

Innovative applications of lignin nanoparticles in food packaging: A comprehensive review

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ABSTRACT

Lignin nanoparticles (LNPs) are the most abundant natural biopolymer and green nano reinforcement, which, compared to lignin, have increased surface activity and specific surface area and antimicrobial, antioxidant, and ultraviolet ray-blocking properties. As a biological compound, LNPs are included as fillers in food packaging films (FPFs) to increase their mechanical, microbial, thermal, and barrier properties. In addition, films and matrices containing LNPs maintain the quality and safety of food products and increase the shelf life of food. This study examines the effect of LNPs on the physical, mechanical, antioxidant, antimicrobial, optical, and thermal properties of biodegradable films. Furthermore, this research investigates the properties of films incorporating LNPs within various matrices and assesses the relationship between polymers and LNPs. The potential applications of LNPs in food packaging have been emphasized, demonstrating their beneficial and encouraging role in sustainable food packaging.

1. Introduction

Nowadays, due to the depletion of natural resources and the threat to the environment, the need to choose suitable alternatives for fossil fuels and chemical resources is felt more and more (Charles et al., 2025). Rising issues linked to plastic waste in municipal solid waste have raised alarms among food packaging researchers in recent years. Most food products are packed in disposable, non-biodegradable plastics derived from petroleum. After consumption, this packaging often ends up in the environment, harming soil fertility and polluting air and water with microplastics. To mitigate these impacts, it's crucial to explore sustainable, biodegradable alternatives to replace conventional plastics (Abdullahi et al., 2025; Zhang et al., 2025).

Recent studies have focused on using natural polymers for food packaging materials. Biopolymers, such as polysaccharides, proteins, and lipids, are commonly used to create films and coatings that help preserve food and extend its shelf life. However, their inherent properties often fall short of those of synthetic polymers, particularly for flexible packaging (Li, S. et al., 2025). One effective solution is to incorporate filler materials into biopolymer matrices to enhance their physical and chemical properties. More so, adding functional fillers like nanomaterials enhances these properties and enables active packaging features (Bahramian et al., 2024; Xu et al., 2025).

Lignin, often referred to as "green filler," can be incorporated into biopolymers to enhance their antioxidant, UV-protective, thermal stability, and antibacterial properties, boosting their suitability for food

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packaging. It is a byproduct of the chemical pulp production process (Mehdi et al., 2024; Tavassoli et al., 2024a). Lignin is the second most abundant natural biopolymer after cellulose. While it is widely accessible, projections suggest that global market revenues from lignin could reach \$ 1.1 billion by 2027 (Giuliana et al., 2024). Lignin structure contains approximately 30 % of organic carbon. Lignin is a complex biopolymer composed of phenylpropanoid units (Atanu Kumar et al., 2024). Lignin is present in different types of plants (abundantly in the middle layer of the tissue and the secondary cell wall of plants), and it is chemically composed of three monomer precursors, including sinapyl, coniferyl alcohol, and coumaryl (Behera et al., 2023), which are respectively syringyl (S), guaiacyl (G), and p-hydroxyphenyl (H) form (Pylypchuk et al., 2023). Its diverse functional groups, such as carbonyl, carboxylic, methyl, aliphatic hydroxyls, and phenolic groups, contribute to its antibacterial, antioxidant, and UV-protective functions.

Lignin faces several limitations in its applications due to its low solubility, complex structure, poor compatibility with other biopolymers, and tendencies to aggregate caused by hydrogen bonding and π - π interactions (Gillet et al., 2017; Shiyi et al., 2024). To overcome these challenges and enhance its value, converting lignin into lignin nanoparticles (LNPs) and integrating them into polymer films represents an effective strategy. The increased surface area-to-volume ratio of LNPs imparts unique and improved chemical and physical properties compared to traditional lignin (Hanieh et al., 2024; Liu, R. et al., 2022). Rich in ketone structures and benzene rings, LNPs provide suitable protection against UV rays; their efficacy as a sunscreen has been well-documented in blocking UV radiation (Jiawei et al., 2023). In comparison to conventional lignin powder, LNPs offer significant advantages, including enhanced surface activity, specific surface area, and other nanoscale properties, which facilitate better dispersion in aqueous solutions and improved adhesion to hydroxy compounds (Shiyi et al., 2024). LNPs are the most abundant natural biopolymer, characterized by an amorphous three-dimensional structure made up of interconnected propanoid segments (Melissa et al., 2024). In recent years, LNPs have been widely used in combination with various types of composite materials (for various purposes such as improving mechanical properties, providing antioxidant, antibacterial, anti-corrosion, UV blocking, anti-corrosion and metal adsorption properties (Fig.1) (Limenew Abate et al., 2024; Worku et al., 2024b).

