. These variations in raw material sources result in fluctuations in the purity and quality of the extracted lignin, complicating efforts to meet the stringent quality consistency requirements for lignin in the food sector^[172].

The extraction process significantly influences the purity and quality of lignin. Different extraction methods can result in variations in both the purity and structure of lignin. Among the chemical extraction methods, acid and alkali techniques can easily compromise the structural integrity of lignin, thereby reducing its purity and potentially introducing impurities. In the acid extraction process, the highly corrosive nature of acids can lead to lignin degradation, producing smaller molecules and diminishing its purity. Conversely, in alkaline extraction, excessive alkali can engage in side reactions with lignin, resulting in structural changes that compromise its quality. Although the biological extraction method is less destructive to the structure of lignin, it suffers from low extraction efficiency, and impurities such as microorganisms or enzymes may remain, adversely affecting its purity. Among the physical extraction methods, ultrasonic and microwave techniques can lead to thermal degradation or structural alterations of lignin if the parameters are not properly calibrated, thereby impacting its quality. In microwave extraction, excessive microwave power or prolonged exposure can cause lignin to undergo pyrolysis, producing volatile substances that diminish its purity. Additionally, factors such as temperature, time, solvent concentration, and other parameters during the extraction process significantly influence the purity and quality of lignin. Elevated temperatures or extended extraction times can lead to degradation or oxidation, further reducing its quality. Inappropriate solvent concentrations may hinder the dissolution and separation of lignin, resulting in decreased purity^[173-175].

5.1.3 Direction of technical improvement and research progress

In order to overcome the limitations of the existing extraction methods and improve the purity and quality of lignin, researchers have carried out a lot of research on the improvement of lignin extraction and purification technology, and have made some important progress.

In terms of advancements in extraction technology, an increasing number of studies are focused on developing green and efficient extraction methods. Combining the advantages of multiple extraction techniques to create a unified extraction technology has emerged as a significant research direction. Ultrasonic-assisted alkaline extraction technology, which combines the cavitation effect of ultrasound with alkaline extraction, can accelerate the dissolution of lignin, enhance extraction efficiency, and reduce both the amount of alkali used and environmental pollution. Research indicates that during the ultrasonic-assisted alkaline extraction of lignin, optimal ultrasonic power and duration can increase the extraction rate by 20% to

30%, while decreasing the alkali requirement by approximately 30%. Microwave-assisted enzyme extraction technology utilizes the thermal effects of microwaves in conjunction with enzyme catalysis to achieve efficient lignin extraction in a shorter time frame, while minimizing structural damage to the lignin. By optimizing microwave power, enzyme dosage, and reaction time, the extraction rate of lignin can exceed 80%, resulting in high-purity lignin with excellent biological activity^[176-177].

In the realm of purification technology, new separation and purification methods are continually emerging. Membrane separation technology, recognized for its efficiency, has been widely adopted for lignin purification. Ultrafiltration and nanofiltration membranes effectively eliminate impurities in lignin based on molecular size and charge properties, thereby enhancing lignin purity. The purification of alkaline lignin through ultrafiltration membranes can remove small molecule sugars, proteins, and other contaminants, increasing lignin purity to over 90%. Nanofiltration membranes can further eliminate inorganic salts and low molecular weight phenolics from lignin, resulting in high-purity lignin. Additionally, ion exchange technology can purify lignin by exchanging impurity ions with ion exchange resins, achieving the desired level of purification. The purification of lignosulfonates using strongly acidic cation exchange resins effectively removes metal ions, thereby improving the quality of lignin^[178-180]. Some research has yielded promising results in the protection of lignin structure and the optimization of its properties. By fine-tuning extraction conditions—such as temperature and pH—structural damage to lignin during the extraction process can be minimized, thereby preserving its biological activity^[181]. In chemical extraction methods, the structural integrity of lignin can be effectively maintained by employing mild reaction conditions and avoiding high temperatures, as well as the adverse effects of strong acids and bases. Studies have shown that deep eutectic solvents (DESs) extraction not only better preserves the structural integrity of lignin and enhances its antioxidant and antimicrobial properties but also is feasible for large-scale application. Its raw materials are low-cost and biodegradable, reducing the extraction cost by 20%–30% compared with traditional organic solvent extraction. Modifying lignin through chemical and physical methods can enhance its properties, making it more suitable for applications in the food industry. The introduction of hydrophilic groups onto the lignin molecule via graft copolymerization can improve its solubility and dispersion, facilitating its incorporation into food systems. The modified lignin produced by grafting acrylic acid onto lignin molecules through a free radical polymerization reaction demonstrated a 5- to 10-fold increase in water solubility and exhibited excellent dispersibility in food emulsion systems^[182-183].

5.2 Safety and Regulatory Standards Issues

5.2.1 Safety assessment of lignin in food applications

Safety assessment of lignin in food applications is a key component to ensure its proper use in food safety. Currently, the safety of lignin is assessed in terms of toxicology, microbiological safety and chemical residues.

In terms of toxicological assessment, animal experiments are among the most commonly used methods. Researchers administer varying doses of lignin to experimental animals (e.g., mice, rats) and observe their

growth and development, physiological indices, histopathological changes, and other factors to evaluate the acute, subchronic, and chronic toxicity of lignin^[184].

The microbial safety assessment examines whether lignin promotes the growth and reproduction of harmful microorganisms and whether it inhibits beneficial microorganisms in food. Given that lignin possesses certain antimicrobial properties, it typically does not encourage the proliferation of harmful microorganisms under normal conditions. However, if lignin is improperly sourced or handled, it may harbor microorganisms or provide nutrients that facilitate microbial growth, thereby increasing the risk of food contamination. Harmful microorganisms, such as *Escherichia coli* and *Staphylococcus aureus*, can be introduced during the extraction and processing of lignin if hygienic conditions are not adequately maintained. Additionally, lignin may impact beneficial microorganisms in food, such as lactic acid bacteria and bifidobacteria. Some studies indicate that high concentrations of lignin may inhibit the growth of lactic acid bacteria, potentially affecting the quality of fermented foods^[185-186].

