BIO Web of Conferences **197**, 04004 (2025) https://doi.org/10.1051/bioconf/202519704004
*ICAS 2025*

# Lignin for Food Packaging: A Review on Its Role as Bio-based Reinforcement and Active Functional Material

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**Abstract.** Lignin, the second most abundant natural polymer after cellulose, presents substantial potential as a sustainable component for food packaging within the circular bioeconomy. As a byproduct of the pulp and paper industries, it is rich in aromatic structures and functional groups that enable dual functionality: acting as a bio-based reinforcing filler and as an active agent with antioxidant, antimicrobial, UV-blocking, and water vapor barrier properties. Incorporation of lignin into biopolymers such as PVA, PLA, chitosan, and protein-based films enhances tensile strength, crystallinity, and thermal stability while imparting biological activity that protects against microbial growth and oxidation. Despite these advantages, large-scale utilization remains limited due to poor compatibility with hydrophobic polymers, variability in lignin sources, color changes, and strict food safety regulations. Advances in chemical modification, surface treatment, and nanoparticle engineering have been proposed to address these challenges. This review emphasizes recent developments and outlines research directions toward optimizing lignin-based composites for industrial food packaging, contributing to sustainable material innovation in line with circular bioeconomy principles.
**Keywords:** Lignin, Food Packaging, Reinforcing Agent, Active Component, Polymer compatibility

## 1 Introduction

Lignin is the second most abundant natural polymer after cellulose, with global annual production estimated at 50–100 million tons as a byproduct of the pulp, paper, and bioethanol industries. However, less than 2% of this vast amount is utilized in value-added products such as surfactants and adhesives, while the majority is incinerated to generate energy [1–4]. As lignocellulosic biofuel production expands, lignin availability is expected to increase, offering opportunities for its valorization as a sustainable raw material for high-value applications, including food packaging, thereby supporting the transition toward a circular bioeconomy.

Lignin is one of the main components of plant cell walls, alongside cellulose and hemicellulose. Lignin contributes to the rigidity and flexibility of plants, protects woody tissues from microbial attack, and enhances resistance to environmental stresses [5], providing mechanical support and pathogen protection to plants. The lignin content in lignocellulosic biomass ranges between 15–35% [6]. Lignin is an amorphous natural polymer with a predominantly polar character. This bio-based material offers several advantages, including low cost, light weight, and good thermal properties [7]. Lignin is commonly isolated from pulp fibers and is considered a bioessential resource for biocomposite production due to its aromatic structure and functional groups [8]. It is regarded as a promising eco-friendly substitute for petroleum-based aromatic compounds [3, 9].

One potential application of lignin is as a reinforcing agent. Previous studies have shown that lignin incorporation can improve the mechanical properties of starch-PVA [10] polylactic acid (PLA) [11], Polyvinyl alcohol (PVA) [12–15] Poly (butylene adipate-co-terephthalate) (PBAT) polybutylene succinate (PBS), Polyhydroxybutyrate/ polyhydroxyalkanoate (PHB/PHA), Carboxymethyl cellulose (CMC) isolat protein whey (WPI), cellulose, Faba bean protein, chitosan, starch, and cationic wood nanofibers (CWNF). Furthermore, lignin is cost-effective, biocompatible, and non-toxic, making it a promising alternative for conventional food packaging materials. Additionally, there is a significant drive to develop more environmentally friendly composite materials, reduce reliance on synthetic reinforcements, and utilize abundant natural materials such as lignin. Increasing the utilization of lignin in composites can contribute to sustainability and reduce the environmental footprint of materials.

The use of reinforcing agents significantly influences the mechanical properties of films. The purpose of adding reinforcing agents is to produce films with desired characteristics. For example, metal matrix composites (MMC) can be tailored by incorporating appropriate reinforcements to achieve specific properties. The incorporation of natural fibers, such as sugarcane bagasse and coffee powder, into polymer matrices can either improve or reduce tensile strength, depending on the fiber aspect ratio and fiber-matrix interfacial compatibility.

In addition to its potential as a reinforcing agent, lignin also holds promise as a food packaging material or as an additive to enhance food packaging films, providing protection and extending the shelf life of food products. The incorporation of lignin into films can improve thermal properties, antioxidant and antimicrobial activities, UV-blocking capacity, and water vapor barrier properties. Moreover, lignin is cost-effective, biocompatible, and non-toxic, positioning it as a promising alternative to conventional food packaging materials. Despite its promising multifunctionality, the large-scale application of lignin in food packaging remains limited due to unresolved scientific and technological challenges. The most critical research gap lies in overcoming the poor interfacial compatibility between hydrophilic lignin and hydrophobic polymer matrices, which restricts uniform dispersion and mechanical reinforcement efficiency. Additionally, inconsistencies in lignin's molecular structure and composition across sources complicate its standardization for industrial use. Other issues such as undesirable color changes, processing difficulties, and stringent food safety regulations further hinder commercialization. Addressing these barriers requires an integrated approach combining chemical and physical surface modifications, nanoparticle engineering, and green treatment technologies such as plasma-assisted modification. Therefore, this review aims to summarize recent advances in lignin-based food packaging, highlight its dual role as a reinforcing and active functional material, and discuss current limitations and future research directions essential for enabling scalable, sustainable applications aligned with circular bioeconomy goals.

## 2 Methodology

This review adopted a systematic literature study approach to comprehensively evaluate lignin's role as a bio-based reinforcing and active material in food packaging applications. To ensure scientific rigor, only peer-reviewed journal articles indexed in Scopus and Web of Science were included.