The three most prominent databases for scientific peer-reviewed literature, Web of Science, Scopus, and PubMed, were utilized to identify relevant journal articles and conference papers. The following search term was implemented to screen titles, abstracts, and keywords: lignin nanoparticles AND food packaging* AND (films* OR coatings* OR nanofibers* OR casting* OR electrospinning* OR electrospun*). The search included studies published in English from these three databases over a twenty-five-year period, specifically from January 1, 2000, to July 1, 2025. In total, 147 records from these databases were screened, which we carefully reviewed. After carefully reviewing the results and excluding review articles, conference proceedings, books, and book chapters, we ultimately identified 103 articles. The objective of this study is to explore LNP as a natural and multifunctional material for sustainable food packaging solutions. We investigate various applications of LNP, their synthesis methods, and the effects of incorporating LNP into food packaging matrices. Unlike previous studies, our review provides a detailed discussion of contemporary advancements and methodologies that enhance the physical-mechanical and functional properties of packaging materials. We emphasize innovative composite solutions that synergize LNP with bioactive components, leading to improved packaging performance. Additionally, we present practical case studies that demonstrate the effectiveness of LNP-based films in real-world food packaging scenarios. Through comprehensive tables, we categorize LNP-based FPFs by their properties and analyze the additives used, contributing significantly to the field of sustainable food packaging. By addressing these areas, our review offers new insights and a forward-looking perspective on the use of LNP in food packaging systems.

2. Characteristics, general aspects, and modes of action of LNPs

LNPs are a green nano-reinforcement for which wide applications have been suggested (Aswathy et al., 2022). LNPs consist of a hydrophobic core and a hydrophilic shell (Fuyuan et al., 2023). Several factors influence the production of LNPs, including temperature, ionic strength, salt content, pH, and light (which provides greater stability at room temperature or 4 degrees Celsius) (Behera et al., 2023). In general, LNPs have various shapes, including spheres (uniform and individual), clusters, aggregates, hollow spheres, quasi-spheres, non-spherical shapes,