Chemical residue assessment, on the other hand, focuses on determining whether harmful substances, such as heavy metals, organic solvents, and pesticide residues, remain in lignin during extraction and processing. In the chemical extraction method, acids, alkalis, and organic solvents may persist in the lignin if not completely removed, posing potential risks to human health^[187-188]. When lignin is extracted using an alkaline method, any residual lye can increase the pH level of the lignin, which may adversely affect the taste and stability of food. Additionally, highly alkaline lignin can irritate the gastrointestinal tract. Some lignin raw materials may originate from plants contaminated with pesticides, leading to the presence of pesticide residues in the lignin^[189]. Therefore, conducting chemical residue testing on lignin to ensure compliance with food safety standards is a crucial measure for ensuring its safe use in food products.

5.2.2 Inadequacies in relevant regulations and standards

There are many imperfections in the existing food safety regulations and standards for the application of lignin, which, to a certain extent, restrict the wide application of lignin in the field of food safety.

In terms of food additive regulations, there are relatively few provisions for lignin as a food additive. The regulations governing food additives in many countries and regions are primarily designed for traditional synthetic additives, resulting in a lack of clear guidelines regarding the scope of use, usage limits, and quality standards for lignin, which is a novel type of natural food additive. In China, lignin is not explicitly listed among the permitted food additives in the food additive use standard GB 2760-2014. Although lignin exhibits various biological activities, such as antioxidant and antibacterial properties, and holds potential for use as a food additive, the absence of clear regulatory provisions has led food companies to hesitate in utilizing lignin as an additive for fear of non-compliance with regulatory requirements. Additionally, there is a lack of standardized safety assessment methods and procedures for evaluating lignin as a food additive. Different research organizations and enterprises may employ varying assessment methods, resulting in poor comparability and reliability of the assessment outcomes.

Regarding the regulations on food packaging materials, while some regulations address the safety and hygiene standards of these materials, the unique properties and potential risks associated with lignin-based packaging are not adequately considered. The biodegradability, antioxidant, and antimicrobial properties of lignin-based packaging materials provide distinct advantages in the food packaging sector; however, current regulations lack established testing methods and standards for these characteristics. When lignin-based packaging materials come into contact with food, both lignin and its degradation products may migrate into the food, alongside issues related to the migration of limited standard substances. Unfortunately, these aspects are not clearly defined in the regulations. In the European Union's food contact material regulations, although overall migration limits for packaging materials are specified, there is a notable absence of specific testing methods and limit requirements for the migration of lignin in lignin-based packaging materials. This gap complicates the ability of food companies to ascertain whether lignin-based packaging materials comply with regulatory standards during use, and it also hinders enforcement efforts by regulatory authorities.

In terms of food testing standards, there is a significant lack of standardized methods for lignin-related testing. As previously mentioned, lignin has potential applications in food testing, where it can be utilized to detect pesticide residues, microbial contamination, freshness, and other factors in food^[190-191]. However, the absence of unified testing standards leads to discrepancies in test results obtained by different organizations and methods, ultimately affecting the accuracy and reliability of the tests. For instance, when detecting pesticide residues in food using the emulsion liquid-liquid microextraction technique developed with lignin, the lack of a standardized method results in variations in extraction conditions, testing instruments, and data analysis across different laboratories. This inconsistency leads to poor comparability of test results. The quality control standards for lignin-based food testing products are also imperfect, making it difficult to ensure the quality and performance of the products.

5.2.3 Suggestions for Establishing Sound Regulations and Standards

In order to promote the healthy and orderly development of lignin in the field of food safety, it is essential to establish and improve relevant regulations and standards.

The characteristics and application scenarios of lignin must be thoroughly considered when formulating regulations and standards. For lignin used as a food additive, it is essential to clarify its scope of use, usage limits, and quality standards. The application scope of lignin across different food categories should be determined based on its source, extraction method, and biological activity. In oil and fat-based foods, lignin can serve as an antioxidant; therefore, its maximum usage level should be specified to ensure it effectively fulfills its role as an antioxidant without posing risks to human health. Quality standards for lignin as a food additive should be established, encompassing purity, impurity content, active ingredient concentration, and other relevant indices to ensure the stability, safety, and reliability of lignin products.

Strengthening international cooperation and fostering exchanges while learning from advanced global experiences is a crucial approach to establishing effective regulations and standards. Currently, several countries and regions are exploring international regulations and standards related to lignin. China can

actively engage in the development and revision of these international standards, drawing insights from the advanced practices of other nations. The European Union has established comprehensive regulations regarding food contact materials, which China can reference. By adapting these relevant EU regulations to align with China's specific circumstances, we can develop regulations and standards for lignin-based packaging materials that are suitable for the country's needs. Additionally, enhancing collaboration with the International Organization for Standardization (ISO) and other international bodies will promote the advancement of lignin-related international standards and strengthen China's influence in the global discourse on lignin.

It is essential to establish an effective mechanism for the implementation and oversight of regulations and standards. Supervisory departments should enhance their monitoring of lignin production, food processing, and food packaging enterprises to ensure strict adherence to these regulations and standards. Quality testing of lignin products must be intensified, with regular sampling of lignin additives and lignin-based packaging materials available in the market, and appropriate actions taken against products that fail to meet the established standards. A robust complaint and reporting mechanism should be established to encourage consumers and businesses to report violations, thereby strengthening social oversight. Additionally, efforts should be made to improve public awareness and training regarding regulations and standards, enhancing the knowledge and understanding of both enterprises and consumers about lignin regulations, and promoting the effective implementation of these standards.

5.3 Costs and Barriers to Scale-up Production

5.3.1 Analysis of the reasons for the higher cost of lignin production

The higher cost of lignin production is mainly affected by a variety of factors such as raw materials, processes, equipment and other factors. From the perspective of raw materials, although lignin is widely present in plant cell walls, there are certain difficulties in obtaining high-quality and stable lignin raw materials. Different plant sources of lignin exhibit significant variations in their structure and properties. Lignin derived from hardwoods, softwoods, and herbaceous plants differs in the composition ratio of phenylpropyl alkyl units, connection modes, and other factors^[192]. This variability results in inconsistent quality of lignin extracted from different raw materials, making it challenging to meet the consistency requirements for industrial production. To obtain lignin with specific properties, it is often necessary to screen and pre-treat the raw materials, which increases costs. Additionally, some lignins used in the food sector may need to be extracted from specific plant species that are expensive to cultivate, harvest, and transport, further escalating the overall cost of the raw material^[193].