The literature search was conducted across major databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Wiley Online Library, using combinations of keywords such as "lignin," "food packaging," "reinforcing agent," "bio-based composites," "antioxidant," "antimicrobial," and "UV-blocking." The selection criteria included (1) publication year between 2018 and 2025, (2) relevance to lignin incorporation in polymer matrices (e.g., PLA, PVA, chitosan, starch, protein-based films), and (3) focus on mechanical, thermal, and functional performance (antioxidant, antimicrobial, and barrier properties).

More than **120 scientific articles** were initially identified. After removing duplicates and irrelevant studies (e.g., lignin applications in non-packaging sectors such as energy storage or construction materials), a final set of **approximately 80 core articles** was selected and analyzed. These articles form the basis of the discussion in this review.

The data extracted from the selected literature were synthesized and presented in the form of **tables, figures, and comparative analysis**. Mechanical, thermal, and functional properties were compared across different polymer matrices to highlight the reinforcing and active roles of lignin. Additionally, specific attention was given to identifying **challenges, limitations, and future research directions** to bridge the gap between laboratory-scale studies and industrial applications.

## 3 Results and Discussion

### 3.1 Lignin Structure and Its Potential as a Reinforcing Agent

Lignin is a complex and rigid aromatic biopolymer composed of phenylpropane units connected through C–C and C–O linkages, forming a three-dimensional network structure (Figure 1). Its structural diversity, with functional groups such as phenolic, hydroxyl, and carboxyl, provides opportunities for interactions with various polymers. The abundance of aromatic rings also contributes to lignin's inherent thermal stability, while its amorphous nature offers flexibility for chemical modification [5]

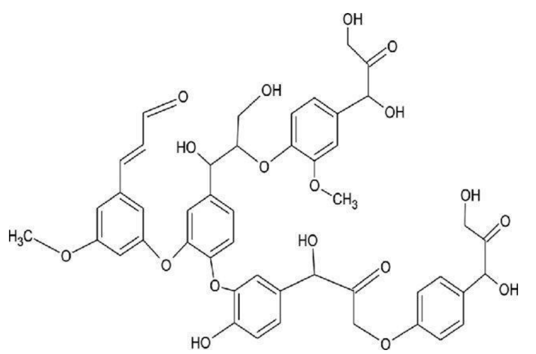

**Fig. 1** General schematic structure of lignin composed of phenylpropane units with various functional groups [5]

The incorporation of lignin into polymer matrices has been widely reported to enhance both mechanical and thermal performance. As shown in Table 1, lignin improves tensile strength, modulus, elongation at break, and thermal degradation resistance in a range of biopolymer matrices such as CMC, PLA, PVA, PBAT, PBS, PHB/PHA, whey protein isolate, faba bean protein, and chitosan-based films [12, 19]. For instance, the addition of kraft lignin increased the tensile strength of PVA by up to 80% [15], while faba bean protein films exhibited a 90% increase in tensile strength with 10% lignin loading. Similarly, lignin nanoparticles (LNPs) have shown superior reinforcing effects due to their high surface area and ability to form strong hydrogen bonds with PVA, chitosan, and chitin matrices, resulting in tensile strength improvements of up to 48% [12]

**Table 1** Percentage improvement in mechanical and thermal properties of polymer matrices reinforced with lignin.

| No. | Reinforcing Agent | Matrix | Percentage Improvement | |
|---|---|---|---|---|
| | | | Mechanical | Thermal |
| 1. | Lignin from date palm tree leaves (5%, 10%, 15%). | CMC | Tensile strength increased by 78.3% and elongation by 39.4%. | Improvement of 16.5%. |
| 2. | Kraft Lignin (KL) precipitated using a basic medium (KL A) and an acidic medium (KL B) at concentrations of 0.0, 0.5, 1.0, 2.5, and 5.0%). | PVA | Tensile strength increased by 80.0% for KL A and 46.0% for KL B | Increase in oxidation onset temperature (OOT) to 368.5°C for KL B at concentration of 1% [15]. |
| 3. | Lignin Nanoparticles (LNPs) from *Oxytenanthera abyssinica* | Film PVA, PVA/chitosan (PVA/CI), and PVA/chitin (PVA/CH). | Tensile strength increased by 15.04% in PVA/CI/LNP3 and 48.21% in PVA/CH/LNP 3 compared to binary composites without LNP. | Thermal properties significantly improved [12]. |
| 4. | Kraft Lignin (KL) (0, 2, 4, 6, and 8%). | Whey protein isolate (WPI) | Tensile strength increased by 9.8% at 4% lignin. | Maximum degradation temperature (Tmax) increased by approx. 1.65% at 6% lignin. |
| 5. | Lignin obtained from pine seeds (PL) with concentrations of 2.5, 5.0, 7.5, and 10% by weight. | Faba bean protein (FBP), plasticized with glycerol. | Tensile strength increased by 90% at 10% lignin content, and elongation at break increased by 107% at 5% lignin content. | Thermal degradation temperature increased especially in films with 10% lignin. |
| 6. | Grape seed lignin at concentrations of 1, 5, and 10%. | PHB and PHA. | 5% lignin increased the elastic modulus from 240 MPa (PHB/PHA without lignin). However, elongation at break decreased from 95.2 to 68%. | 5% lignin increased the thermal degradation temperature of film by 9-20°C. |
| 7 | Rice husk lignin was grafted with acrylic acid. Lignin concentrations of 30, 40, and 50%, | PBAT (Polybutyliene Adipate-Co-Terephthalate). | Lignin 30% increased the tensile strength by 4.73% and christality by 26%. | A significant increase in melting temperature. |

