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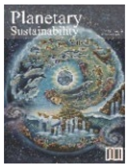

LIGNIN-BASED ACTIVE FOOD PACKAGING: FROM FUNCTIONAL PROMISE TO FOOD-USE READINESS AND PRACTICAL CHALLENGES

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HIGHLIGHTS

- Lignin-based active packaging shows promise, but food-use readiness remains application-specific.
- Film-level functionality alone does not prove real-food preservation or shelf-life extension.
- Lignin is most defensible as a UV-protective and antioxidant additive.
- Practical adoption requires food-specific validation of safety, sensory quality, scalability, and sustainability.

GRAPHICAL ABSTRACT

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ABSTRACT

Lignin-based active food packaging has emerged as a promising route for linking food preservation, renewable material use, and valorisation of lignocellulosic side streams. The aromatic and phenolic structure of lignin enables ultraviolet shielding, radical scavenging, interfacial reinforcement, and barrier improvement in biodegradable films and coatings. Nevertheless, these material functions do not automatically establish practical readiness for food packaging. This critical review evaluates the progress of lignin-based active packaging from laboratory film development toward food-use application by connecting structure–function relationships with real food preservation, food-contact safety, migration, sensory quality, processing scalability, environmental performance, economic feasibility, and regulatory credibility. Current evidence supports lignin most strongly as a UV-protective and antioxidant additive, whereas antimicrobial performance remains less predictable and depends on lignin source, extraction route, molecular structure, particle form, polymer matrix, formulation design, and target food system. Recent studies on bread, mango, fish, banana, strawberry, apple, tomato, ketchup, and other perishable foods demonstrate encouraging preservation effects, particularly when lignin is used within designed active systems rather than as a standalone preservative. However, the field remains dominated by material-level characterisation, with limited standardised lignin reporting, real-food validation, migration and toxicity assessment, sensory analysis, regulatory evaluation, and integrated techno-economic and life cycle assessment. The most defensible pathway forward is application-specific validation, where lignin functions are matched to defined deterioration mechanisms such as photooxidation, lipid oxidation, fungal spoilage, moisture loss, browning, or barrier failure. This shift is necessary for advancing lignin-based active food packaging from a promising material concept toward an evidence-based food-packaging technology.

Introduction

Food packaging is an essential component of modern food systems because it protects food during storage, transportation, distribution, retail display, and consumption (Han *et al.*, 2018). Its role is not limited to product containment. Packaging also controls exposure to oxygen, moisture, light, microorganisms, volatile compounds, and physical damage, thereby helping to maintain food quality and safety. At the same time, packaging creates a sustainability dilemma. Conventional packaging materials contribute to post-consumer waste and environmental burdens, whereas insufficient or poorly designed packaging can accelerate food deterioration and increase losses across the supply chain. This balance is particularly important because food waste remains a significant global challenge. The UNEP Food Waste Index Report 2024 estimated that 1.05 billion tonnes of food were wasted in 2022 across retail, food service, and household sectors (UNEP, 2024). Therefore, sustainable food packaging should not be evaluated only through material replacement or biodegradability (Heller *et al.*, 2019; Molina-Besch *et al.*, 2019; Zolfaghari *et al.*, 2022). It should also be assessed through its ability to protect food, extend shelf life, reduce avoidable losses, and improve the environmental performance of the whole food-packaging system (Pauer *et al.*, 2019; Hemachandra, 2024).

Active packaging has emerged from this need to move beyond passive protection. Unlike conventional packages that mainly act as inert barriers, active food packaging deliberately incorporates components able to absorb undesirable compounds or release protective agents into the package environment in a controlled manner. Oxygen, moisture, and ethylene scavengers, carbon dioxide or ethanol emitters, antimicrobial agents, and antioxidant systems are used to delay chemical, enzymatic, or microbial deterioration (Restuccia *et al.*, 2010; Yildirim *et al.*, 2018). These functions can support longer shelf life and better-quality retention, especially for perishable foods. However, active food packaging also raises stricter requirements than passive materials. A functional package must not only inhibit deterioration, but also comply with food-contact safety requirements, control migration, preserve sensory quality, remain compatible with industrial processing, and demonstrate environmental and economic justification at the food-packaging system level (Sharma, 2023; Lestido-Cardama *et al.*, 2025).

Lignin has attracted increasing attention as a naturally derived functional material for active food packaging. It is an abundant aromatic biopolymer generated mainly as a side stream of pulp, paper, and lignocellulosic biorefinery processes (Saleknezhad *et al.*, 2026). Its valorisation in packaging can therefore connect renewable material use with the higher-value use of an underutilised biomass-derived resource (Wang, 2021; Priyadarshi *et al.*, 2024). More importantly, lignin contains aromatic rings and phenolic structures that can provide ultraviolet shielding, radical-scavenging activity, interfacial reinforcement, and barrier modification in polymer films and coatings (Espinoza-Acosta *et al.*, 2016; Sadeghifar and Ragauskas, 2020). These properties allow lignin to act not only as a bio-based filler, but also as a multifunctional active component. Recent progress in lignin nanoparticles has further increased interest because nanoscale lignin can improve dispersion, interfacial interactions, surface area, and active performance in biodegradable matrices such as PLA, PBAT, PBS, PVA, chitosan, starch, and cellulose-based systems (Yang *et al.*, 2016; Cavallo *et al.* (2021); Peng & Wang, (2025).

Despite these advantages, the practical value of lignin-based active food packaging remains only partly established. Lignin is not a uniform material. Its structure and performance depend strongly on biomass source, extraction route, purity, molecular weight, functional-group accessibility, particle form, and post-treatment (Saleknezhad *et al.*, 2026). As a result, antioxidant activity, antimicrobial behaviour, UV-blocking capacity, colour, solubility, compatibility, barrier performance, and processability can vary substantially among lignin types and formulations (Song, 2024; Cernekova *et al.*, 2025). This variability makes broad claims about lignin-based packaging difficult to justify unless material characteristics are connected to application-specific performance. In particular, the most frequently reported film-level tests, including UV transmittance, DPPH or ABTS radical-scavenging assays, water vapor or oxygen barrier measurements, tensile properties, and inhibition-zone assays are useful for screening but do not by themselves prove real food preservation.

A second limitation is the incomplete translation from laboratory films to food-use readiness. Several lignin-containing films and coatings have shown promising performance in model systems, yet many studies remain at the level of solvent-cast film characterisation or short-term in vitro assays (Yang *et al.*, 2018;

Zheng, 2024; Zou *et al.*, 2023). Real food systems are more complex because food composition, pH, water activity, fat content, microbial ecology, storage temperature, headspace composition, and active-agent release all influence packaging performance. Recent studies on bread, mango, fish, banana, strawberry, apple, tomato, ketchup, and other foods provide encouraging evidence that lignin-based systems can contribute to shelf-life extension when the material function is matched to a specific deterioration pathway (Moe *et al.*, 2023; Zhang, 2023; Nuamduang *et al.*, 2024; Xu, 2024; Abraham *et al.*, 2025; Meenu, 2025; Santhosh, 2025; Wijaranakul *et al.*, 2025). Nevertheless, these examples also show that lignin often performs most effectively as part of a designed active system, for example in combination with cinnamaldehyde, thymol, chitosan, cellulose nanocrystals, essential oils, or other functional matrices, rather than as a universal standalone preservative.