The complexity and high energy consumption associated with the extraction process are significant factors contributing to the elevated cost of lignin production. As previously mentioned, various challenges exist with the chemical extraction methods commonly employed today, including acid, alkali, and organic solvent techniques. Acid and alkali methods necessitate the use of substantial quantities of acidic and alkaline reagents during the extraction process, leading to high costs for purchasing these reagents and managing

subsequent processing. In alkaline extraction, not only is a large amount of sodium hydroxide and other alkaline substances required, but the resulting alkaline wastewater also demands extensive treatment to comply with environmental regulations, further increasing production costs^[194-196].

The investment and maintenance costs of production equipment significantly impact lignin production expenses. The extraction and processing of lignin necessitate specialized equipment, making the research, development, and manufacturing of such machinery both challenging and costly. High-efficiency lignin extraction equipment, such as continuous alkaline extraction systems and advanced membrane separation technologies, often comes with a substantial acquisition cost, representing a significant investment for enterprises. Additionally, the maintenance and upkeep of this equipment require skilled technicians and considerable capital investment. During operation, these machines are susceptible to corrosion from chemical reagents and material wear and tear, necessitating regular maintenance and the replacement of parts, which further increases production costs. Upgrading the equipment also demands ongoing investment to enhance production processes and improve product quality^[101].

5.3.2 Technical and market challenges for large-scale production

In the realm of technology, while the extraction and application of lignin continue to advance, several key technical challenges remain unresolved, hindering the potential for large-scale production. For instance, the extraction methods currently in use lack efficiency, cost-effectiveness, and environmentally friendly practices for large-scale lignin extraction. The environmental pollution associated with chemical extraction methods, the low efficiency of biological extraction techniques, and the high energy consumption and equipment costs of physical extraction methods all require further research and improvement. Additionally, lignin modification technology needs enhancement. To meet the diverse application needs across various food sectors, lignin must be modified to improve its solubility, dispersion, stability, and other properties. Presently, the existing modification methods often involve harsh reaction conditions and yield unstable results, making widespread application in large-scale production challenging. Furthermore, when lignin is incorporated into food emulsion systems, achieving even dispersion and stability within the emulsion through modification presents a significant technical challenge that must be addressed.

The application of lignin in the food industry requires further optimization. In food packaging, while lignin-based materials offer certain advantages, challenges remain in ensuring consistent performance and quality stability during large-scale production. Additionally, improving the production efficiency of these packaging materials is a critical issue that must be addressed. In the realm of food additives, it is essential to determine the optimal quantity and method of lignin incorporation, as well as to ensure its compatibility with other food ingredients, which warrants in-depth research. Furthermore, in bread making, the inclusion of lignin may impact the fermentation performance of the dough and the texture of the final product. It has been reported that lignin nanoparticles (LNPs) incorporated into polybutylene succinate (PBS) composite films exhibit antifungal effects against *Aspergillus niger* and *Penicillium* spp., the major fungi causing bread spoilage. At 0.5% (w/v), LNPs showed in vitro fungal growth inhibition of 51.89% and 55.94% against A.

niger and *Penicillium* spp., respectively. Additionally, it has been observed that adding lignin at a concentration of 1% to 3% of the flour mass can significantly improve the texture and flavor of the bread without adversely affecting the fermentation and baking processes ^[197-198]. These challenges necessitate the optimization of both formulation and processing techniques.

From a market perspective, lignin has relatively low awareness and acceptance in the food safety sector, presenting a significant challenge for large-scale production. Consumers possess limited knowledge about lignin and are often skeptical regarding its safety and functionality in food, which, to some extent, hampers the marketing of lignin-based food products. Some consumers view lignin as an unfamiliar substance and worry that its inclusion in food may pose adverse health effects, leading them to prefer traditional, lignin-free products when making purchases. Food companies also express concerns about the application of lignin, fearing that its use will increase production costs and diminish the competitiveness of their products in the market. Given the current high production costs associated with lignin, food companies may need to raise the prices of their products when incorporating lignin as an additive or packaging material, potentially resulting in a loss of consumers. Additionally, the lack of standardized market regulations and specifications for lignin-related products exposes businesses to certain risks during the production and sales processes. The lack of uniform quality standards and testing methods makes it difficult for companies to ensure the consistency of product quality and can easily lead to market confusion.

5.3.3 Strategies to reduce costs and promote large-scale production

To reduce the cost of lignin production and promote large-scale manufacturing, various strategies can be implemented. In terms of technological innovation, it is essential to increase research and development (R&D) investment in lignin extraction and modification technologies. Governments and enterprises should encourage scientific research institutions to conduct relevant studies and explore new extraction methods and modification techniques. The development of greener and more efficient joint extraction technologies is vital. This involves combining the advantages of different extraction methods, such as integrating ultrasonic-assisted extraction with bio-extraction techniques. Utilizing ultrasonic cavitation can enhance the efficiency of bio-extraction while simultaneously minimizing the use of chemical reagents to reduce environmental pollution. Regarding modification technology, research should focus on gentler and more efficient modification methods. This includes applying green chemistry principles and developing new modification reagents and reaction conditions to achieve precise structural control of lignin and enhance its performance. Additionally, through genetic engineering, microorganisms can be modified to secrete more effective ligninolytic enzymes, thereby improving the efficiency of biological extraction methods.

The optimization of the production process is a crucial strategy for reducing costs. Enhancing existing extraction and processing methods can significantly improve production efficiency while minimizing energy consumption and waste of raw materials. In chemical extraction, it is essential to optimize reaction conditions—such as temperature, duration, and reagent concentration—to increase the lignin extraction rate and decrease the quantity of reagents used. Implementing a continuous production process can enhance

equipment utilization and lower production costs. In the manufacturing of lignin-based packaging materials, optimizing the laminating process is vital for improving the compatibility of lignin with other materials, reducing the defect rate, and boosting production efficiency. Additionally, employing an automated control system to monitor and adjust parameters in real time can ensure production stability and maintain product quality.