*to be continued…*

**Table 1** Percentage improvement in mechanical and thermal properties of polymer matrices reinforced with lignin.

| No. | Reinforcing Agent | Matrix | Percentage Improvement | |
|---|---|---|---|---|
| | | | Mechanical | Thermal |
| 8. | Kraft Lignin (unmodified and modified via esterification with phthalic anhydride). | Polybutylene succinate (PBS) | Tensile modulus increased by up to 110%. Flexural strength increased by approx. 40%. Impact strength increased by approx. 28% | Theral conductivity increased by around 8% (from 0.0903 to 0.0983 W/mK) |
| 9. | Klason lignin extracted from rubberwood sawdust. | Natural Rubber (NR) (cis-1,4-polyisoprene). | Tensile strength increased by 30% at 10 phr. Toughness increased by approx. 20%. Modulus (100 and 300%): Max. at 10 phr (Significant increase). | Thermal stability (T50) increased by approx. 9% from 357.9°C to 390.8°C. |
| 10. | Alkali lignin KOH-extracted lignin from sugarcane leaf (SCL) | Natural rubber (NR)-cis-1.4-polyisoprene. | Tensile strength increased by 9%, crosslink density increased by 31%, elongation at break reduced by approx. 7% from 735 to 681% due to higher crosslinking. | Thermal stability (T50) increased by 1.3% from 389 to 394°C. |
| 11. | Wood powder (10 wt%). | Kraft lignin (90 wt%, unmodified, precipitated from black liquor). | Storage modulus (E') increased by 60% for coarse beech (B1) vs. fine beech (B2). It is increased by 35% for coarse beech (B1) vs. spruce composites. | - |
| 12. | Modified lignin (Renol®) Biochar. | Acrylonitrile-Butadiene-Styrene (BS) thermoplastic | Young's modulus increased by 32%. Tensile strength increased by 23% (trade-off). Elongation at break reduced by 67%. | - |
| 13. | Kraft Lignin | Polyvinyl Chloride (PVC). | Young's modulus increased by 8.8%, elongation reduced by 73%, combustion indices increased by 50-80%. | |

The reinforcing effect of lignin is primarily attributed to its rigid aromatic backbone, ability to act as a nucleating agent, and hydrogen bonding interactions with polymer matrices. These interactions enhance stress transfer, increase crystallinity, and improve the stability of films under thermal stress [15]. For example, XRD analysis has revealed that the incorporation of lignin into CMC films leads to a more ordered and crystalline structure, correlating with a 78% increase in tensile strength and a 39% improvement in elongation.

However, the effect of lignin is highly dependent on concentration and dispersion. At moderate levels, lignin improves strength and barrier properties, but at high loadings (>15%), agglomeration occurs, disrupting the film matrix and reducing performance [10]. In PLA matrices for 3D printing, excessive lignin addition (20–40%) caused poor interlayer adhesion, resulting in brittleness and decreased tensile strength. These findings highlight the importance of optimizing lignin loading and ensuring good dispersion.

Overall, lignin's reinforcing role demonstrates strong potential for food packaging applications, where improved tensile strength, elasticity, and thermal stability are critical. Nevertheless, achieving uniform dispersion and compatibility with non-polar polymers remains a key challenge. Strategies such as esterification, surface modification, and the use of lignin nanoparticles have been proposed to overcome these limitations and maximize lignin's reinforcing potential in bio-based composites.

## 3.2 Requirements and Factors Influencing the Mechanical Properties of Reinforcement Agents

Natural resources and biomass are excellent candidates as reinforcing agents to produce sustainable "green composites" Biomass can also be derived from agricultural waste, offering significant potential as a reinforcing agent in polymers, resulting in improved composite properties across physical, mechanical, chemical, and thermal aspects. These materials can also serve as fillers in polymer composites reinforced with natural or synthetic fibers, enhancing the physical, mechanical, chemical, and thermal properties of the composites [7]. Additionally, natural reinforcements can be used in their raw state or modified after undergoing pretreatment procedures to remove unwanted substances and prepare them for composite applications. It has also been demonstrated that the chemical composition of the reinforcement significantly influences its mechanical properties. These characteristics aid in determining the most suitable type of reinforcement for specific applications.

Reinforcement is agent that provide mechanical strength to composite materials, including tensile strength and stiffness. The use of reinforcing agents is essential as they significantly influence the mechanical properties of films. The purpose of adding reinforcing agents is to achieve films with desired characteristics. For example, metal matrix composites (MMC) are created by incorporating suitable reinforcing agents to achieve the desired properties. In dental base resins (polymethyl methacrylate), the addition of micron or nano-sized metal/metal oxide particles and glass fibers enhances fracture strength (FS), fracture toughness (FT), and other related mechanical properties [7]. Similarly, the addition of natural fibers such as sugarcane sawdust and coffee powder into a polymer matrix can either enhance or reduce tensile strength depending on the fiber aspect ratio and fiber-matrix interfacial compatibility.

The requirements for reinforcing agents in composites include compatibility with the matrix, uniform distribution, proper proportion, surface treatment, high strength, and modulus (Fig. 2). Several factors influencing the mechanical properties of reinforcement agents in composites include filler type, filler aspect ratio, filler orientation, filler content, interfacial compatibility, and filler distribution within the matrix (Fig. 2).