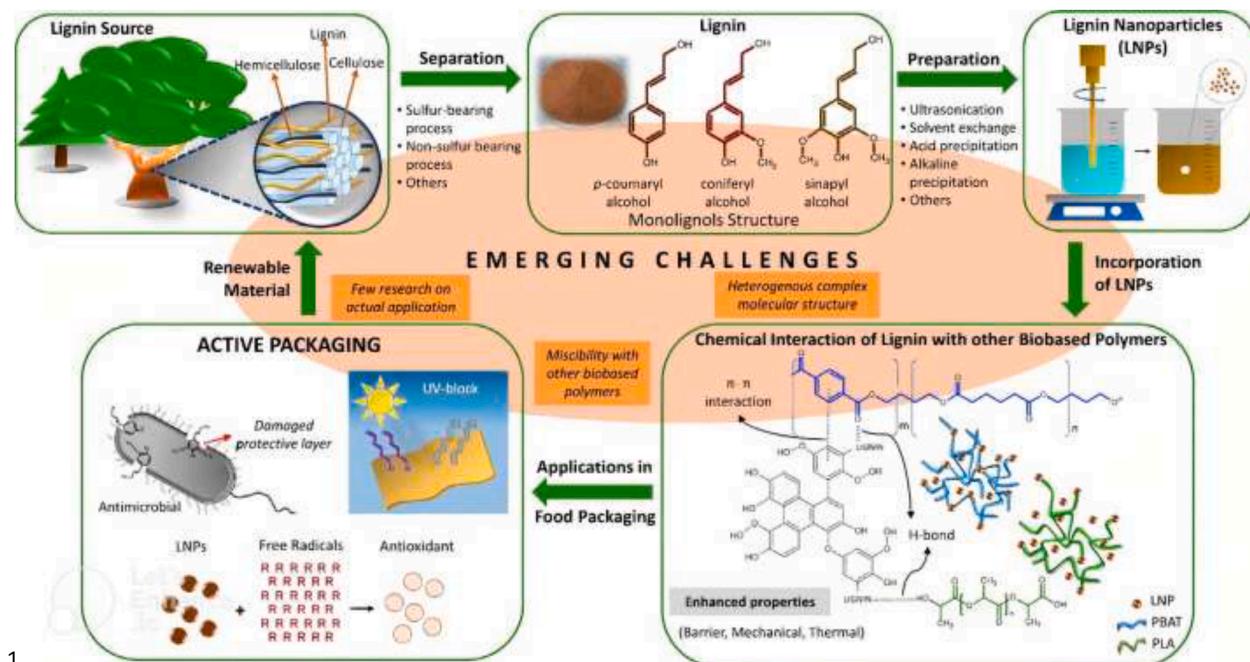


Fig. 1. Application of lignin nanoparticles in food packaging, Ref. (Hararak et al., 2022).

cuboids, and irregular shapes. Also, a higher concentration of lignin leads to an increase in the efficiency of LNPs (Fig. 2) (Willian Daniel Hahn et al., 2021). LNPs are typically produced by solvent exchange techniques, which involve dissolving lignin in an organic solvent to form these nanoparticles. The production of lignin nanoparticles is carried out by the aggregation of lignin through π - π stacking of aromatic rings and hydrophobic interactions that occur when the volume fraction of the organic solvent is reduced. Additionally, van der Waals forces and intra- and intermolecular hydrogen bonding contribute to the stabilization of the formed lignin nanoparticles. The formation of lignin nanoparticles is therefore controlled by the (in)solubility of lignin molecules and molecular size. The researchers reported that stable particles have relatively more hydrophobic cores (composed of higher molecular weight lignin molecules) and surfaces composed of relatively smaller lignin molecules enriched with hydrophilic groups (Moreno and Sipponen, 2024). Lignin nanoparticles are produced by a growth-nucleation mechanism, which has been confirmed by SEM and GPC analyses, while liquid-state ^1H nuclear magnetic resonance spectroscopy has demonstrated the presence of hydrophilic carboxylic acid, hydroxyl and methoxy groups on the surfaces of lignin nanoparticles, originating from S and G units and β -O-4' substructures (Pylypchuk et al., 2020; Sipponen et al., 2018). It is worth noting that ionized carboxylic acid groups increase the charge on the surface of lignin nanoparticles, which is crucial for their stabilization through electrostatic repulsion (Tarasov et al., 2022).

LNPs are materials used for their high added value in lignin applications. LNPs have characteristics such as dyeability, high surface permeability, high density, and a specific surface. As a result, the development of new materials based on nano-lignin can help to use lignin with high added value. LNPs can be used as antibacterial agents, drug carriers, electrocatalytic carbon materials, emulsion stabilizers, and anti-ultraviolet radiation agents (Zhang et al., 2022). The presence of phenolic units and the benzene ring of LNP gives it a remarkable antibacterial ability. LNP penetrates the bacterial cell wall (by the lysis effect) and, by interacting with reactive oxygen species (ROS), leads to the leakage of internal liquid inside the cell membrane, which process is

dependent on the antioxidant behavior of LNP. Also, due to their small size, LNP penetrates the bacterial cell and leads to a decrease in the pH inside the cell, and to destroy the cell, they release adenosine triphosphate. But in general, the AmAC of lignin is dependent on its phenolic compounds, such as the methyl group in the Y position and double bonds (in α , β positions). Compared to lignin, LNP exhibited a more outstanding AmAC due to an increase in specific surface area and phenolic fragments, as well as a decrease in molecular weight (Yingchao et al., 2022). Because lignin contains large amounts of intramolecular hydrogen bonds, ketones, and phenols, it has potential in UV stability (Liu, K. et al., 2022). The functional groups in lignin, such as phenolic and methoxy hydroxyl groups, can terminate oxidative diffusion reactions by donating hydrogen atoms, allowing LNPs to be incorporated into various materials to produce antioxidant products for diverse applications across multiple industries (Tang et al., 2020).

The performance of LNPs can differ from that of other bio-based nanomaterials such as chitosan nanoparticles (CSNPs), as demonstrated in various studies. Polyelectrolyte complex nanoparticles composed of lignin and chitosan exhibited smaller sizes compared to chitosan nanoparticles alone at a similar pH of 6, and they also displayed significantly lower surface tension at various levels. This characteristic enhances their adsorption and emulsion stabilization abilities, indicating that LNP/chitosan composites possess superior interfacial performance compared to chitosan nanoparticles by themselves (Shulga et al., 2023).