Strengthening marketing and collaboration is essential for promoting the large-scale production of lignin. Enterprises and related organizations should enhance the publicity and dissemination of information about lignin to increase consumer and food industry awareness and acceptance. By organizing product promotion seminars, popular science lectures, and online marketing campaigns, the source, properties, functions, and safety of lignin can be effectively communicated to consumers, addressing any concerns they may have. Additionally, providing technical support and application solutions to food enterprises will help them overcome challenges associated with using lignin and reduce their application costs. It is also important to foster cooperation among enterprises to create a synergistic development model within the industrial chain. Lignin producers, food processing companies, and packaging material manufacturers should establish collaborative relationships to jointly develop lignin-related products, facilitating resource sharing, leveraging each other's strengths, reducing production costs, and enhancing market competitiveness. Furthermore, relevant regulatory bodies should strengthen oversight and management of the lignin market by establishing unified quality standards and testing methods, thereby promoting the healthy development of the industry.

6. Strategies to Address Challenges and Future Trends

6.1 Technological Innovation and Process Improvement

6.1.1 Research and Development of High-Efficiency Extraction and Purification Technologies

To address the technical challenges associated with lignin extraction and purification, researchers are dedicated to developing new and efficient technologies. Among these methods, enzymatic digestion has garnered significant attention due to its unique advantages. This method employs specific enzymes to hydrolyze plant fibers, facilitating the separation of lignin^[199].

The supercritical fluid method is an innovative extraction technology with significant potential. A supercritical fluid is defined as a substance that exists above its critical temperature and critical pressure, exhibiting properties of both liquids and gases. It possesses low viscosity, a high diffusion coefficient, and excellent solubility. In lignin extraction, carbon dioxide is a commonly used supercritical fluid due to its non-toxic, harmless, non-flammable, and cost-effective nature. Supercritical carbon dioxide can rapidly penetrate plant cell walls and dissolve lignin, which can then be separated from the supercritical fluid by altering the temperature and pressure. This method not only enables efficient lignin extraction but also minimizes the use of organic solvents, thereby reducing environmental pollution. Additionally, the lignin obtained through this process is of high purity and low impurity content. Several studies have demonstrated the use of supercritical carbon dioxide for lignin extraction, achieving extraction rates exceeding 70% under

optimized process conditions. The extracted lignin also exhibits enhanced structural integrity and biological activity^[200-201].

To enhance the purity of lignin, membrane separation technology plays a crucial role in its purification. Ultrafiltration and nanofiltration membranes can effectively separate and purify lignin solutions based on molecular size and charge properties. Ultrafiltration membranes are capable of removing large molecular impurities, such as proteins and polysaccharides, from lignin solutions, while nanofiltration membranes target smaller molecular impurities, including inorganic salts and low molecular weight phenolics. By integrating ultrafiltration and nanofiltration technologies, a multistage purification process for lignin can be achieved, significantly increasing its purity. Preliminary purification of alkali lignin using ultrafiltration membranes can eliminate most large molecular impurities, raising the purity of lignin to 70% - 80%. Subsequent purification through nanofiltration membranes can further elevate the purity to over 90%. Membrane separation technology offers advantages such as ease of operation, high separation efficiency, and low energy consumption, making it a vital area of development in lignin purification technology^[202-203].

6.1.2 Optimize lignin modification and application process

In order to improve the application performance of lignin in the field of food safety, it is key to improve the performance of lignin through modification. Chemical modification is one of the commonly used methods, through esterification^[204], etherification^[205], graft copolymerization and other reactions, the introduction of specific functional groups on the lignin molecule, thus changing the physical and chemical properties of lignin. Esterification can introduce ester groups into the lignin molecule, enhancing its hydrophobicity and thermal stability. By esterifying lignin with fatty acids, the solubility of the resulting esterified lignin in organic solvents is significantly improved, and its stability at elevated temperatures is enhanced. This makes esterified lignin more suitable for the production of food packaging materials that require high stability. Etherification, on the other hand, introduces ether bonds that improve the solubility and reactivity of lignin. When lignin is subjected to an etherification reaction with ethylene oxide, its solubility in water is significantly increased, facilitating its application in aqueous food systems^[206].

Graft copolymerization is a significant modification method that imparts new properties to lignin. Graft copolymers with unique characteristics can be synthesized by grafting monomers, such as acrylic acid and acrylamide, onto lignin molecules through free radical polymerization and other reactions. When acrylic acid is grafted onto the lignin molecule, the resulting graft copolymer exhibits excellent hydrophilicity and adsorption properties. This makes it suitable for use as a food preservative, as it can effectively absorb moisture and odors in food, thereby extending its shelf life. Additionally, the graft copolymer formed by grafting acrylamide onto lignin possesses flocculation properties, making it useful in the treatment of food processing wastewater. It can effectively remove suspended solids and organic matter from the wastewater, achieving the goal of water purification^[207-208].

In optimizing the application of lignin in the field of food safety, various strategies are required for different application scenarios. In food packaging, it is essential to optimize the lignin composite process in

conjunction with other materials. By adjusting the ratio and compounding method of lignin with biopolymers such as polylactic acid (PLA) and starch, the compatibility of lignin with these materials can be improved, thereby enhancing the overall performance of the packaging materials can be enhanced. In the preparation of lignin-PLA composite packaging materials, the co-extrusion method is employed. This involves the addition of compatibilizers and the optimization of extrusion process parameters, such as temperature and screw speed, to ensure that lignin is uniformly dispersed within the PLA matrix. This uniform dispersion enhances the mechanical, barrier, and antioxidant properties of the packaging materials. When applying lignin as a food additive, it is crucial to determine the optimal quantity and method of incorporation. Experiments are conducted to assess the effects of lignin addition in various food systems, taking into account factors such as food quality, taste, and safety, in order to establish the ideal amount of lignin to be added. In bread-making, it has been observed that adding lignin at a concentration of 1% to 3% of the flour mass can significantly improve the texture and flavor of the bread without adversely affecting the fermentation and baking processes. Employing appropriate addition techniques, such as pre-dissolving or dispersing lignin in suitable solvents before incorporating it into the food system, ensures even distribution of lignin in the food products, thereby maximizing its functional benefits^[209-211].