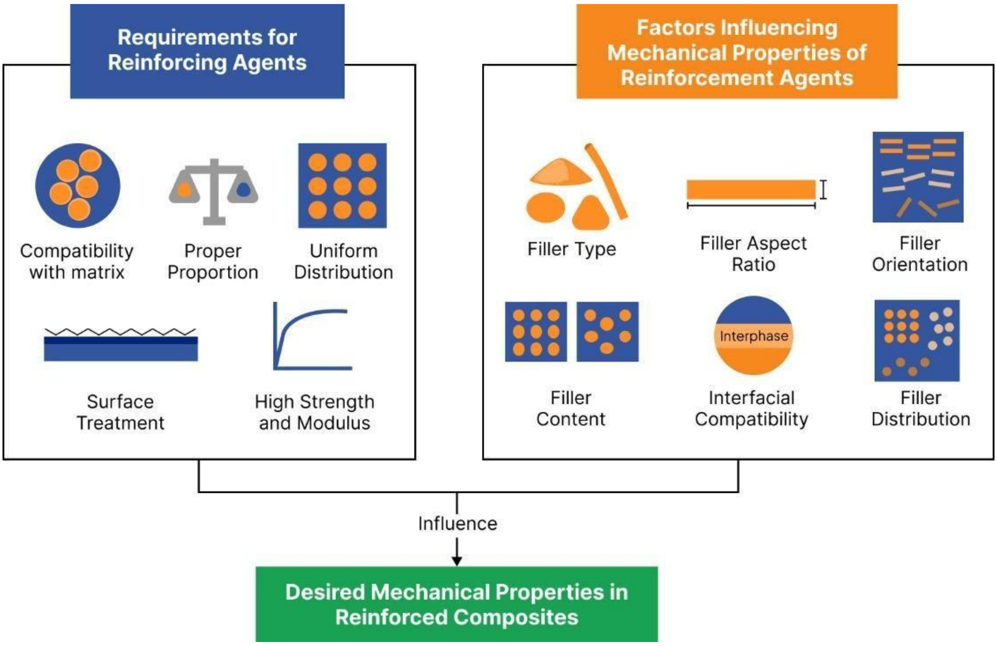


**Fig. 2** Requirements and Factors Influencing the Mechanical Properties of Reinforcement Agents

The effectiveness of a reinforcing agent in polymer composites is determined by several interrelated factors, which influence stress transfer, dispersion, and overall mechanical performance. First, the aspect ratio and particle size of the reinforcing agent play a critical role. Fillers with high aspect ratios, such as fibers, tend to provide better reinforcement due to greater interfacial contact with the matrix. In contrast, particulate fillers like lignin require good dispersion at the nanoscale to achieve significant strengthening effects.

Second, the interfacial adhesion between the filler and polymer matrix is a key factor. Strong interfacial bonding ensures efficient stress transfer from the matrix to the reinforcing agent. For natural fillers such as lignin, compatibility with hydrophobic polymer matrices often becomes a limitation, as their polar surface groups may cause poor adhesion and phase separation. Strategies such as chemical modification, coupling agents, or nanoparticle processing are therefore necessary to improve compatibility.

Third, the filler concentration directly affects composite performance. At optimum loading, reinforcement improves tensile strength and stiffness. However, excessive addition often results in agglomeration, creating stress concentration points and reducing mechanical performance [10]. This balance is particularly important in lignin-based composites, where loadings above 15–20% can lead to poor dispersion and deterioration of mechanical properties.

Fourth, the distribution and orientation of fillers also contribute to composite strength. Uniform dispersion allows even stress distribution, while orientation can improve directional properties. In the case of lignin, uniform nanoscale distribution maximizes the reinforcing effect by preventing weak zones in the polymer matrix.

Finally, the intrinsic properties of the reinforcing agent, including chemical structure, functional groups, and thermal stability are critical determinants of its reinforcing performance. Lignin's aromatic backbone and abundance of hydroxyl groups contribute to enhanced rigidity, hydrogen bonding, and thermal resistance, making it a particularly interesting candidate compared with other natural fillers

In summary, the performance of reinforcement agents in biopolymer films depends on a combination of particle characteristics, interfacial adhesion, concentration, distribution, and intrinsic properties. These factors must be carefully optimized to fully exploit lignin's dual role in improving both mechanical strength and functional properties of food packaging composites.

### 3.3 The Benefits of Lignin in Its Application as Food Packaging

Lignin is an aromatic polymer abundant in nature, possessing a variety of functional properties that make it a promising candidate for food packaging applications. The incorporation of lignin into polymer matrices not only improves the mechanical and thermal performance of films but also provides a wide range of functional properties that are essential for food packaging. These functionalities include antioxidant activity, antimicrobial activity, UV-blocking capacity, barrier performance, biodegradability, and food safety compliance, as summarized in **Table 2 and Fig. 3**.