CSNPs have demonstrated high stability under simulated gastric conditions, maintaining their size, homogeneity, and zeta potential during storage. This stability highlights their advantages as drug carriers in comparison to nanostructured lipid carriers (Nerli et al., 2023). In contrast, LNP/chitosan composite nanoparticles stabilized Pickering emulsions that showcased excellent stability, pH-responsive reversible emulsification, and remarkable reusability when compared to conventional two-phase systems. Furthermore, they improved the catalytic reaction rate by approximately threefold, suggesting that LNP-infused nanosystems may offer enhanced functional stability and efficacy (Tang et al., 2022).

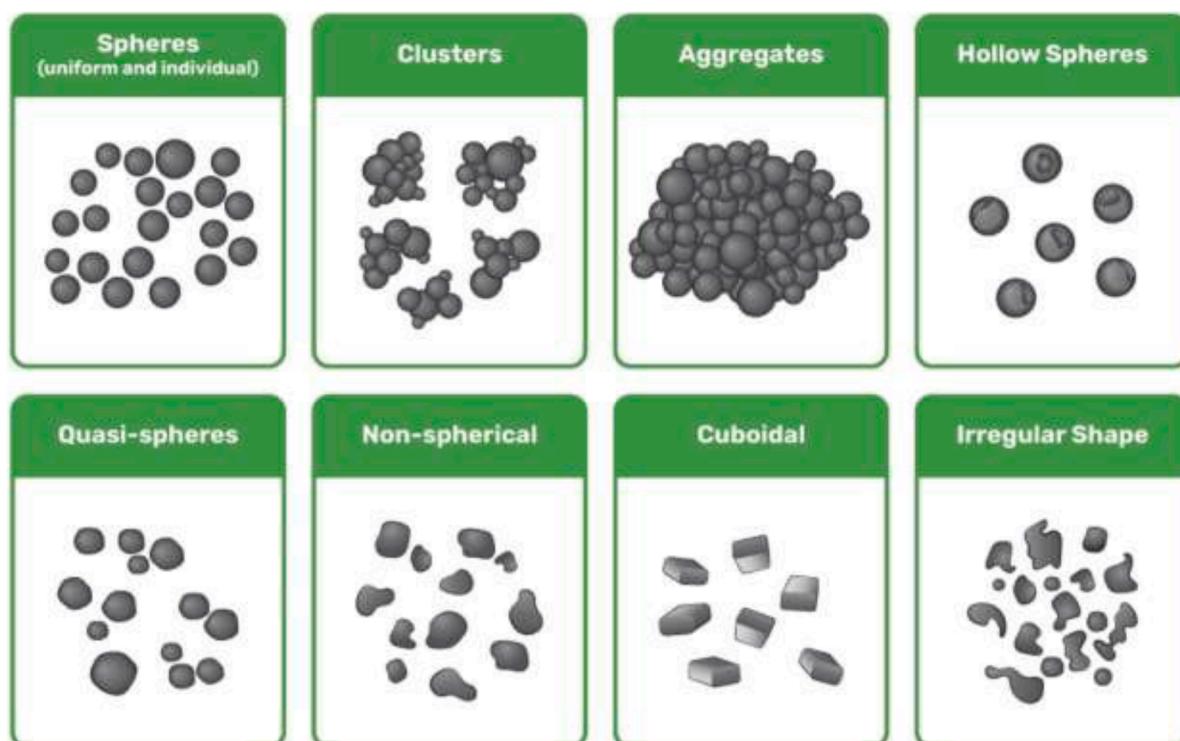


Fig. 2. Pictures of different shapes of LNPs. Reproduced from Ref. (Willian Daniel Hahn et al., 2021) with permission.

CSNPs loaded with bioactive compounds, such as oleuropein, have displayed greater bioactivity than their individual solutions, exhibiting superior antioxidant, anti-inflammatory, and gastroprotective effects at lower doses (Abd-Allah et al., 2024). This underscores the enhanced efficacy of CSNPs in drug delivery applications. Additionally, lignin-based nanoparticles combined with silver nanoparticles have shown antioxidant and antibacterial properties, along with high cellular compatibility, making them suitable for tissue engineering applications (Argenziano et al., 2024).