6.1.3 Utilize innovative technologies to enhance the effectiveness of lignin applications.

With the continuous advancement of science and technology, intelligent analytical instruments, nanotechnology, and other emerging technologies offer innovative methods to enhance the application of lignin in the field of food safety. Intelligent analytical instruments play a crucial role in lignin research and application. Advanced analytical tools, such as high-performance liquid chromatography-mass spectrometry (HPLC-MS) and nuclear magnetic resonance spectroscopy (NMR), enable rapid and precise analysis of the structure, composition, and content of lignin. HPLC-MS can separate and identify various components of lignin, determining its molecular weight and structural characteristics through accurate mass analysis, which provides essential structural information for the modification and application of lignin. NMR offers insights into the chemical environment and bonding modes of atoms within lignin molecules, aiding researchers in understanding the structure and reaction mechanisms of lignin. In studies examining the interaction between lignin and α -amylase, NMR technology can be employed to analyze the impact of lignin on the secondary and tertiary structures of α -amylase, thereby elucidating its mechanism of action. The application of these intelligent analytical instruments not only enhances the efficiency and accuracy of lignin research but also provides a more scientific foundation for the use of lignin in food safety applications^[212-214].

The role of nanotechnology in the application of lignin is becoming increasingly significant. The transformation of lignin into nanomaterials, such as lignin nanoparticles and nanofibers, can substantially alter the properties of lignin and broaden its range of applications. Lignin nanoparticles possess a high specific surface area and excellent dispersibility, enhancing their effectiveness as antioxidants and antimicrobials in food systems. Research has demonstrated that lignin nanoparticles exhibit a stronger inhibitory effect on common food contaminants, such as *Escherichia coli* and *Staphylococcus aureus*. This enhanced efficacy is

attributed to the ability of nanoparticles to more readily interact with microbial cell surfaces, disrupting the cell membrane structure and thereby inhibiting the growth of microorganisms. Lignin nanofibers possess exceptional mechanical and barrier properties, making them suitable for the production of high-performance food packaging materials. Incorporating lignin nanofibers into packaging materials, such as polylactic acid, can significantly enhance both the tensile strength and barrier properties, effectively prolonging the shelf life of food products. Additionally, nanotechnology can be employed to further improve lignin's performance through surface modification and the introduction of specific functional groups. By attaching antimicrobial peptides to the surface of lignin nanoparticles, the resulting composite nanomaterials exhibit enhanced antimicrobial activity, paving the way for the development of innovative food preservatives.

6.2 Strengthen the construction and supervision of regulations and standards

6.2.1 Improve the regulation and standard system of lignin in the field of food safety

The improvement of lignin regulations and standards in the field of food safety must begin with several key aspects. When formulating regulations and standards related to food additives, the use of lignin as a food additive should be clearly defined. The scope of lignin's application in various food categories—such as oils and fats, meat products, and dairy products—should be specified, taking into account its antioxidant, antimicrobial, and other functional properties.

For lignin-based packaging materials, regulatory standards should encompass testing methods and criteria for their biodegradability, antioxidant properties, antibacterial effectiveness, and other performance indicators. It is essential to establish biodegradability testing standards that specify the degradation time and rate of lignin-based packaging materials in natural environments, such as soil. For instance, the degradation rate should exceed 80% within a defined timeframe, such as six months. Additionally, it is important to develop testing methods and standards for evaluating antioxidant and antimicrobial properties. This can be achieved by assessing the impact of lignin-based packaging materials on oxidation indices and microbial counts in food products. Furthermore, migration limit standards for lignin-based packaging materials in contact with food must be clearly defined, including the maximum allowable concentration of lignin and its degradation products that can migrate into food. Migration experiments should simulate actual food packaging conditions to accurately determine these limits, ensuring that the concentration of lignin monomers does not exceed a specified threshold, thereby safeguarding food safety.

In the field of food testing, it is essential to develop standardized methods for lignin-related tests. For testing techniques that utilize lignin to detect pesticide residues, microbial contamination, freshness, and other factors, it is important to establish standards for uniform testing procedures, instrumentation requirements, data analysis methods, and more. Specifically, for the detection of pesticide residues in food using lignin-based emulsion liquid-liquid microextraction technology, clear standards should be defined for the selection of extractants, extraction conditions, and parameter settings of the testing instruments. This will ensure that test results from different laboratories are comparable and accurate. Additionally, quality control standards for lignin-based food testing products should be established, including requirements for product

stability, repeatability, sensitivity, and other performance indicators to guarantee product quality and effectiveness.

6.2.2 Strengthening Regulatory Measures and Quality Control

Strengthening regulatory measures and quality control is essential to ensure the safe application of lignin in the field of food safety. At the regulatory level, oversight of lignin production enterprises must be enhanced. Manufacturers should be required to maintain comprehensive production facilities and robust quality control systems, with strict monitoring of the production process. Additionally, manufacturers should implement a raw material inspection system that involves rigorous testing of purchased lignin raw materials to ensure their sources are reliable and that their quality meets established standards.

It is essential to enhance the oversight of food processing and packaging enterprises. When food processing companies utilize lignin as an additive, they must adhere strictly to the usage limits and guidelines established by regulations and standards. Regulatory authorities can verify compliance by sampling and testing the actual amount of lignin incorporated into food products, imposing penalties on companies that violate these standards. Additionally, when employing lignin-based packaging materials, food packaging enterprises must ensure that the quality of these materials meets the relevant standards. Regulatory agencies can assess the performance of packaging materials, including barrier properties, antioxidant capabilities, and antibacterial effectiveness, and prohibit the use of any materials that fail to meet established criteria.