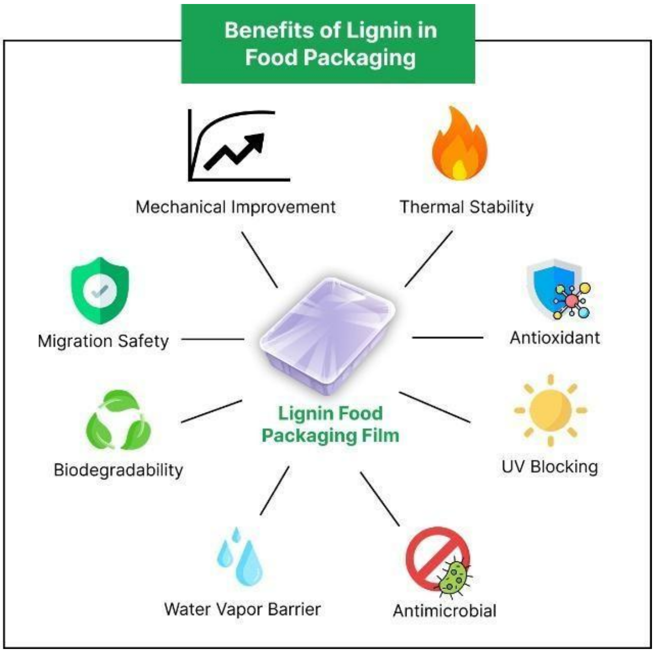


**Fig. 3** Schematic representation of the multifunctional benefits of lignin in bio-based food packaging films.

**Table 2**. The Effect of lignin addition on the improvement of mechanical, thermal, antioxidant, antibacterial, uv protection, and water vapor barrier properties.

| Filler | Matrix | Method/Process conditions | Functional Properties of Filler | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mechanical | | Ther-mal | Anti-oxi-dant | Anti-micro-bial |
| | | | Tensile strength (TS) | Elongation at break (EB) | | | |
| Lignin | Starch and PVA | Casting method | √ | √ | √ | √ | √ |
| Lignin nano-particles (LNPs) derived from *Oxytenanther a abyssinica* | PVA | Oven method | √ | √ | √ | √ | √ |
| Lignin extracted from date palm leaves | CMC | Oven method | √ | √ | √ | √ | √ |
| Kraft lignin (KL) solubilized in an alkaline solution | Whey protein isolate (WPI) | casting method | √ | √ | √ | √ | - |
| Phenolated lignin (P-AL) (the result of modifying alkali lignin with phenol to increase the phenolic group). ε-Polylysine (ε-PL) (antimicrobial agent) | Dissolving wood pulp | Oven method | √ | √ | √ | √ | √ |
| Lignin synthesized from waste *Ficus auriculata* leaves | PVA | Oven method (under vacuum at 50ºC for 15 h) | √ | √ | √ | √ | - |
| Pine cone lignin | Faba bean protein | solution casting method | √ | √ | √ | - | - |
| Lignin Nanoparticles (LNP) | Chitosan (main matrix), Micro-crystaline Cellulose (MCC): acts as a micro-reinforcement in composite films. | casting method | √ | √ | √ | - | - |
| Lignin and AL/Fe (III) complex | PVA | flow casting method | √ | √ | - | - | - |
| Epoxidized Soya Bean Oil (ESO) and Encapsulated Lignin (Lig)/Tannic Acid (Ta) (ESO-Lig-Ta) | PBAT | Casting method using dichloromethane (DCM) as a solvent. | √ | √ | √ | - | - |
| Softwood Kraft Lignin Nano-particles (SLNPs) | Polybutylene succi-nate (PBS) | A blown film, single-screw extruder | √ | √ | √ | - | √ |
| Lignin-ZnO Hybrid Particles (LZn) | Polybutylene adipate-terephthalate)/PBAT | Extrusion | √ | √ | √ | √ | √ |

*To be continued…*

**Table 2**. The Effect of lignin addition on the improvement of mechanical, thermal, antioxidant, antibacterial, uv protection, and water vapor barrier properties.

| Filler | Matrix | Method/Process conditions | Functional Properties of Filler | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mechanical | | Ther-mal | Anti-oxi-dant | Anti-micro-bial |
| | | | Tensile strength (TS) | Elongation at break (EB) | | | |
| Ramie fibers and lignin | Chitosan with a degree of deacetylation greater than 95% and a molecular weight between 120–250 kDa. | Casting method. | √ | √ | √ | √ | √ |
| Cellulose Nanocrystals (CNC) | lignin | Oven method | √ | √ | √ | - | - |
| Lignin and Cellulose Nanofibers derived from bamboo plants | Thermo-plastic Starch obtained from cassava | Extrusion | √ | √ | √ | - | - |
| Lignin | PLA | The method of copolymerizing lignin and lactic acid using stannous chloride at room temperature. | √ | √ | √ | - | √ |
| Kraft lignin | PVA | casting method | √ | √ | √ | √ | √ |
| Nanoparticulated lignin resulted from simultaneous enzymatic saccharification and comminution (SESC lignin) | PVA | Film-casting knife | √ | - | √ | - | - |
| Modified lignin microparticles (LMP) | PLA | Vacuum oven method | √ | √ | √ | √ | - |
| Grape seeds lignin | PHB/PHA | Casting method | √ | √ | √ | √ | - |
| Natural lignin in wood (sawdust) | cationic wood nano fibers (CWNF) | solvent- casting method | √ | √ | √ | - | √ |
| Technical Hydrotropic Lignin | Cellulose | Casting method | - | - | - | √ | - |
| Lignin from oil palm black liquor | starch-based films | Casting method | √ | √ | √ | - | - |

**Antioxidant Properties.** The purpose of antioxidant testing is to evaluate the antioxidant capacity of composite films with the addition of lignin, providing insights into the film's effectiveness in scavenging free radicals and protecting materials from oxidative damage. These results are crucial for understanding the material's ability to prevent damage caused by free radicals, which can deteriorate the structure, taste, aroma, and nutritional value of food or other materials.