Food-contact safety and regulatory credibility represent another critical barrier (Sharma, 2023). The renewable origin of a material does not automatically establish its suitability for food-contact applications. Lignin-based films may contain residual solvents, additives, degradation products, low-molecular-weight phenolics, non-intentionally added substances, or released active agents. Bio-based and biodegradable food-contact materials can therefore require the same level of chemical safety assessment as conventional materials, including attention to overall migration, specific migration, impurities, oligomers, degradation products, and non-intentionally added substances (European, 2011a; Lestido-Cardama *et al.*, 2025). Lignin nanoparticle systems also require consideration of particle characterisation, potential particle release, exposure, and toxicity according to nano-specific risk assessment principles (Committee, 2021). In addition, lignin can darken films, reduce transparency, and potentially affect odour or product appearance, which makes sensory acceptability and consumer perception relevant to practical adoption (Yang *et al.*, 2016b; Boz *et al.*, 2020; Ketelsen *et al.*, 2020). These issues are especially important for active packaging because deliberate interaction between the package and the food or package environment increases the need for controlled migration, toxicological evidence, and clear regulatory positioning (Panel, 2019; Restuccia *et al.*, 2010).

Processing and sustainability add additional layers of complexity. Many lignin-based films are still prepared by laboratory casting, whereas food packaging production usually requires extrusion, blown film processing, coating, lamination, paper-board coating, or heat sealing. During scale-up, lignin aggregation, matrix incompatibility, loss of volatile active agents, coating defects, darkening, and batch-to-batch variability can limit performance (Cavallo, 2021; Botta *et al.*, 2022). Recent studies using extrusion, blown film extrusion, melt-extrusion-based particle formation, and pilot coating show important progress, but they also reveal practical bottlenecks such as rheology control, active-agent retention, pinholes, heat-seal performance, and migration control (Javed *et al.*, 2021; Bamps *et al.*, 2022; Hararak *et al.*, 2024). In parallel, environmental and economic benefits cannot be inferred only from lignin abundance or biodegradability. Lignin extraction, purification, modification, nanoparticle preparation, compatibiliser use, processing energy, end-of-life route, and avoided food waste should all be considered (Müller-Carneiro, 2023; Sampaio, 2023). For active packaging, the most meaningful sustainability question is whether the added material complexity is justified by measurable food preservation and waste reduction (Heller *et al.*, 2019; Settier-Ramírez, 2022; Hemachandra, 2024).

This review critically evaluates lignin-based active food packaging from a food-commercial readiness perspective. Rather than focusing only on lignin chemistry, film properties, or individual active functions, it examines how these functions translate into practical food-packaging performance. The review first discusses the material basis of lignin functionality and the main lignin forms used in packaging. It then connects film-level functionality with real-food validation, food-contact safety, migration control, sensory acceptability, scalable processing, environmental and economic assessment, and regulatory credibility. By integrating these dimensions, this review provides a readiness-oriented synthesis that distinguishes promising material functions from the evidence required for practical food-use application. Finally, an integrated readiness framework is proposed to identify where lignin-based active packaging is already convincing, where evidence remains incomplete, and which application-specific validation steps are still needed before practical adoption can be claimed (Figure 1).

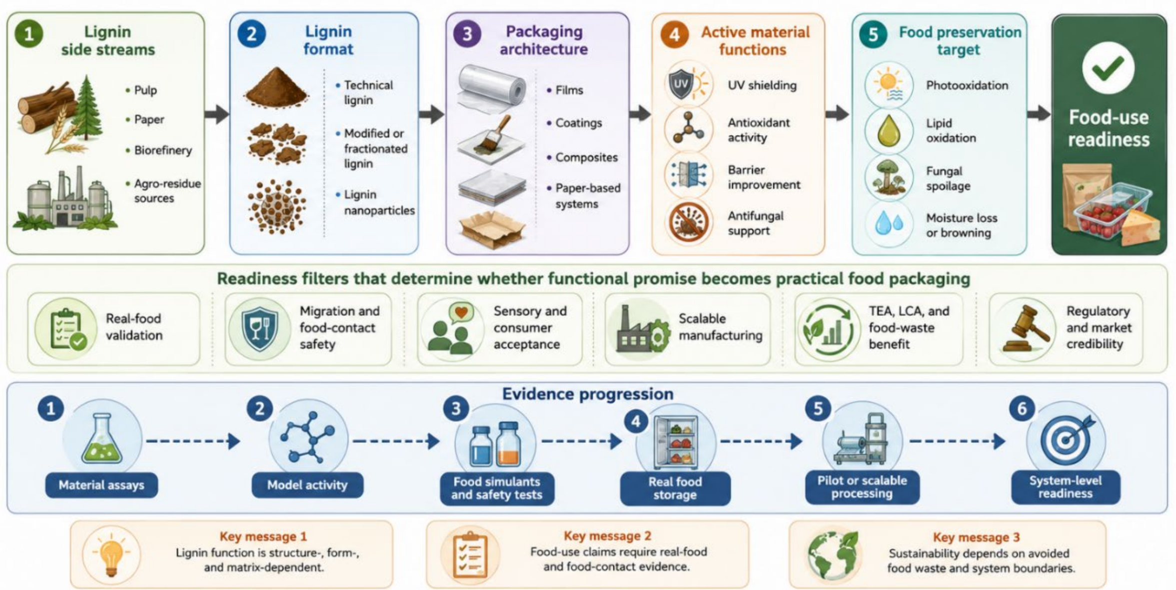

Figure 1: Conceptual framework illustrating the progression of lignin-based active food packaging from biomass-derived side streams to food-use readiness.

Lignin Functionality in Active Packaging Systems

Chemical Basis of Lignin Activity

Lignin is relevant to active food packaging because it combines renewable origin, high availability, and intrinsic chemical functionality. However, only a limited fraction of technical lignin is converted into higher-value materials, while most of it is still used for energy recovery or low-value applications (Wang, 2021). This underutilisation creates an opportunity to transform lignin from an industrial side stream into a functional component for sustainable packaging materials (Espinoza-Acosta *et al.*, 2016; Priyadarshi *et al.*, 2024).

Lignin's functional value comes from its aromatic and polyphenolic structure. Lignin is mainly built from p-hydroxyphenyl, guaiacyl, and syringyl units connected through ether and carbon–carbon linkages (Saleknezhad *et al.*, 2026). It contains phenolic hydroxyl, aliphatic hydroxyl, methoxyl, carbonyl, and carboxyl groups, which influence radical-scavenging activity, UV absorption, hydrophobicity, thermal stability, reactivity, and interaction with polymer matrices (Sadeghifar & Ragauskas, 2020; Song, 2024). These structural features explain why lignin can act not only as a passive bio-based filler, but also as an active component in food packaging films and coatings.

At the same time, lignin should not be treated as a uniform additive. Its composition and behaviour depend on biomass source, extraction route, purification method, molecular weight, phenolic hydroxyl content, degree of condensation, solubility, colour, and post-treatment. Kraft lignin, soda lignin, organosolv lignin, lignosulfonates, deep eutectic solvents (DES)-extracted lignin, and fractionated lignin can differ markedly in sulfur content, impurity profile, molecular architecture, reactivity, and polymer compatibility (Madadi *et al.*, 2026). This variability is central to active packaging design because the performance of lignin-based systems cannot be interpreted without connecting lignin chemistry to processing behaviour, film properties, food-contact safety, and preservation outcome (Song, 2024; Cernekova *et al.*, 2025).

From Technical Lignin to Engineered Lignin Nanoparticles

In food packaging research, lignin is mainly used as technical lignin, modified or fractionated lignin, and lignin nanoparticles. Technical lignin is attractive because it is available at large scale and relatively low cost. Its direct use can provide UV shielding, antioxidant activity, and partial reinforcement in polymeric matrices (Sadeghifar & Ragauskas, 2020). However, technical lignin can also show poor compatibility, broad molecular-weight distribution, dark colour, limited solubility, and heterogeneous activity. These limitations explain why direct addition of bulk lignin often yields inconsistent results, especially when high optical clarity, stable dispersion, and strong mechanical performance are required (Domenek *et al.*, 2013; Xing *et al.*, 2017).