The establishment of a robust quality testing system is essential for ensuring the quality of lignin. We are developing rapid and accurate lignin testing techniques, utilizing advanced instruments such as high-performance liquid chromatography-mass spectrometry (HPLC-MS) and nuclear magnetic resonance spectroscopy (NMR) to facilitate the swift analysis of lignin's structure, composition, and content. We have established comprehensive quality testing standards and procedures to rigorously evaluate the indices of lignin products. When assessing the purity of lignin, it is crucial to adhere to the specified testing methods to guarantee the accuracy of the results. Additionally, we are enhancing the training of testing personnel to improve their skills and professional expertise, thereby ensuring the quality of the testing process.

6.2.3 Promote Regulations and Standards in Accordance with International Standards

Promoting regulations and standards that align with international benchmarks can enhance the international competitiveness and application of lignin in the field of food safety in China. An analysis of international regulations and standards regarding lignin in food safety reveals significant differences in the formulation and implementation of these regulations across various countries and regions. The European Union has established comprehensive regulations for food contact materials, including clear provisions on biodegradability, migration limits, and other criteria for lignin-based packaging materials. In contrast, the United States enforces stringent procedures for the approval and regulation of new food additives under its food additive regulations. Understanding the characteristics and trends of these international regulations and standards provides valuable insights for China as it seeks to develop and improve its own relevant regulations and standards.

China should actively engage in the development and revision of international standards while strengthening cooperation with international organizations, such as the International Organization for Standardization (ISO). In the process of formulating international standards related to lignin, it is essential to leverage China's technical advantages and practical experience, proposing standards that align with both China's national conditions and international development trends. By participating in the development of international standards, China can enhance its international influence in the field of lignin, ensuring that its regulations and standards are better aligned with global benchmarks.

In the process of developing domestic regulations and standards, it is essential to draw from internationally advanced practices while considering China's specific circumstances. This approach will help create regulations and standards that align with both global trends and national conditions. When establishing regulations and standards for lignin-based packaging materials, we can reference relevant standards from the European Union and integrate them with the production and usage of packaging materials in China. This will allow us to formulate standards for biodegradability, migration limits, and other indicators that are appropriate for the Chinese context. Additionally, it is important to enhance our monitoring and research on international regulations and standards, enabling us to adjust our own regulations and standards promptly to meet the evolving demands of the international market.

6.3 Promoting Industrial Cooperation and Development

6.3.1 Strengthening Cooperation Among Industry, Universities, and Research Institutions to Promote Innovation and Development in the Lignin Industry

Industry-university-research cooperation plays an indispensable and crucial role in the research and development of lignin technology, as well as in the transformation of achievements and their industrial applications. As a source of knowledge innovation, colleges, universities, and research institutions possess a profound theoretical foundation and specialized scientific research capabilities in lignin-related basic research and technology development. These institutions are equipped with advanced scientific research tools and professional research teams that can initiate projects focused on the fundamental analysis of lignin structure, performance optimization, and the exploration of lignin's properties and application potential of lignin in depth. Scientific research institutions can conduct targeted research and development in technology, such as new lignin extraction and modification techniques, tailored to actual application needs. Research teams from universities specializing in chemical engineering and materials science have elucidated the mechanisms behind lignin's antioxidant, antibacterial, and other biological activities through in-depth studies of its molecular structure. This research provides theoretical support for the application of lignin in the field of food safety. Additionally, these institutions have developed various lignin extraction and modification processes, including enzyme extraction technology and ultrasound-assisted modification techniques, utilizing advanced experimental equipment and methodologies. These innovations have significantly enhanced the quality and performance of lignin.

Enterprises, as the primary entities in the market, play a crucial role in the transformation and industrial application of lignin research findings. They possess keen market insights and extensive experience in production practices, enabling them to convert the scientific achievements of universities and research institutions into tangible products and services. Enterprises can optimize and enhance lignin-related technologies based on market demand, facilitating industrial-scale production.

Industry-university-research cooperation can create complementary advantages and accelerate the innovative development of the lignin industry. Through collaboration, universities and research institutions can gain timely insights into market demand, ensuring that scientific research results are more targeted and practical. Meanwhile, enterprises can leverage the technical expertise of universities and research institutions to enhance their own innovation capabilities and product competitiveness. In the research and development of lignin extraction technology, universities and research institutes focus on technological innovation, while enterprises participate in pilot testing and industrial-scale production, collectively advancing the upgrading and application of lignin extraction technology. Additionally, industry-university-research cooperation can cultivate a pool of interdisciplinary talent proficient in both technology and market dynamics, providing essential support for the growth of the lignin industry.

6.3.2 Promote the synergistic development of upstream and downstream lignin industry

The synergistic development of the upstream and downstream of the lignin industry is of great significance for perfecting the industrial chain and improving the competitiveness of the industry.

In the upstream segment of the lignin industry, the focus is primarily on the supply of raw materials, as well as the extraction and processing of lignin. Raw material suppliers ensure a stable supply of lignin feedstock through strategic planning of plant cultivation. Some enterprises specialize in cultivating lignin-rich plants, such as fast-growing timber and herbaceous species, to provide adequate raw materials for lignin extraction companies. Lignin extractors continuously optimize their extraction processes to enhance both the yield and quality of lignin. The implementation of advanced extraction technologies, such as supercritical fluid extraction and ionic liquid extraction, not only improves the purity of lignin but also minimizes environmental impact.

In the midstream segment of the industry, the focus is primarily on lignin modification and deep processing. Modification enterprises enhance the performance of lignin through chemical and physical modification, among other methods, to make it more suitable for various applications. Modification enterprises enhance the performance of lignin through chemical and physical modification, among other methods. First, green chemical modification methods, such as enzymatic modification and microwave-assisted grafting modification, can improve lignin's solubility and dispersibility under mild reaction conditions, reduce environmental pollution, and retain its inherent biocompatibility. Second, composite modification with natural polymers can synergistically enhance lignin's functional properties, including antifungal activity and barrier performance, while lowering modification costs. Further processing enterprises then transform the modified lignin into a range of products, including lignin-based packaging

materials, food additives, and food testing reagents. The utilization of lignin to create high-performance food packaging materials not only provides excellent barrier properties but also imparts antioxidant and antibacterial functions to the packaging.