Lignin is rich in polyphenols, which provide strong antioxidant activity. This property helps reduce food oxidation caused by exposure to free radicals, thereby extending the shelf life of food products. Incorporating lignin into formulations enhances the antioxidant properties of films and composites. The addition of lignin to composite films improves antioxidant capacity because the active phenolic hydroxyl groups in lignin's structure can scavenge free radicals through electron transfer mechanisms, providing strong antioxidant properties to the films [10]. The conversion of lignin into nanoparticles enhances antioxidant activity due to the higher number of phenolic groups on the nanoparticle surface [12]. Lignin extracted from date palm leaves significantly improves the antioxidant capacity of CMC-lignin films. Studies show that the antioxidant activity of films increases significantly with higher lignin concentrations, attributable to the phenolic-rich antioxidant properties of lignin.

**Antimicrobial Properties**. The purpose of antibacterial testing is to evaluate the ability of films and composites with lignin to inhibit the growth of microorganisms, including bacteria and fungi. This property is particularly essential for food packaging to protect food products from microbial contamination.

Lignin has antimicrobial properties derived from its polyphenol content and functional groups. These properties help inhibit the growth of microorganisms that can spoil food, thereby improving food safety. Lignin has been shown to improve antimicrobial properties against *Escherichia coli*, *Staphylococcus aureus [10]*, *Klebsiella pneumoniae, Staphylococcus epidermidis* [12], *Listeria monocytogenes, Salmonella typhimurium, Colletotrichum gloeosporioides* dan *Lasiodiplodia theobromae*. These microorganisms are commonly associated with food contamination and are significant contributors to food poisoning and human infections.

Lignin's antimicrobial properties stem from its phenolic groups, which can interact with bacterial cell membranes, causing damage, cell lysis, and the release of cellular content. Lignin can also interact with peptidoglycan in bacterial cell membranes, causing structural damage [10, 12]. Additionally, lignin's complex chemical structure contributes to its antibacterial properties [12]. Lignin can also inhibit the growth of pathogenic microorganisms by inducing oxidative stress through its phenolic groups. Lignin has been studied as an antibacterial agent both in composites and as a standalone agent. It is effective against both Gram-positive and Gram-negative bacteria, with lower cytotoxicity towards host tissues. Lignin can also work synergistically with antibiotics.

Composite films containing lignin have been evaluated directly on food products. In one study, commercial packaging materials showed mold growth on bread samples by day three, with full mold coverage by day four. In contrast, PVA films with lignin inhibited mold growth for up to 15 days [13], Lignin nanoparticles (LNPs) added to chitosan (main matrix) and microcrystalline cellulose (MCC) successfully extended the shelf life of fresh-cut cherry tomatoes up to seven days without spoilage, highlighting the potential of these green composite films for food packaging applications. Similarly, SLNPs in PBS composite films enhanced antifungal effects against mango fruit fungi, with 1% SLNPs and 10% thymol showing strong inhibition against *Colletotrichum gloeosporioides* and *Lasiodiplodia theobromae.*

Lignin fractions with varying phenolic group contents, when blended with high-density polyethylene (HDPE), provide insect-repellent properties against two types of insects: attackers (*Sitophilus oryzae*) and penetrators (*Plodia interpunctella*). This combination of properties makes films made from these materials ideal candidates for protecting products from insect attacks.

**UV-Blocking Properties**. The purpose of UV-blocking testing is to evaluate the ability of composite films with lignin to block UV penetration and UVA radiation while understanding changes in UV protection functionality resulting from lignin addition to the polymer matrix.

The addition of lignin to composite films enhances UV-blocking capabilities because lignin's aromatic structure can absorb UV radiation [10]. Incorporating lignin nanoparticles (LNPs) into PVA/CH and PVA/CI films increases UV-blocking ability due to the high UV absorption capacity of LNPs, which convert UV radiation into heat using chromophores such as carboxyl, carbonyl, and phenolic hydroxyl groups [12]. Lignin-containing starch-PVA films with 10% lignin can block UVB (280–320 nm) radiation and reduce UVA (320–400 nm) radiation by approximately 89.1% [10]. Films containing 4% lignin in whey protein isolate (WPI) matrices can block 95% UVA and 100% UVB radiation while maintaining visible light transparency, highlighting their potential as UV-protective packaging materials Cellulose-based films containing 30% lignin and ε-polylysine exhibit outstanding UV protection properties, blocking 100% UVB and 99.91% UVA radiation.

The addition of lignin nanoparticles obtained through the SESC process into poly (vinyl alcohol) (PVA) films improves mechanical and UV-absorbing properties without compromising transparency. A 5 w/w% lignin SESC addition achieved 91% UVA protection and 100% UVB protection with 89% total light transmission (TLT). The phenolic syringyl units in lignin significantly enhance antioxidant and UV-blocking properties. Lignin possesses UV-blocking capability due to its phenolic groups, which can absorb UV radiation and protect materials from damage caused by UV exposure.

**Water Vapor Permeability (WVP) Properties.** The purpose of the Water Vapor Permeability (WVP) test is to evaluate the film's resistance to water vapor penetration and understand changes in this property due to lignin incorporation into the polymer matrix. The addition of lignin in composite films can enhance resistance to water vapor penetration because lignin has hydrophobic properties that reduce water vapor permeability in the film [10]. Lignin extracted from date palm leaves has been shown to improve the ability of CMC-Lignin films to reduce water vapor permeability. The addition of lignin significantly decreased the Water Vapor Permeability (WVP) of the films, indicating improved barrier capability against water molecule movement through the film. Lignin films reinforced with cationic wood nano fibers (CWNF) exhibit good oxygen barrier properties at 50% relative humidity, which is crucial for food packaging applications to maintain freshness. However, at higher humidity levels, oxygen barrier properties decrease but are still considered adequate.