Chemical modification, physical fractionation, and surface engineering are used to improve lignin compatibility and functional control. Esterification, grafting, compatibilisation, and molecular-weight fractionation can improve hydrophobicity, interfacial adhesion, dispersibility, and matrix compatibility (Saleknezhad *et al.*, 2026). In biodegradable polyesters such as PLA and PBAT, these approaches can reduce aggregation and help maintain UV-shielding and antioxidant performance while improving mechanical behaviour (Cavallo, 2021; Liu, 2021; Zheng, 2024). However, modification also introduces additional processing cost, chemical input, and potential regulatory complexity. Therefore, modification should be justified by a defined performance, processing, or safety need rather than treated as an automatic improvement (Xing *et al.*, 2017).

Lignin nanoparticles have gained particular attention because they can address some of the limitations of bulk lignin. Their smaller size, higher surface area, and improved dispersibility can strengthen interfacial interactions with biodegradable polymers and enhance UV-blocking, antioxidant, antimicrobial, mechanical, and barrier properties. lignin nanoparticles (LNP) have been incorporated into PVA, chitosan, PLA, PBS, PBAT, PHBV, starch, casein, and cellulose-based systems, often with better dispersion and stronger structure–function performance than neat lignin (Yang *et al.*, 2016a; Marcoaldi, 2025; Peng and Wang, 2025). Nevertheless, LNPs also introduce questions related to particle-size control, reproducibility, aggregation at high loading, scalable production, migration, nanoparticle release, and regulatory acceptance. They should therefore be viewed as an important route for improving lignin performance, but not as a complete solution to practical readiness.

Lignin has been incorporated into flexible films, coatings, nanocomposites, paper-based coatings, hydrogels, and electrospun membranes (Javed *et al.*, 2021). It has been combined with synthetic biodegradable polymers such as PLA, PBAT, PBS, PHBV, and PVA, and with natural polymers such as chitosan, starch, gelatin, casein, cellulose nanocrystals, bacterial cellulose, and xyloglucan. In these systems, lignin may function as a reinforcing filler, UV absorber, antioxidant contributor, antimicrobial-supporting component, carrier for volatile active agents, coating additive, or barrier modifier (Halloub, 2022; Nuamduang *et al.*, 2024). This versatility is useful, but it also makes comparison among studies difficult because packaging performance depends on both lignin characteristics and matrix properties.

Main Active Functions and Formulation-Dependent Limitations

The most frequently reported active functions of lignin in food packaging are UV shielding, antioxidant activity, antimicrobial or antifungal support, and barrier or mechanical modification (Sanches-Silva *et al.*, 2014). Among these, UV shielding is one of the most reliable functions because lignin contains chromophoric structures that absorb ultraviolet radiation. This function is relevant for light-sensitive foods and packaging systems where photooxidation, pigment degradation, or light-induced quality loss is a concern. However, the same chromophores can darken films and reduce transparency, which may limit applications where product visibility, package appearance, or consumer acceptance is important (Wijaranakul *et al.*, 2025).

The antioxidant activity of lignin is also well supported and is mainly associated with phenolic hydroxyl and methoxyl groups that participate in radical-scavenging reactions. However, antioxidant performance is not determined only by adding lignin to a film. It depends on phenolic hydroxyl content, molecular weight, solubility, accessibility of active groups, extraction method, and formulation environment. DES-extracted lignins and high-phenolic lignin nanoparticles show that lower molecular weight and higher phenolic hydroxyl availability can improve antioxidant activity, but these effects should be interpreted together with solubility, colour, processing stability, and food-contact behaviour (Yu, 2023; Song, 2024).

Lignin's antimicrobial function is more conditional. Some lignin and lignin-derived fractions inhibit microbial growth, but this effect is not universal. Antimicrobial activity depends on lignin origin, isolation method, solubility, molecular structure, functional-group accessibility, particle form, and the presence of other active components (Cernekova *et al.*, 2025). This distinction is important because many studies report antimicrobial activity through inhibition-zone tests or model microbial assays, while fewer studies show consistent antimicrobial protection in real foods (Han *et al.*, 2018). Therefore, lignin should not be described as a generally strong antimicrobial agent unless the activity has been validated for the specific formulation, microorganism, and target food system (Moe *et al.*, 2023; Cernekova *et al.*, 2025).

Lignin can also improve barrier and mechanical performance, but this effect is strongly formulation-dependent. Good dispersion and favourable interfacial interactions can increase tensile strength, stiffness, oxygen barrier, UV stability, and water resistance in selected matrices. In contrast, excessive loading, poor compatibility, particle aggregation, or weak interfacial adhesion can reduce ductility, transparency, and film uniformity. Thus, barrier and reinforcement effects should be evaluated as matrix-specific outcomes rather than intrinsic properties of lignin alone (Liu, 2021; Marcoaldi, 2025).

Taken together, lignin provides a strong material basis for active food packaging because it can contribute to renewable material design and preservation-related functionality. Its most defensible roles are UV protection, antioxidant activity, and reinforcement or barrier improvement in selected polymer systems. Its antimicrobial role and broader packaging benefits are more formulation-dependent and require stronger validation. These structure-function relationships and formulation-dependent constraints are summarised in Figure 2. This section therefore frames lignin as a promising but variable active material. The next section examines whether the functional properties observed in lignin-containing films can be translated into real food preservation evidence.

Translating Film-level Functionality into Food Preservation Evidence

Limits of Material-level Assays as Readiness Evidence

The active functions discussed above provide the material basis for lignin-based packaging, but they do not by themselves confirm food preservation performance. Most lignin-containing packaging studies still rely on film-level indicators, including tensile strength, thermal stability, water vapor permeability, oxygen permeability, UV transmittance, antioxidant assays, and in vitro antimicrobial tests. These measurements are useful for formulation screening, but they remain indirect evidence. A film with strong UV shielding, high DPPH or ABTS scavenging activity, or inhibition against selected microorganisms does not necessarily preserve food under realistic storage conditions. Therefore, positive film-level results should be interpreted as preliminary screening evidence and should not be used to claim real food preservation or shelf-life extension unless they are confirmed by real-food storage tests using appropriate controls and spoilage or quality indicators.

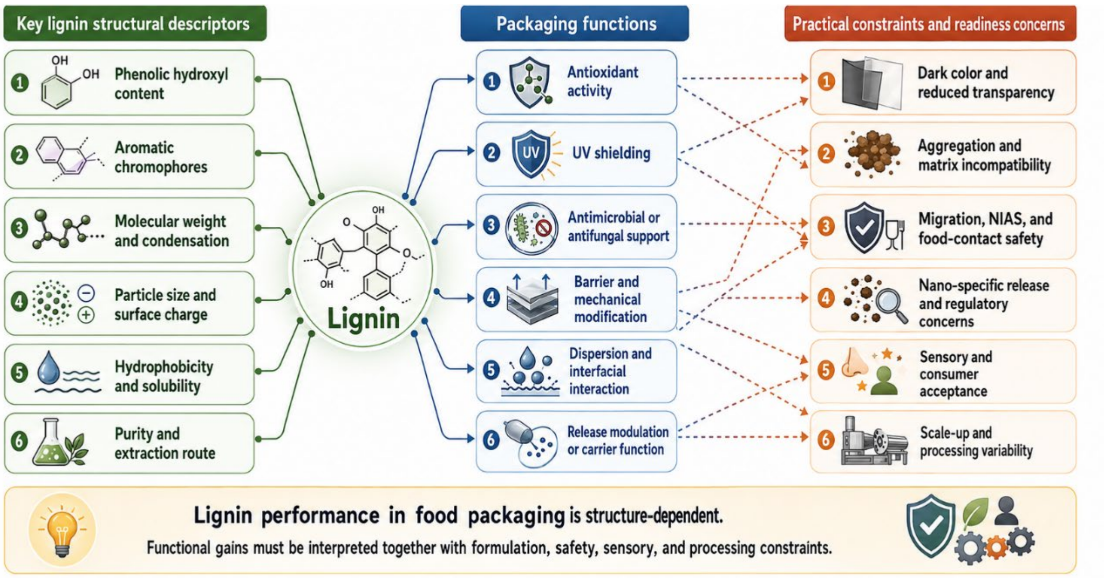

Figure 2. Structure–function–constraint map of lignin in active food packaging. The map connects key lignin descriptors with packaging functions and the main formulation, safety, sensory, regulatory, and processing constraints

This distinction is important because active packaging operates in a complex food environment. Food composition, pH, water activity, fat content, surface structure, microbial ecology, storage temperature, headspace composition, and active-agent release can all change packaging performance. Therefore, lignin-based systems should be evaluated according to whether their function addresses a defined deterioration mechanism rather than according to film activity alone.