The downstream segment of the industry primarily focuses on the application and marketing of lignin products. Food processing companies and packaging material manufacturers are increasingly incorporating lignin into their production processes, leading to the development of food and packaging products with unique characteristics. Food processing enterprises use lignin as an antioxidant and preservative to enhance the quality and shelf life of their products. Meanwhile, packaging material companies leverage lignin-based materials to offer safe and environmentally friendly packaging solutions for food items. To boost consumer awareness and acceptance of lignin products, effective marketing strategies are essential to promote their benefits.

Synergistic cooperation between upstream and downstream enterprises facilitates resource sharing, leverages each other's strengths, and enhances the overall efficiency of the industry. Upstream enterprises supply high-quality lignin raw materials to midstream enterprises, which in turn provide downstream enterprises with lignin products that exhibit excellent performance. Additionally, downstream enterprises offer valuable market feedback to upstream and midstream enterprises, guiding product improvement based on consumer demand. In the production of lignin-based packaging materials, upstream lignin extraction companies collaborate closely with midstream modification and deep processing firms to ensure the consistent quality of packaging materials. Meanwhile, downstream food packaging companies provide feedback on the performance of these materials in response to market needs, prompting upstream and midstream enterprises to continuously refine their technologies and products. Through the synergistic development of upstream and downstream industries, we can also reduce production costs, enhance industry competitiveness, and promote the sustainable growth of the lignin sector.

6.3.3 Expanding the Market for Lignin Applications in Food Safety

To expand the application of lignin in the field of food safety, it is essential to implement a series of effective strategies. Strengthening publicity and promotion is a crucial means of increasing awareness and acceptance of lignin among consumers and food enterprises. Organizing various food industry exhibitions, seminars, technical exchanges, and other activities can effectively showcase the results and advantages of lignin in food safety applications. At food industry exhibitions, a dedicated lignin display area should be established to showcase lignin-based packaging materials, food additives, and other products, allowing consumers and food companies to intuitively understand the performance and applications of lignin. Additionally, inviting experts and scholars to deliver lectures and training sessions can help introduce the source, properties, functions, and safety of lignin, thereby alleviating any concerns from consumers and enterprises. Furthermore, utilizing the Internet, social media, and other platforms to conduct online promotional activities and publish scientific articles and videos related to lignin can significantly enhance public awareness of its benefits.

Carrying out demonstration application projects is an essential strategy for expanding the market. We should select representative food enterprises to implement lignin demonstration projects in areas such as food packaging and food additives. In the food packaging demonstration project, we will provide lignin-based packaging materials to food enterprises and assist them with packaging design and application testing. Through practical applications, we will showcase the advantages of lignin-based packaging materials in terms of freshness preservation, antioxidant properties, and antibacterial effects, allowing food enterprises to experience the benefits of lignin firsthand. In the food additive demonstration program, we will collaborate with food enterprises to develop new food products that incorporate lignin and promote these products in the market. By gathering consumer feedback, we will continuously optimize product formulations and processes, enhance product quality and taste, and accumulate valuable experience in the application of lignin within the food additives sector.

Strengthening collaboration with food enterprises to jointly develop new products and applications is essential for market expansion. Establishing long-term and stable partnerships with food companies allows for a deeper understanding of their needs and challenges. Together, we can create lignin products and application technologies tailored to the food industry. This includes the development of lignin-based preservatives and antiseptics that offer effective preservation and antimicrobial properties, addressing the food enterprises' requirements for food safety and longevity. Additionally, collaborating with food companies on research into the application of lignin in functional foods—such as lignin-rich dietary fiber products and antioxidant-rich foods—will help meet consumer demand for healthier options. Through these partnerships, we can not only broaden the application market for lignin but also foster innovation and growth within food enterprises, ultimately achieving mutual benefits and a win-win situation.

7. Conclusion

7.1 Summary of Research Results

This study has thoroughly explored the application of lignin in the field of food safety. As a natural and abundant biomass resource, lignin presents significant potential in food safety due to its unique chemical structure and diverse biological activities. In the realm of food additives, lignin can enhance the activity of α -amylase, thereby improving the processing performance of food. Additionally, it can be utilized to enhance flavor and increase the nutritional value of food. For instance, in bread production, the incorporation of lignin can result in a fluffier texture and extend the shelf life of the product.

In the area of food testing, lignin has been employed to develop innovative testing technologies, such as emulsion-liquid microextraction for detecting pesticide residues in food. Furthermore, it has been used in the creation of light-stabilized, multifunctional intelligent packaging films that monitor food freshness, providing a novel approach to ensuring food safety and quality control.

In terms of the current status of applications, lignin has significant uses in food packaging, food additives, and food testing and safety assurance. In food packaging, lignin-based materials have been developed and implemented, such as the lignin-reinforced polylactic acid created by KraussMaffei, which

demonstrates excellent mechanical properties, antioxidant capacity, and biodegradability. These materials effectively enhance the freshness and quality protection of food.

Regarding the safety evaluation of lignin as a food additive, *in vivo* toxicological studies have indicated that oral administration of lignin and its derivatives does not induce obvious pathological lesions in the major organs of experimental animals. Only mild lymphoid hyperplasia has been observed in a small number of animals, which doesn't compromise the overall safety of lignin. Furthermore, lignin and its derivatives can mitigate food contaminant-induced pathological damage to the liver and colon by reducing hepatocyte necrosis and mucosal inflammation—further confirming the safety and potential protective effects of lignin in food applications from a pathological perspective.

In response to these challenges, a series of coping strategies have been proposed. Regarding technological innovation and process improvement, research and development efforts are focused on high-efficiency extraction and purification technologies, such as enzymatic digestion, supercritical fluid extraction, and membrane separation techniques. Additionally, optimizing lignin modification and application processes, employing chemical modification and graft copolymerization to enhance lignin performance, and refining composite processes and additive methods are essential to improve its application in food safety. The integration of intelligent analytical instruments, nanotechnology, and other emerging technologies will further enhance the effectiveness of lignin applications. To strengthen the construction and supervision of regulations and standards, it is crucial to improve the regulatory framework for lignin in the food safety sector. This includes enhancing supervision measures and quality control, as well as aligning regulations and standards with international benchmarks to ensure the safe and standardized use of lignin in food safety. In terms of promoting industrial cooperation and development, it is important to foster collaboration among industry, academia, and research institutions. This will facilitate the synergistic development of the upstream and downstream lignin industry, expand the application market for lignin in food safety, and enhance recognition and acceptance of lignin through public outreach, demonstration projects, and partnerships with food enterprises. Ultimately, these efforts will drive the innovative development of the lignin industry.