**Biodegradability Properties.** Biodegradability tests on lignin-added films and composites were performed to assess whether these films could still degrade in soil. Biodegradability studies revealed that lignin-PLA biodegradable films could easily degrade in soil within a shorter period [11]. Results from biodegradability tests also showed that chitosan-based composite films reinforced with ramie fibers and lignin exhibited good biodegradability potential.

Lignin acts as a stabilizer but also contributes to the degradation process of composite films due to its oxidative nature, which may trigger free radical reactions leading to polymer degradation. Incorporating lignin into polyolefins is proposed as a method to reduce the environmental impact of plastic waste, particularly from the packaging industry, by making plastics more biodegradable.

**Other Functional Properties.** Several tests have also been conducted on lignin-added films and composites. Results from overall migration tests indicate that the overall migration values are lower in PVA films with lignin compared to those without lignin [12].

The total migration value of PBAT films combined with ESO-encapsulated lignin (Lig)/tannic acid (Ta) remains below the maximum allowable limit of 10 mg/dm² set by the European Commission for plastics in food contact materials [16].

Overall migration into various food simulants and degradation characteristics of composite films showed that the addition of lignin to chitosan-based composite films successfully reduced overall migration into food simulants by up to 60%. This result indicates that these composite films remain inert when in contact with food, with total migration below the legal limit of 10 mg/dm². The addition of LMP-g-PLA increased toughness, reduced gas permeability, and improved UV resistance of PLA composites without exceeding migration limits for food contact materials [50]

Overall, the incorporation of lignin into different polymer matrices consistently enhances both the reinforcing and active functionalities of bio-based films. In hydrophilic matrices such as PVA, starch, and chitosan, lignin effectively forms hydrogen bonds, leading to improved tensile strength, reduced water vapor permeability, and strong antioxidant activity. In more hydrophobic matrices such as PLA, PBAT, and PBS, lignin primarily contributes to UV protection and thermal stabilization, although compatibility issues often limit dispersion and mechanical reinforcement. Protein-based films, such as those from whey isolate or faba bean protein, benefit from lignin's phenolic interactions, which enhance both structural rigidity and biological activity. Despite variations in performance depending on the polymer type and lignin source, the overall evidence demonstrates lignin's multifunctionality and its potential as a sustainable additive for food packaging applications. These findings highlight the importance of optimizing interfacial compatibility and dispersion to maximize lignin's synergistic effects across different biopolymer systems.

# 4 Challenges and Future Perspectives in the Application of Lignin for Food Packaging

Lignin holds significant potential as a reinforcing material for composites due to its abundance, cost-effectiveness, and eco-friendly nature. Furthermore, lignin holds significant promise for sustainable food packaging due to its biodegradability, antimicrobial, antioxidant, and UV-blocking properties. However, several challenges remain before its potential can be fully realized in industrial-scale applications (Figure 4).

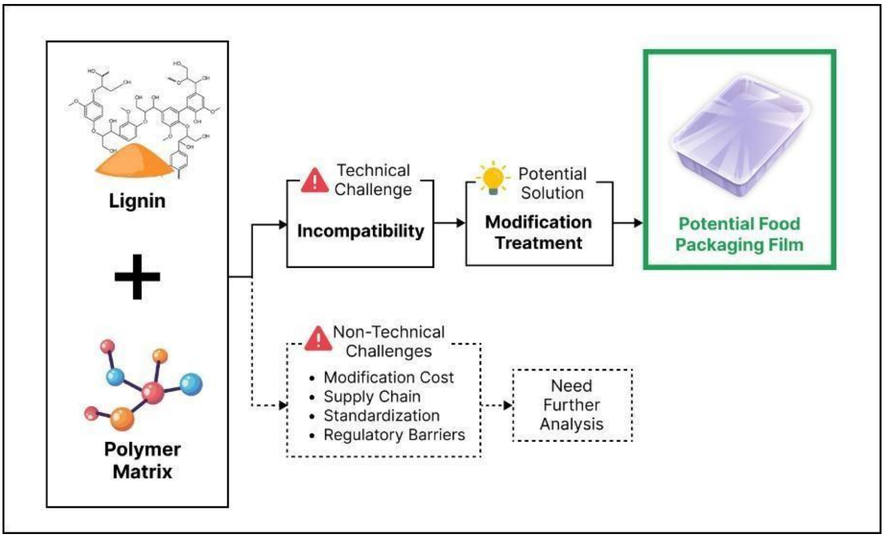


**Fig. 4** Schematic illustration of the challenges and future perspectives in applying lignin as a reinforcing agent for food packaging films.

**Technical Challenges.** One of the primary issues is the polarity mismatch between hydrophilic lignin and hydrophobic polymer matrices, which hinders uniform dispersion and interfacial adhesion. Advances in the rational design of lignin-based systems, including molecular modifications and blending techniques, can enhance the mechanical and barrier properties of lignin-based packaging materials.

Lignin requires modification to enhance its usability in various applications. Several techniques have been developed to modify lignin, including chemical, biological [69, 70], and physical treatments, each with specific benefits and challenges. Development of lignin modification technology is also needed to produce modifications that are in accordance with the target and environmentally friendly, such as Microwave-Assisted Extraction (MAE), Ionic Liquids (ILs), Deep Eutectic Solvents (DES) and plasma-assisted treatments [73–75], show potential to improve lignin hydrophobicity and compatibility with non-polar polymers, while maintaining its bio-based and sustainable nature.