Several studies illustrate this limitation. PVA/chitosan films containing lignin nanoparticles showed improved mechanical, thermal, antioxidant, migration, and antibacterial properties, but the evidence remained mainly at the level of material characterisation and microbial assays (Yang *et al.*, 2016a). Chitosan composite films containing LNPs and acylated soy protein nanogel also showed improved barrier, UV-blocking, mechanical, and sustained antibacterial properties, but real food storage was not demonstrated (Zou *et al.*, 2023). Similarly, PVA/LNP nanocomposite films showed UV-shielding, antioxidant, and antibacterial activity against selected bacteria, but the application remained at the film-performance stage (Zheng, 2024). These studies are useful for screening functional formulations, but they do not provide direct evidence of shelf-life extension. Figure 3 summarises the evidence hierarchy required to move lignin-based active packaging from film- level functionality toward deployment readiness.

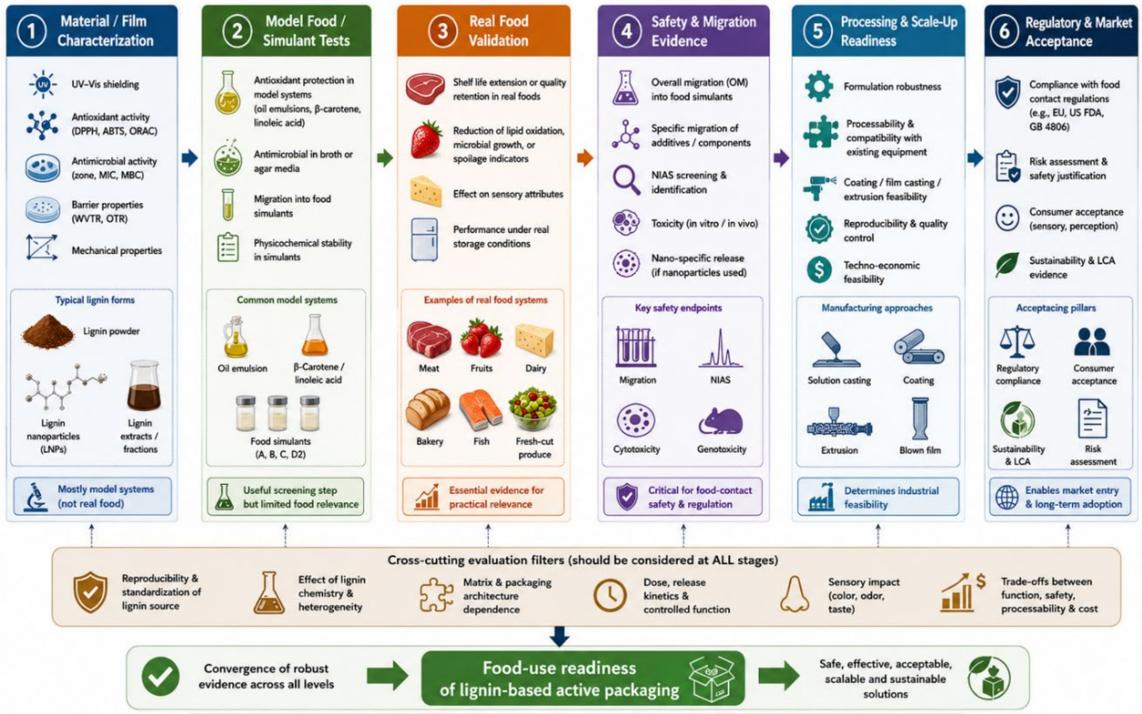

Figure 3: Evidence hierarchy for food-use readiness of lignin-based active packaging, progressing from material and model tests to real-food validation, safety assessment, scalable processing, and regulatory or market acceptance

Real-food Validation Across Deterioration Pathways

Recent studies have begun to connect lignin-based packaging functions with real food deterioration pathways. This transition is essential because food preservation depends not only on the intrinsic activity of lignin, but also on the type of food, spoilage route, storage condition, and release or contact behaviour of the active system.

Bread preservation is one of the clearest examples. Moe *et al.* (2023) developed PBS-based antifungal films containing lignin nanoparticles and cinnamaldehyde. LNPs alone showed moderate in vitro fungal growth inhibition against *Aspergillus niger* and *Penicillium* spp., while the strongest real-food effect was obtained when LNPs were combined with cinnamaldehyde. Bread packed in PBS containing 1 wt% LNPs and 5 wt% cinnamaldehyde maintained yeast and mould counts below 1.0 log CFU g−1 after 14 days at 25°C ± 2°C, whereas other samples exceeded 2.0 log CFU g−1 (Moe *et al.*, 2023). This case shows that lignin can strengthen a designed active system rather than act as a universal standalone antimicrobial agent.

Mango preservation provides another strong case because the packaging system was prepared by blown film melt extrusion. Nuamduang *et al.* (2024) developed PBS films containing LNPs and trans-cinnamaldehyde. LNPs improved compatibility with PBS, helped retain cinnamaldehyde, improved barrier properties, and supported sustained antifungal release. During mango storage at 13°C ± 1°C, control fruits packed in PBS showed rotten spots by day 10, while several active-film treatments showed no external symptoms for 20 days. The authors also noted that sensory analysis, release behaviour, diffusion, partition, and migration studies remain necessary before industrial application can be claimed.

Fish and fresh produce studies further show that lignin-based systems can be useful when the packaging function matches the deterioration route. Chitosan films containing DES-derived LNPs improved UV shielding, radical scavenging, swelling resistance, water vapor barrier, and mechanical strength, while extending the refrigerated shelf life of grass carp to 10 days at 4°C ± 1°C (Zhang, 2023). Litchi seed starch/xyloglucan/LNP coatings reduced weight loss and slowed colour change in bananas, indicating delayed quality deterioration and browning (Santhosh, 2025). Armoured lignin nanoparticles incorporated into cellulose acetate membranes extended apple shelf life by at least three days under ambient conditions (Xu, 2024). PVOH-based films containing cellulose and lignin nanoparticles with tea tree oil preserved strawberry quality for 14 days under chilled storage (Abraham *et al.*, 2025).

Other food-related demonstrations broaden the application space but should be interpreted carefully. Lignin nano-encapsulated anthocyanins in PVA-PEG films improved post-harvest quality retention of tomatoes for at least 15 days, mainly showing the value of lignin as a protective carrier for sensitive bioactive cells (Meenu, 2025). PLA films containing bagasse lignin reduced UV transmittance and limited ketchup colour change under UV exposure, while migration and cytotoxicity remained below the tested safety thresholds (Wijaranakul *et al.*, 2025). Lignin/cellulose nanocrystal films also showed UV-protective behaviour in a red cabbage leaf demonstration, although this should be considered food-related light-protection evidence rather than full shelf-life validation (Halloub, 2022).