3. Synthesis approach of LNPs

In general, the production of nanomaterials using physicochemical techniques can have adverse environmental effects, and in many cases, expensive equipment is required. Therefore, it is crucial to employ safe, straightforward, and environmentally friendly methods for the production of nanomaterials. The production of nanomaterials using greener biological methods or raw materials from renewable resources is a promising technique. The synthesis of nanomaterials from renewable sources is very important due to their biodegradability (Iravani and Varma, 2020). There is a difference between the preparation method of LNPs and traditional adsorbent carbon materials because the preparation of LNPs does not include the activation process using high temperature, which is a simple method with increased product yield. The use of the self-assembly mechanism in the synthesis of LNPs results in the enrichment of functional groups, which leads to the provision of additional absorption sites or the possibility of modifying the surface further to increase the absorption capabilities (Tian-Shui et al., 2023). Several methods have been used for the synthesis of LNPs. Among these methods, we can refer to homogenization, ultrasonication, solvent exchange, aerosol flow, dialysis, acid deposition, supercritical flow, and flash precipitation (Table 1) (Liang Ee et al., 2021; Udari Prasadini et al., 2023; Vivian and Altaf, 2024). Physical properties (synthesized particles) such as stability, surface charge, and hydrophobicity depend on the nanoparticle synthesis method and the type of lignin precursor (Richter et al., 2016). Several of the methods mentioned for LNP preparation have limitations. For example, methods such as acid precipitation and solvent exchange require high consumption of water and solvents. On the other hand, some methods use dangerous solvents such as dichloromethane, pyridine, and toluene disocyanate (Perera et al., 2023).

The method of synthesis is a crucial factor influencing the size distribution, stability, and morphological properties of LNPs. Various cutting-edge techniques have been investigated for this purpose, including nanoprecipitation, deep eutectic solvent (DES) approaches, flash nanoprecipitation, solvent-induced self-assembly, and sonochemical transformations. This section aims to offer a thorough comparative evaluation of these techniques (Tian-Shui et al., 2023; Udari Prasadini et al., 2023).

Anti-solvent nanoprecipitation, which includes deep eutectic solvent methods, along with nanoprecipitation utilizing different solvent systems (such as DES or a mixture of acetone and water), can result in significant differences in the resulting particle sizes, typically falling within the range of 20 to 200 nm. This variability is greatly affected by several factors, including the choice of solvent, the lignin concentration used, and the solution's pH level. The resulting nanoparticles generally display a uniform dispersion, an essential quality for their use in various applications. Notably, DES-water nanoprecipitation has shown exceptional long-term colloidal stability, with studies demonstrating that such systems can remain stable at room temperature for several months without significant aggregation. A high zeta potential, exceeding ± 30 mV, indicates strong colloidal stability, which further improves these nanoparticle suspensions' resistance to agglomeration (Luo et al., 2021). Moreover, the lignin source and its initial concentration are key factors. Experimental findings indicate that using five different lignin sources in a solvent mixture of 90 % acetone and 10 % water, with lignin concentrations maintained between 1–2 %, results in successful nanoparticle formation with sizes consistently under 100 nm. Conversely, increasing the lignin concentration leads to larger particle sizes and a reduction in the uniformity of the nanoparticle size distribution (Ortega-Sanhueza et al., 2024).

Flash nanoprecipitation is another effective synthesis technique that involves quickly mixing the lignin solution with an anti-solvent, such as water. This method is particularly beneficial for scaling up to industrial production due to its efficiency. The initial lignin concentration is a critical parameter affecting particle size; lower concentrations yield smaller nanoparticles (around 50 nm), while higher concentrations can produce sizes surpassing 200 nm. The higher flow rates used during mixing promote rapid nucleation, resulting in a narrow size distribution typically characterized by a particle dispersion index (PDI) of less than 0.15. The concept known as "explosive nucleation" is particularly relevant here, as it generates nanoparticles with highly uniform sizes and

Table 1
Summary various synthesis methods for lignin nanoparticles (LNPs).