7.2 Outlook on Future Research Directions

In the future, research on lignin in the field of food safety will expand in various directions to provide robust theoretical and technical support for its broader and more efficient application.

In the development of new lignin-based materials, the focus will be on composites made from lignin and other biomaterials. By combining lignin with polysaccharides (such as chitosan and sodium alginate), proteins (such as soy protein and gelatin), and other biomaterials, we can create new composite materials that exhibit synergistic effects. The lignin-chitosan composite, for instance, leverages chitosan's antibacterial and excellent film-forming properties in conjunction with the antioxidant properties of lignin. This combination aims to develop food packaging materials and preservation films with enhanced antibacterial properties and improved interaction mechanisms among various biomaterials and lignin. The goal is to optimize the performance of these composites, thereby enhancing their mechanical properties, barrier properties,

biodegradability, and more. Additionally, the research will explore the modification of lignin nanomaterials and the preparation of lignin-based products, such as nanofibers and nanoparticles. Nanosized lignin possesses a higher specific surface area and unique physicochemical properties, which can significantly enhance its dispersion and activity within food systems. Lignin nanoparticles can serve as carriers for functional ingredients, facilitating their precise delivery and slow release in food applications, ultimately improving the utilization and effectiveness of these functional ingredients.

In terms of in-depth research on the application effects of lignin, the mechanisms by which lignin interacts within complex food systems will be further explored. Food is a multifaceted system composed of various components, and the interaction mechanisms between lignin and these components have not been fully elucidated. This study aims to investigate the interactions of lignin with proteins, fats, carbohydrates, and other food components under different conditions, including physical interactions (e.g., adsorption, complexation) and chemical interactions (e.g., covalent bond formation, redox reactions). The goal is to reveal how lignin influences the quality, stability, and safety of food. Through advanced analytical techniques, such as nuclear magnetic resonance spectroscopy (NMR), Fourier transform infrared spectroscopy (FT-IR), and molecular dynamics simulations, this study conducts an in-depth analysis of the microstructure and dynamic changes of lignin within food systems. The goal is to provide a more scientific basis for the rational application of lignin. Research will be carried out on the application of lignin in various food processing techniques to evaluate its impact on food processing and the quality of the final products.

In the realm of safety research, it is essential to not only enhance toxicological evaluations and chemical residue detection but also to examine the potential risks associated with lignin during food processing and storage. As food processing technology continues to evolve, new methods may alter the structure and properties of lignin, potentially introducing new safety risks. Therefore, it is crucial to investigate the changes in lignin under these novel processing conditions, assess their impact on food safety, and develop appropriate safety control measures. Additionally, attention should be directed towards the stability and safety of lignin during long-term storage, specifically studying whether it degrades or produces harmful substances. This research aims to support the long-term storage and quality assurance of food products.

In terms of regulations, standards, and marketing, the increasing application of lignin in the field of food safety necessitates the enhancement of regulations and standards, as well as the strengthening of marketing efforts. Participating in the formulation and revision of international regulations and standards will promote the globalization of lignin-related guidelines and facilitate the circulation and application of lignin products in the global market. It is essential to conduct thorough market research to understand consumer demand and acceptance of lignin products, enabling the development of products that align with market needs. Additionally, increasing consumer awareness and trust in lignin through effective marketing and public relations will support the expansion of lignin's market presence in the food safety sector.

7.3 Significance and Implications for the Development of the Food Safety Sector

The application of lignin in the field of food safety holds significant importance and has a profound impact on both the protection of food safety and the advancement of the food industry. Regarding food safety, lignin offers a natural and safe solution for food preservation and corrosion resistance. Its antioxidant properties effectively inhibit the oxidative deterioration of food, helping to maintain both the nutrients and color of various products. In the case of oils and fats, lignin can slow down oxidative rancidity, reduce the formation of harmful substances, and protect the health of consumers. In meat products, dairy products, and other foods susceptible to microbial contamination, lignin's antimicrobial properties play a crucial role in inhibiting the growth and reproduction of microorganisms, thereby reducing the risk of food spoilage. Additionally, lignin can be utilized in food testing and the development of new detection technologies, such as those for identifying pesticide residues, microbial contamination, and assessing food freshness. This comprehensive approach to food safety enables timely detection of hazards, ultimately protecting the quality and safety of food.

From the perspective of promoting the development of the food industry, the application of lignin presents opportunities for innovation and enhancement. In the realm of food packaging, the development of lignin-based materials aligns with environmental protection principles and effectively addresses the pollution issues associated with traditional plastic packaging. These materials not only exhibit excellent biodegradability but also provide additional functions such as antioxidant and antibacterial properties, which help to maintain food freshness and offer food companies more competitive packaging options. In the realm of food additives, lignin serves as a novel multifunctional ingredient that enhances processing performance, flavor, and nutritional value. In bread production, the incorporation of lignin results in a fluffier texture, extends shelf life, and increases dietary fiber content, thereby addressing consumer demand for healthier options. This innovation enables food companies to create more functional products with unique attributes, expand their market share, and advance the food industry towards greener, healthier, and more sustainable practices.

The application of lignin in the field of food safety also fosters the synergistic development of related industries. As the use of lignin in food applications continues to grow, it drives advancements in lignin extraction, processing, and modification, thereby benefiting upstream industries. Additionally, this growth stimulates innovation in food packaging, food processing, and other downstream sectors. The collaboration between upstream and downstream enterprises has been strengthened, resulting in a comprehensive industrial chain that enhances the overall competitiveness of the industry. Furthermore, the application of lignin opens new research avenues for scientific institutions and universities, promoting the development of related technologies and innovations while providing technical support for the long-term advancement of the food industry.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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