Lignin also has a strong odor and dark color, which may limit its use in consumer products. Incorporating lignin into films can lead to characteristic changes, particularly in the color of the film. The addition of lignin to faba bean protein films alters the film's color parameters. Specifically, increasing the lignin content reduces the L* value (lightness) and causes changes in a* and b* values, indicating a color shift. These changes suggest that the films become darker and more brownish with lignin addition, which aligns with the natural color of lignin [24]. In PVA films, lignin causes minor color changes, yet these films remain sufficiently transparent for packaging applications. Such changes may influence consumer perception, as transparency and appearance remain important in food packaging. On the other hand, lignin's natural color could be exploited as a bio-based pigment. Future research should include consumer perception studies to evaluate acceptance of lignin-based packaging materials.

Agglomeration and poor dispersion at high lignin loadings present another limitation. High concentrations of lignin can cause agglomeration in polymer matrices, posing challenges in achieving homogeneous and functional films. While moderate concentrations improve mechanical, thermal, and barrier performance, excessive additions (>15–20%) often cause phase separation and performance deterioration. The development of lignin nanoparticles has shown promise in improving the efficacy of lignin as a multifunctional filler, enhancing properties such as UV protection, antioxidant activity, and mechanical strength. Achieving uniform nanoscale dispersion, through nanoparticle engineering, compatibilizers, or surface functionalization, remains a key research priority.

**Economic and Industrial Challenges.** From an economic standpoint, lignin is abundant and low-cost, but processing and modification costs may offset its financial advantages. A comprehensive cost benefit analysis is therefore necessary to evaluate economic feasibility. Moreover, to ensure real applicability, future studies must investigate lignin-based films under industrial processing conditions such as extrusion, injection molding, blow molding, and 3D printing. Most current research relies on solution casting, which is not representative of large-scale manufacturing. Validating lignin-based composites under real distribution and storage conditions (temperature and humidity fluctuations, vibration, stacking, light exposure) is also critical for commercialization.

**Regulatory and Standardization Challenges.** Another barrier is lignin's heterogeneous molecular structure, which varies depending on botanical source and isolation method. This variability complicates efforts to establish standardized quality metrics. Developing consistent characterization protocols and harmonized processing methods will be necessary for industrial adoption. Finally, food safety and regulatory approval represent critical hurdles. Migration and toxicity testing must confirm that lignin-based composites comply with international standards such as EU and FDA regulations [83, 84]. Because lignin is still relatively new in direct food-contact applications, regulatory approval processes can be lengthy. Collaboration among academia, industry, and regulatory agencies will therefore be essential to accelerate approval and ensure consumer safety. Establishing standardization frameworks (e.g., ISO, ASTM) and food-contact testing guidelines will further support safe commercialization.

**Future Perspectives.** Looking ahead, future perspectives for lignin-based packaging also extend beyond these immediate challenges. Life cycle assessment (LCA) and techno-economic analysis (TEA) are needed to validate the environmental and economic sustainability of lignin-based systems compared to petroleum-based plastics. In addition, hybrid approaches, combining lignin with cellulose nanocrystals, starch, or bio-based nanoparticles, could generate synergistic effects that enhance reinforcement, barrier properties, and bioactivity. Finally, integrating lignin into smart and active packaging systems, such as freshness indicators, controlled release systems, and antimicrobial delivery platforms, represents a promising direction that could further elevate its commercial appeal. In summary, while lignin offers multifunctional benefits for food packaging, its widespread adoption requires overcoming challenges related to compatibility, color perception, dispersion, cost, heterogeneity, and regulatory approval. Addressing these barriers through green modification methods, industrial-scale validation, sustainability assessments, and smart packaging innovations will be key to translating lignin from laboratory-scale studies into viable commercial solutions.

## 5 Conclusion

Lignin demonstrates remarkable potential as a sustainable material for food packaging due to its dual functionality as both a reinforcing and active component. Acting as a bio-based reinforcement, lignin enhances the mechanical and thermal stability of polymer matrices, while its intrinsic phenolic structure imparts antioxidant, antimicrobial, UV-blocking, and barrier properties. Numerous studies have confirmed that lignin incorporation into biopolymers such as PLA, PVA, chitosan, starch, and protein-based films results in significant improvements in tensile strength, crystallinity, degradation resistance, and overall functionality.

Despite these advantages, large-scale industrial application of lignin-based packaging remains constrained by challenges such as poor compatibility with hydrophobic polymers, dark coloration, agglomeration at higher loadings, economic limitations, and stringent food safety regulations. Emerging strategies including chemical modification, surface treatment, and lignin nanoparticle development offer promising pathways to address these issues. However, comprehensive validation under real storage and distribution conditions, coupled with techno-economic and life-cycle assessments, is still essential to ensure scalability and long-term viability.

Overall, this review underscores both the potential and the challenges of lignin as a bio-based reinforcement and active functional material for food packaging. Future progress will depend on close collaboration among materials scientists, food technologists, and regulatory authorities to translate laboratory findings into industrial applications. Ultimately, optimizing lignin utilization can contribute significantly to the development of sustainable packaging solutions that align with the principles of the circular bioeconomy and global efforts toward environmental responsibility.

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## Acknowledgment

The authors gratefully acknowledge the financial support provided by the Agency for the Assessment and Application of Technology (BPPT), Indonesia Endowment fund for Education (LPDP), and The Education Financing Service Center (Puslabdik). Their generous sponsorship made the research and publication of this article possible.

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