Synthesis Method	Description	Advantages	Disadvantages	Ref
Homogenization	High pressure/shear reduces particle size without chemicals.	Simple, effective for large-scale production, and yields stable nanoparticles.	Requires long processing times (up to 4 hours) and may need high energy input.	(Liang Ee et al., 2021; Nair et al., 2014; Ortega-Sanhueza et al., 2024)
Ultrasonic Method	Uses ultrasonic waves to reduce particle size to 9–10 nm.	Simple and widely used; effective against polymerization.	Produces broad size distribution and can be less efficient for large-scale production.	(Manisekaran et al., 2022; Song and Nisar, 2023)
Solvent Exchange	Lignin is dissolved in organic solvents and precipitated with water; employs self-assembly mechanisms.	Produces nanoparticles of adjustable sizes, simple method with wide applications.	High solvent consumption and potential irregular, aggregated particle morphology.	(Nor Najhan et al., 2024)
Flash Precipitation	Rapid addition of acid promotes fast nanoparticle formation and limits aggregation.	Quick production method; can control particle growth during synthesis.	Requires careful control of reaction parameters to avoid undesired aggregation.	(Kim et al., 2024; Liang Ee et al., 2021; Ortega-Sanhueza et al., 2024; Sharma et al., 2024)
Aerosol Flow	Lignin is synthesized in an aerosol flow reactor, creating spherical nanoparticles.	High production yield, tiny size control, and minimal solvent use.	Requires specialized equipment; stability of nanoparticles depends on various factors.	(Hao et al., 2022; Kim et al., 2024; Ortega-Sanhueza et al., 2024)
Supercritical Flow	Utilizes supercritical fluids to precipitate lignin, resulting in small, narrowly distributed nanoparticles.	Non-toxic solvent (CO_2) and high efficiency; produces well-defined particle sizes.	Requires high-pressure equipment and may be costly.	(Ortega-Sanhueza et al., 2024; Zhang et al., 2021)
Acid Deposition	Slow acidification of lignin solution leads to nanoparticle formation.	Can produce nanoparticles with specific properties under controlled conditions.	Loss of self-assembly in neutral/acidic conditions; may require hazardous acids.	(Anderson do Espírito Santo et al., 2022; Kim et al., 2024; Lu et al., 2024; Wu et al., 2024)
Dialysis	Removes solvents from lignin solution using a semi-permeable membrane.	Effective purification and preparation of nanoparticles.	Time-consuming; limited to specific types of lignin solutions.	(Liang Ee et al., 2021; Ortega-Sanhueza et al., 2024)

permits precise adjustment of the final product through careful control of process variables (Conner et al., 2020).

Microwave-assisted and sonochemical conversion methods further enhance the flexibility of lignin nanoparticle synthesis. Studies show that when using DES in combination with microwave-assisted techniques, nanoparticles of sizes ranging from 48 to 95 nm can be produced, whereas sonochemical methods can generate nanoparticles at sizes below 700 nm, particularly with longer sonication times (Yan et al., 2023). The molecular weight of lignin significantly influences the characteristics of the resultant nanoparticles; lignin with a lower molecular weight often results in more monodispersed nanoparticles, achieving PDIs below 0.1, indicating a high degree of size uniformity (Long et al., 2025). Additionally, zeta potential measurements indicate that the electrical charge of these particles is usually quite negative, ranging from -26 to -38 mV, which is important for ensuring the long-term stability of the suspended particles (Lee et al., 2020).

3.1. Homogenization method

In the homogenization technique, high pressure or shear is used with the aim of mechanically reducing the particle size (from macro to nano dimensions). This method is used to produce LNP without using other chemicals. According to the studies of Nair et al. (2014), a minimum homogenization time of 2 hours at 15,000 rpm is required for the synthesis of LNPs with dimensions less than 1000 nm. If the mechanical cutting time is increased to 4 hours, monodispersed LNPs with dimensions less than 60 nm are formed. Based on the studies conducted, LNP produced by the homogenization technique has higher thermal stability (Liang Ee et al., 2021; Nair et al., 2014).

3.2. Ultrasonic methods

The ultrasonic method is included in the group of mechanical methods. Like other mechanical methods, this method reduces the mass particle size to 9 to 10 nanometers. On the other hand, the imbalance in particle size and wide distribution are considered the main obstacles to this method. However, due to the simplicity of this process, it is mostly used by research communities and manufacturing industries to produce LNPs. Also, this method has been used for the synthesis of LNPs and various types of carbon-based nanoparticles (NPs), such as graphene oxide nanosheets, etc. (Yadav et al., 2022). For the synthesis of LNPs, ultrasound is an important process against polymerization. In general, the ultrasonic process is affected by the operating conditions of the liquid type, temperature, and pressure (Song and Nisar, 2023).