Evidence Hierarchy and Application-specific Interpretation

The available evidence shows that lignin-based active packaging is moving beyond film-level functionality, but the transition remains uneven. The strongest cases are those where the target deterioration pathway is clearly defined and the packaging function is matched to that pathway. Fungal spoilage in bread, postharvest decay in mango, refrigerated quality loss in fish, water loss and browning in banana, colour degradation in ketchup, and quality loss in fresh fruits represent more convincing applications than general claims of antioxidant or antimicrobial activity (Choe and Min, 2009; Espinoza-Acosta *et al.*, 2016; Moe *et al.*, 2023). On the other hand, many real-food studies use lignin together with other active agents, especially cinnamaldehyde, thymol, essential oils, anthocyanins, or chitosan-based matrices. This does not weaken the value of lignin, but it changes the interpretation. In these systems, lignin often functions as a UV absorber, antioxidant contributor, reinforcing filler, carrier, interfacial modifier, or release-modulating component rather than as the only preservative agent (Nuamduang *et al.*, 2024; Abraham *et al.*, 2025; Meenu, 2025). Therefore, broad statements that lignin-based films are antimicrobial or shelf-life extending should be avoided unless the claim is supported by formulation-specific and food-specific evidence.

Future studies should move from property screening toward application-specific validation. A stronger study design should begin with a defined food deterioration problem, select a lignin type and polymer matrix that match that problem, and test the package under realistic storage conditions using appropriate controls and key spoilage indicators. Table 1 compares representative studies according to the level of evidence reported, from film characterisation and model assays to real-food validation, safety assessment, processing relevance, and sensory evidence.

Safety, Regulatory and Manufacturing Barriers to Food-use Readiness

Food-contact Safety, Migration and Nano-specific Concerns

Preservation performance alone is not sufficient to establish the practical value of lignin-based active packaging. A film may reduce oxidation, delay fungal growth, or improve shelf life, but it cannot be considered ready for food use unless safety under intended contact conditions is demonstrated. This requirement is particularly important for lignin-based systems because lignin may act as an active additive, nanofiller, coating component, carrier of volatile compounds, or interfacial modifier. Each role may create a distinct migration or exposure scenario.

Food-contact regulations are based on the principle that packaging materials should not transfer substances to food at levels that may endanger human health, change food composition, or deteriorate organoleptic properties. In the EU framework, Regulation EC No 1935/2004 provides general requirements for food-contact materials, while Regulation EU No 10/2011 defines requirements for plastic food-contact materials, including overall migration, specific migration, food simulants, and functional barriers (Restuccia *et al.*, 2010; European, 2011a). Active and intelligent packaging requires further attention because these systems are designed to interact deliberately with food or the package environment. Therefore, Regulation EC No 450/2009 becomes relevant when lignin-based materials are intended to release, absorb, or control active compounds during storage (European, 2009; Yildirim *et al.*, 2018).

Renewable origin should not be treated as evidence of food-contact safety. Bio-based and biodegradable materials may contain additives, monomers, oligomers, impurities, reaction products, degradation products, residual solvents, or non-intentionally added substances. These compounds may migrate into food or food simulants, and their identity or toxicological relevance is not always known (Lestido-Cardama *et al.*, 2025). The EFSA reassessment of untreated wood flour and fibers for plastic food-contact materials supports this caution because plant-origin materials can contain variable natural constituents, contaminants, and extractable compounds, while migration data may be insufficient for assuming inert behaviour (Cavallo *et al.*, 2021). This issue is directly relevant to lignin-based packaging, where feedstock, extraction route, purification, modification, and particle form can change the profile of possible migrants.

Migration evidence remains limited in lignin-based active packaging studies. Many papers report UV shielding, antioxidant activity, antimicrobial inhibition, mechanical reinforcement, or barrier improvement, but do not include migration testing, toxicological screening,

Table 1: Evidence progression from film functionality to food validation in lignin-based packaging

Packaging	Target	Film	Model	Food	Safety	Processing	Sensory	Key Finding	References
Lignin/CNC	Cabbage leaf	✓	±	±	–	–	–	Strong UV protection in a food-related light exposure test	Halloub (2022)
PBS/LNP/cinnamaldehyde	Bread	✓	✓	✓	–	±	–	Yeast and mold remained below 1.0 log CFU g−1 after 14 days	Moe *et al.* (2023)
PBS/LNP/cinnamaldehyde	Mango	✓	✓	✓	–	✓	–	Delayed visible spoilage and preserved quality	Nuamduang *et al.* (2024)
Chitosan/LNP films	Grass carp	✓	✓	✓	–	–	–	Extended refrigerated shelf life to 10 days	Zhang (2023)
Litchi starch/ xyloglucan/LNP	Banana	✓	±	✓	–	–	–	Reduced weight loss and slowed peel colour change	Santhosh (2025)
LNP/cellulose acetate	Apples	✓	✓	✓	–	–	–	Extended shelf life by at least three days	Xu (2024)
PVOH/NCP/LNP/tea tree oil	Strawberry	✓	✓	✓	–	–	–	Preserved quality for 14 days at 4°C	Abraham *et al.* (2025)
PVA–PEG films with A-LNP	Tomato	✓	✓	✓	–	–	–	Retained quality for at least 15 days	Meenu (2025)
PLA/lignin films	Ketchup	✓	✓	±	✓	✓	–	UV protection with migration and cytotoxicity evidence	Wijaranakul *et al.* (2025)

Note: ✓ = Reported; ± = Partially reported or limited; – = Not reported. Film refers to material-level characterisation. Model refers to model antioxidant or antimicrobial assays. Food refers to real food storage or food-related validation. Safety refers to migration, cytotoxicity, non-intentionally added substances (NIAS), or food-contact assessment. Processing refers to extrusion, blown film, coating, or pilot-scale routes. Sensory refers to sensory or consumer-relevant evaluation or sensory evaluation. Some studies provide stronger evidence. Cavallo *et al.* (2021) evaluated extruded PLA films containing pristine and modified lignin nanoparticles and included migration testing in food simulants together with functional and composting-related evaluation. Wijaranakul *et al.* (2025) developed blown PLA films containing organosolv bagasse lignin and assessed UV-barrier performance, antioxidant activity, overall migration, cytotoxicity, and ketchup colour protection. In that system, 0.5 - 1.0 wt% bagasse lignin reduced UV transmittance and limited ketchup colour change, while overall migration and cytotoxicity remained below the tested safety thresholds.

Earlier work on PLA-lignin films also shows why migration should be interpreted carefully. Domenek *et al.* (2013) showed that thermal processing can increase the low-molecular-weight fraction and influence the migration of antioxidant compounds into ethanol or water food simulants. This means that lignin migration is not only a risk marker. It may also contribute to active packaging function, but only when the migrating substances are identified, controlled, and safe for the intended use.

Lignin nanoparticles require additional scrutiny because nanoscale formulation can change surface area, dispersion, reactivity, polymer interaction, and exposure behaviour. Conventional migration testing may not distinguish between soluble lignin-derived fragments, low-molecular-weight phenolics, released active agents, and intact or aggregated nanoparticles. EFSA guidance for nanomaterial risk assessment emphasises physicochemical characterisation, exposure assessment, hazard identification, toxicological testing, and risk characterisation for nanomaterials used in food and food-contact applications (Committee, 2021). Evidence from non-lignin nanocomposite packaging also supports case-by-case assessment. Maisanaba *et al.* (2014, 2018) used migration extracts from polymer nanocomposites to evaluate cytotoxicity and mutagenicity, showing that nanofiller safety cannot be inferred from material class alone. For LNP-based packaging, future studies should therefore determine whether exposure arises from intact nanoparticles, soluble lignin-derived substances, low-molecular-weight phenolics, residual reagents, or co-active agents.

Sensory and Regulatory Credibility

Food-contact readiness also depends on sensory and consumer-facing properties. A lignin-based film may be chemically safe and functionally active, but still unsuitable if it changes product appearance, creates unacceptable odour, reduces transparency, or affects consumer trust. This issue is especially relevant because lignin chromophores provide strong UV shielding while also darkening films and reducing optical clarity. Yang *et al.* reported that LNP addition improved active properties in PVA/chitosan films, but optical changes such as colour and opacity became relevant at higher loading (Yang *et al.*, 2016c). Similar optical trade-offs are repeatedly reported in lignin-based UV-blocking systems, where improved light protection may be accompanied by reduced transparency or altered package appearance (Sadeghifar & Ragauskas, 2020). Therefore, sensory evaluation should consider not only the film appearance, colour, transparency, and odour, but also possible changes in the visual quality, perceived freshness, and acceptability of the packaged food.

Sensory concerns become more important when lignin is combined with volatile active agents such as cinnamaldehyde, thymol, or essential oils. These compounds can improve antifungal or antimicrobial performance, but uncontrolled release may affect aroma and flavour. This is why real-food validation should include sensory analysis, especially for fresh fruits, bakery products, dairy products, fish, and lipid-rich foods where aroma transfer and surface interactions can strongly influence acceptance. Nuamduang *et al.* (2024) explicitly noted that sensory analysis, release behaviour, diffusion, partition, and migration studies remain necessary before industrial application of PBS/LNP/trans-cinnamaldehyde films can be claimed.

Consumer acceptance adds another constraint. Reviews on environmentally friendly food packaging show that consumers often need clearer guidance to recognise sustainable packaging, may lack knowledge about bio-based materials, and often prioritise price and food quality over packaging sustainability (Ketelsen *et al.*, 2020). Other consumer-oriented studies also show that sustainability claims can become confusing when environmental benefits are not clearly linked to product protection and end-of-life behaviour (Boz *et al.*, 2020). For lignin-based packaging, brown colour, reduced transparency, unfamiliar material claims, and uncertainty around biodegradability or food-contact safety may influence acceptance even when technical performance is promising. Table 2 summarises the safety and regulatory evidence relevant to lignin-based active packaging and shows that food-contact readiness remains less mature than material functionality.

Processing and Scale-up Constraints

Processing readiness is another critical filter between promising lignin-based films and practical food packaging materials. Many reported systems are still prepared by solvent casting, small-scale solution blending, or laboratory coating. These routes are useful for early formulation screening because they allow uniform dispersion and low thermal stress. However, they do not demonstrate industrial readiness. Commercial food packaging usually requires scalable routes such as melt extrusion, blown film extrusion, reactive extrusion, coating, lamination, paper or board coating, thermoforming, and heat sealing. A lignin-based film that performs well after solvent casting should therefore still be considered at an early development stage unless functionality is retained under realistic manufacturing conditions.

This distinction is important because lignin performance depends strongly on dispersion quality, interfacial adhesion, particle size, molecular weight, thermal history, and compatibility with the polymer matrix. Poorly dispersed lignin can act as a defect rather than as an active or reinforcing component. It may reduce elongation, increase opacity, weaken barrier performance, or create non-uniform active release. Therefore, the processing question is not only whether lignin improves a film property, but whether this improvement can survive scalable processing and remain compatible with food-contact requirements. Melt-processing studies provide stronger

Table 2: Summary of evidence relevant to food-contact readiness, including migration, toxicity, NIAS and nano-related concerns, sensory relevance, and remaining safety gaps

System or Focus	Migration	Toxicity	NIAS/ Nano	Sensory	Regulatory Relevance	Remaining Gap	References
Plastic food-contact materials	Guidance	–	±	±	Plastic FCM regulation	Lignin-specific migrants and LNP release need case-specific evaluation	European (2011b)
Active and intelligent packaging regulation	Guidance	–	±	±	Active packaging regulation	Active-agent release must be linked to intended use and labelling	Restuccia *et al.* (2010)
Plant-origin additives in plastic FCMs	Guidance	±	✓	–	EFSA safety opinion	Plant origin requires compositional, contaminant, and migration data	Efsa Panel on Food Contact Materials and Processing (2019)
Nanomaterial risk assessment	Guidance	Guidance	✓	–	Nano-risk guidance	Most LNP packaging studies lack nano-specific exposure evidence	Committee (2021)
Bio-based and biodegradable FCM safety	✓	±	✓	±	Bio-based FCM safety review	Bio-based systems need systematic NIAS and degradation-product testing	Lestido-Cardama *et al.* (2025)
PLA/lignin films	✓	–	±	–	Experimental lignin study	Migrating low-molecular-weight phenolics need identification and control	
Extruded PLA/LNP films	✓	–	±	–	Experimental lignin study	Food-contact evidence remains limited without sensory and food-use testing	Cavallo *et al.* (2021)

Blown PLA/bagasse lignin films	✓	✓	±	±	Experimental lignin study	Evidence is limited to one PLA/lignin system and one food-use scenario	Wijaranakul *et al.* (2025)
Polymer nanocomposite and modified-clay nanofillers	✓	✓	✓	–	Methodological nanotoxicity study	Methodological reference, not lignin-specific evidence	Maisanaba (2018)

Note: ✓, reported; ±, partially reported or limited; –, not reported readiness evidence than solvent-cast films. Hararak *et al.* (2024) proposed a processing-oriented strategy by generating lignin particles directly during melt extrusion of PLA-based films. This route avoided separate nanoparticle drying and reduced the agglomeration risk associated with dry LNP handling. The resulting blown films showed UV-barrier and antioxidant properties, while migration values in food simulants remained below regulatory limits under the tested conditions.

PLA/bagasse lignin films also show that industrially relevant processing can be combined with food-contact screening. Wijaranakul *et al.* (2025) fabricated PLA films containing 0.1 to 1.0 wt% organosolv bagasse lignin by conventional blown film extrusion. Lignin addition reduced UV transmittance, provided antioxidant activity, limited ketchup colour change under UV exposure, and maintained overall migration and cytotoxicity below the tested safety thresholds. PBAT-based systems further show that compatibility control can be as important as lignin addition itself. Modified lignin can improve dispersion, transparency, thermal stability, mechanical behaviour, UV blocking, and biodegradation behaviour in PBAT matrices, but these benefits depend on interfacial design and controlled processing conditions (Xing *et al.*, 2017; Liu, 2021).

Processing becomes more complex when lignin is used with volatile active agents. Cinnamaldehyde, thymol, and essential oils can improve antifungal or antimicrobial function, but they may be lost, degraded, or unevenly distributed during thermal processing. LNPs can help retain or modulate the release of such compounds, as shown in PBS/LNP/cinnamaldehyde systems for bread and mango packaging (Moe *et al.*, 2023; Nuamduang *et al.*, 2024). However, active-agent retention, release kinetics, sensory effects, and migration should be considered part of processing readiness rather than only part of food preservation testing.

Coating and paper-based systems introduce a different set of constraints. Lignin-containing coatings can improve water resistance, UV protection, antioxidant activity, antimicrobial surface behaviour, or barrier properties, but scale-up may introduce adhesion problems, coating defects, pinholes, delamination, migration, and heat-sealing limitations. Javed *et al.* showed that pH and ammonium zirconium carbonate affected lignin migration and water stability in starch/lignin coatings on machine-glazed paper, but pilot coating also revealed pinhole formation (Javed *et al.*, 2021). This example shows that a laboratory-level formulation improvement can create a new defect at pilot scale.

Overall, the current processing evidence shows clear progress, but it remains uneven. The strongest readiness signals come from systems that retain functionality after extrusion, blown film extrusion, reactive extrusion, or pilot coating. Still, lignin aggregation at higher loading, matrix incompatibility, reduced elongation, darkening, opacity, volatile-agent loss, coating defects, heat-seal failure, migration control, batch-to-batch variability, and reproducibility of LNP production remain unresolved barriers. Future studies should report processing route, temperature, residence time, lignin loading, dispersion quality, film thickness, active-agent retention, migration, heat-seal performance when relevant, and shelf-life performance after processing. Without these data, it remains difficult to distinguish a promising laboratory material from a packaging system that can be manufactured reliably.

Sustainability, Economic Feasibility and Integrated Readiness Profile

Functional Unit, Food-waste Reduction and LCA Boundaries

Environmental and economic readiness is still one of the weakest parts of lignin-based active food packaging research. Although lignin is renewable, abundant, and often obtained from industrial side streams, these features alone do not prove that lignin-based packaging is sustainable or cost-effective. A credible assessment should consider the whole food-packaging system, including lignin extraction and purification, film processing, additives or modifications, food-contact safety, end-of-life route, and the ability of the package to reduce food loss. Therefore, the sustainability of lignin-based active packaging should be judged not only by the material itself, but also by its real contribution to food protection and waste reduction.

This point is important because bio-based or biodegradable packaging does not necessarily outperform conventional packaging in every impact category. Environmental outcomes depend on system boundaries, energy source, material yield, solvent recovery, processing intensity, waste-management infrastructure, and the type of food protected. Ex-ante LCA studies of early-stage bio-based films show that laboratory-scale inventories can misrepresent future industrial performance when scale-up, process scenarios, and material substitution factors are not considered (Müller-Carneiro, 2023). Ecodesign studies on bio-based films also emphasise that unclear functional units, limited data on the effect of packaging on packed food, and laboratory-to-industrial inventory gaps remain major barriers to credible environmental assessment (Sampaio, 2023).

For lignin-based active packaging, the functional unit should not be limited to one kilogram or one square meter of film when the material is designed to preserve food. A more meaningful assessment should be based on the service delivered by the package such as maintaining a defined amount of edible food with acceptable quality after storage. This distinction is essential because an active package may have higher direct material impacts than a passive package but still reduce the environmental burden of the whole food-packaging system if it prevents food waste.

The strongest environmental justification for active packaging extends beyond material substitution alone, but food-waste prevention. Packaging LCAs that focus only on direct material impacts may miss the indirect benefit of food protection. Previous studies have shown that environmental conclusions can change when shelf-life extension and packaging-related food waste are included in the assessment (Heller *et al.*, 2019; Molina-Besch *et al.*, 2019). This is directly relevant to lignin-based active systems. If lignin only replaces part of a polymer without improving food protection, the environmental benefit may remain limited. If lignin contributes to UV-protection, antioxidant activity, antifungal performance, barrier improvement, or controlled release that delays deterioration, the environmental case becomes more defensible.

Application-specific cases are therefore needed. Lignin-based UV-protective films may be useful for light-sensitive foods if they reduce pigment degradation, lipid oxidation, or light-induced quality loss. Antioxidant films may be valuable for lipid-rich or oxidation-sensitive foods if oxidative spoilage is delayed. Antifungal lignin-containing systems may be justified for bakery products or fresh produce if fungal growth is reduced without unacceptable migration or sensory effects. For example, lignin-based UV-protective films may be useful for tomato-based sauces or ketchup, where light-induced colour loss is important (Wijaranakul *et al.*, 2025), while antifungal lignin-containing films may be more suitable for bread or fresh fruits such as mango and strawberry, where mold growth and postharvest quality loss are major concerns (Moe *et al.*, 2023; Nuamduang *et al.*, 2024; Abraham *et al.*, 2025). In each case, sustainability should be assessed through the combined performance of material production, food protection, safety, end-of-life route, and cost.

Economic and Market-readiness Gaps

Direct Techno-economic analysis (TEA) studies on lignin-based active food packaging are still scarce. Most studies report film functionality, antimicrobial or antioxidant activity, migration, or food preservation, but rarely quantify production cost, minimum selling price, scale-up cost, solvent recovery, modification cost, active-agent cost, waste-management cost, or the economic value of avoided food loss. As a result, economic readiness is weaker than material-performance evidence.

Evidence from other lignin-based or biodegradable polymer systems can still indicate the main cost drivers. Studies on lignin-derived materials and biodegradable polymers show that feedstock cost, monomer or additive cost, process yield, energy demand, solvent use, purification, and scale strongly affect economic feasibility (Gujjala & Won, 2022; Wang, 2024). For lignin-based active packaging, additional cost may arise from lignin purification, fractionation, chemical modification, nanoparticle preparation, compatibiliser use, active-agent incorporation, and food-contact testing. These added burdens can be justified only when they produce measurable functional value such as longer shelf life, lower food loss, improved quality retention, safer replacement of synthetic additives, or stronger circularity.

Market readiness also depends on practical constraints beyond production cost. Lignin-based films may show strong UV-protection or antioxidant activity, but colour darkening, odor, opacity, reduced transparency, uncertain biodegradation claims, and unfamiliar material identity may limit consumer acceptance. This is particularly relevant for foods where visual appearance and package clarity affect purchase decisions. Therefore, market feasibility should be assessed together with sensory quality, product visibility, label claims, regulatory route, and the expected willingness to accept or pay for a bio-based active package.

The economic case should also be food-specific. A lignin-based package used for a low-value, low-risk, shelf-stable product may not justify added formulation complexity. The same material may be more defensible for foods with higher spoilage losses, higher environmental burden, or stronger sensitivity to light, oxidation, fungal growth, or moisture loss.

This means that economic readiness should not be discussed as a general property of lignin-based packaging. It should be evaluated through the target food, deterioration pathway, shelf-life gain, processing route, and realistic reference package.

Integrated Readiness Profile and Future Validation Priorities

The evidence reviewed in the previous sections shows that lignin-based active food packaging should not be evaluated only as a material innovation. A film may show strong UV shielding, antioxidant activity, antimicrobial inhibition, improved barrier performance, acceptable migration, or successful extrusion, but none of these criteria alone confirms readiness for practical food packaging. Practical readiness requires convergence among material performance, food preservation, food-contact safety, scalable processing, environmental benefit, economic feasibility, sensory acceptability, and regulatory credibility.

Technology readiness level provides a useful conceptual starting point because it describes maturity from basic principles to operational use (Mankins, 1995). However, TRL cannot be transferred mechanically to lignin-based food packaging. When TRL is applied outside its original context, the scale must be adapted to the specific discipline and operating environment (Héder, 2017). In food packaging, the operating environment includes food composition, storage temperature, contact time, migration behaviour, spoilage pathway, sensory quality, consumer perception, end-of-life infrastructure, and regulatory conditions. For this reason, lignin-based active packaging should be assessed as a product-package-process-food system.

This system-level view also explains why readiness is uneven. UV-protective poly (lactic acid) (PLA) or poly (butylene adipate-co-terephthalate) (PBAT) films produced by extrusion may be relatively advanced in functional and processing readiness but still require stronger real-food and sensory validation. Polybutylene succinate (PBS), lignin nanoparticles (LNP) cinnamaldehyde films may show strong antifungal performance in bread or mango, but still need deeper release, migration, sensory, and economic evidence before commercial readiness can be claimed (Moe *et al.*, 2023; Nuamduang *et al.*, 2024). Paper or starch/lignin coatings may be promising for coated packaging, but pilot trials show that coating defects, water stability, and migration can become limiting during scale-up (Javed *et al.*, 2021). The readiness of each system therefore depends on the intended food, active function, matrix, processing route, and safety evidence.

The readiness scores in Figure 4 were assigned as qualitative evidence maturity scores, not as pooled statistical estimates. Scoring was based on the evidence summarised in Tables 1 and 2 and considered the number, directness, and completeness of evidence across functionality, real-food validation, safety, sensory relevance, processing scalability, sustainability, economic feasibility, and regulatory readiness. Accordingly, Figure 4 presents the readiness profile of lignin-based active food packaging using a qualitative scale from 1 to 5, where higher scores indicate stronger and more complete evidence across the main readiness dimensions.

The readiness profile clarifies where the field is strongest and weakest. Functional performance is currently the most mature dimension, especially for UV shielding, antioxidant activity, and selected barrier or reinforcing effects. Real-food validation is improving through studies on bread, mango, fish, banana, apple, strawberry, tomato, and ketchup, but remains incomplete because sensory, release, migration, and commercial benchmarking are not consistently reported. Processing readiness is moderate because extrusion, blown film extrusion, reactive extrusion, and pilot coating have been demonstrated in selected systems, but reproducibility, defect control, active-agent retention, heat sealing, and scale-up economics remain unresolved.

In contrast, food-contact safety, sensory evaluation, environmental assessment, economic feasibility, and regulatory readiness are still less mature. This does not mean that lignin-based packaging is unsuitable. It means that current evidence is uneven and application-specific. Broad claims such as universal antimicrobial packaging, fully sustainable replacement of conventional plastics, or market-ready LNP packaging are not yet supported by sufficient integrated evidence.

Future progress should not simply involve adding lignin to more polymer matrices. Instead, validation should be designed around a defined food deterioration problem and a realistic use scenario. The key question is whether the selected lignin type, polymer matrix, and processing route can deliver measurable preservation while meeting the relevant requirements for safety, sensory quality, scalability, sustainability, and regulation. This application-specific approach provides a clearer basis for identifying which lignin-based systems are genuinely close to food-packaging use.

Conclusions

Lignin-based active food packaging presents considerable potential as a multifunctional material, yet its practical readiness is highly application-specific. The strongest evidence supports its role as a UV-protective, antioxidant, and barrier-enhancing additive in selected biodegradable films and coatings. Conversely, antimicrobial activity is less predictable and dependent on lignin source, extraction method, particle form, polymer matrix, co-active components, and the specific food system. Accordingly, lignin should be considered a tailored functional component rather than a universal preservative.

While the field has progressed beyond simple film development, most studies still rely on material-level assays, radical-scavenging tests, or in vitro antimicrobial evaluations. Comprehensive validation at the food-system level is necessary, encompassing real-food storage, migration and safety assessment, sensory quality, scalable processing, techno-economic and life-cycle analyses, and regulatory compliance. Renewable origin or biodegradability alone cannot substitute for robust evidence of food-contact safety or system-level sustainability.

Near-term practical applications are best pursued through targeted strategies rather than aiming for universal plastic replacement. Defensible opportunities include UV-protective packaging for light-sensitive foods, antioxidant-enriched systems for oxidation-prone products, antifungal packaging for bakery and fresh produce, and lignin-based coatings that

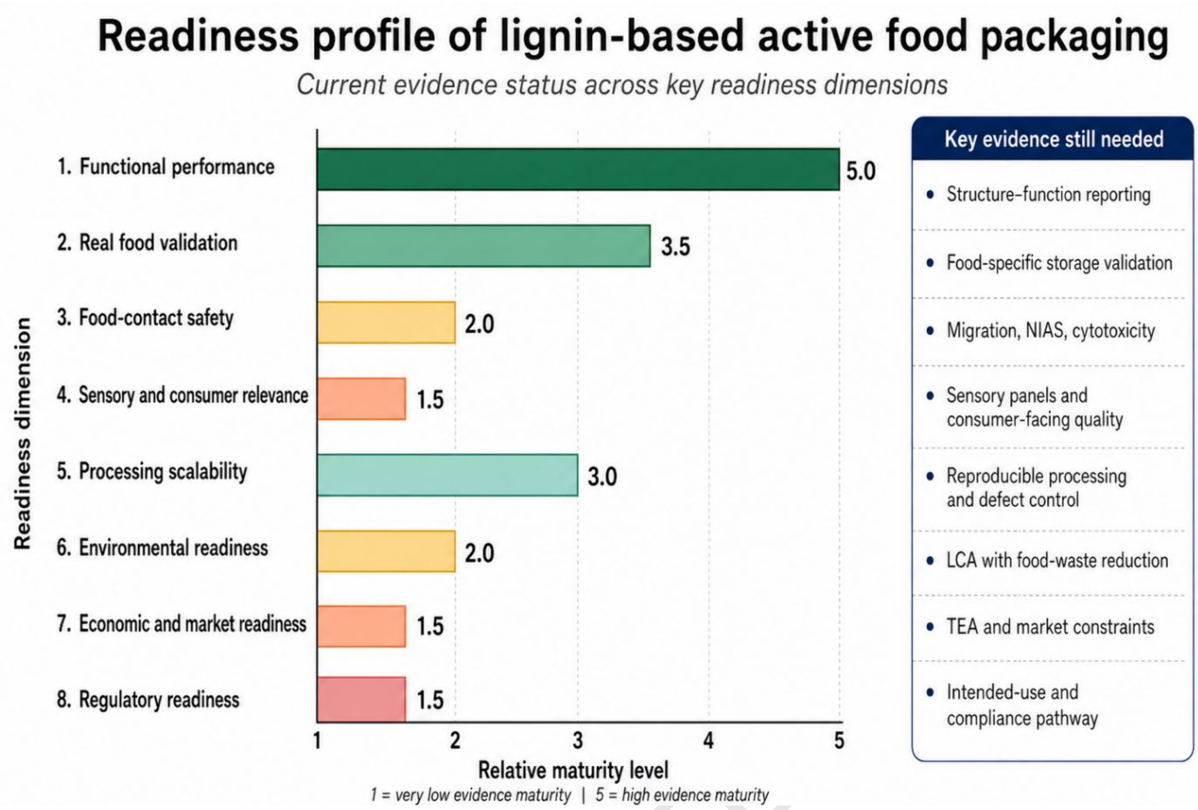

Figure 4: Readiness profile of lignin-based active food packaging. Scores from 1 to 5 summarise qualitative evidence maturity across functionality, food validation, safety, processing, sustainability, economic feasibility, and regulatory readiness

Source: Hararak *et al.* (2024), Hemachandra (2024), Lestido-Cardama *et al.* (2025), Moe *et al.* (2023), Molina-Besch *et al.* (2019), Nuamduang *et al.* (2024), Song (2024), and Wijaranakul *et al.* (2025)

enhance barrier or surface properties. Successful adoption hinges on demonstrating, within specific food-packaging systems, the integration of functional performance, safety, processability, sustainability, and consumer-relevant quality. Future studies should therefore prioritise real-food storage tests, migration and safety analysis, sensory evaluation, and scalable processing under realistic food-packaging conditions.

Future advances will depend less on demonstrating new material functionalities and more on generating evidence that links preservation performance, food-contact safety, consumer acceptance, scalability, and sustainability within clearly defined food-packaging applications.

Authors Contribution Statement

Maryam Saleknezhad: Methodology, formal analysis, writing (original draft). Seyed Sajad Hashemi: Supervision, writing (review and editing). Meysam Madadi: Conceptualisation, project administration, supervision, formal analysis, writing (review and editing).

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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