3.3. Solvent exchange method

The solvent exchange method is used to produce LNPs with good quality and adjustable sizes. This method is often used for the synthesis of LNPs. The solvent exchange method is a simple yet widely applicable method. In this method, first, lignin is dissolved using organic solvents (acetone, THF, DMSO), and then it is subjected to water dialysis. Adding an anti-solvent (usually water) causes precipitation, and the formation of LNPs occurs due to the decrease in their solubility. During the process, a self-assembly mechanism enables the formation of LNPs through hydrogen bonds, van der Waals forces, π - π interactions, and hydrophilic and hydrophobic interactions. A change in solvent leads to phase separation (Nor Najhan et al., 2024). Other names are solvent displacement, poor solvent enrichment, nano/flash precipitation, or poor solvent enrichment. Frangville and colleagues initially proposed a method for creating simple and inexpensive LNPs. By slowly adding the anti-solvent, with one drop every 30 s, and increasing the lignin concentration to over 40 % by weight, they successfully produced LNPs with a size of less than 100 nm. However, the morphology of these LNPs remained unclear, leading to the formation of irregular and aggregated nanoparticles (Ahilan et al., 2022).

3.4. Aerosol flow method

For the first time, a high-yield synthesis for the production of spherical LNPs exhibiting specific inherent hydrophilicity was successfully conducted in an aerosol flow reactor. This process resulted in the formation of particles with diameters of 30 nm and 2 μ m, achieved through the use of an impactor (burner type) to facilitate the breakdown of the target. Also, after subsequent dispersion in each of the strong shears in mineral oil or water, the produced lignin particles had high mechanical integrity, according to the size of the lignin particles used for emulsification. They are effective in stabilizing oil-in-water (O/W) emulsions with adjustable size reduction. The type and concentration of lignin particles affect the stability of the emulsion. A new and efficient method for producing spherical and dry lignin particles was proposed (Shalma et al., 2023). Aerosol methods offer several advantages, including high loading capacity, reduction of the overall reactor footprint (with minimal solvent use), continuous and single-step processing, and high chemical entrapment efficiency. Another aerosol technique, the electrospray method, is used to produce polymer particles in nano and micro sizes (Hao et al., 2022).

3.5. Dialysis method

Dialysis is a process to reduce or remove the concentration of a solvent or certain solutes in a solution. The lignin solution is placed inside a membrane (semi-permeable tubular) with different pore sizes to purify and wash the sample, and this process leads to the removal of the solvent from the lignin solution, and finally, LNP synthesis takes place based on the solubility of LNP in water (Liang Ee et al., 2021).

3.6. Acid deposition method

The acid deposition method for the synthesis of LNP is caused by the slow acidification of the lignin solution, which occurs using acids such as HNO₃, HCl, and H₂SO₄. In neutral and acidic conditions, self-assembly of NPs is lost due to molecular structure, unlike alkaline lignin, strong π - π stacking interaction, and hydrotropic properties (Anderson do Espírito Santo et al., 2022).

3.7. Supercritical flow method

Supercritical flow technology is widely used in the preparation of NPs due to its outstanding physical and chemical properties. The supercritical solvent anti-precipitation process is based on the fact that the solubility of lignin in a supercritical fluid is lower than its solubility in a solvent, and when the solubility of lignin in the main solvent decreases, the supercritical fluid is dissolved in the solution. The produced nano-lignin has a narrow distribution and a small particle size. On the other hand, CO₂ is the most commonly used cheap and non-toxic compound (Zhang et al., 2021).

3.8. Flash precipitation method

Technologically, size-constrained LNP production is very important for its development. Because it can determine the total active surface for NPs. LNPs produced by acid deposition are prone to aggregation. To prevent and overcome the problem of the accumulation of NPs, a method such as flash precipitation can be used. In the flash precipitation method, compared to the addition by the drop count, the step of adding acid for LNP growth and nucleation happens quickly. Furthermore, after the LNP has grown to the desired size, the synthesis is stopped by diluting the reaction medium with water. The growth kinetics of LNP depend on factors such as temperature, acid, the solvent used for dissolution, and reaction time (Liang Ee et al., 2021).

4. Functional properties of LNPs

4.1. Antimicrobial function

One of the mechanisms of lignin nanoparticles is related to the double bond at the $\text{C}\alpha=\text{C}\beta$ position of the side chain and the methyl group at the γ position. In addition, the epoxy and methoxy groups in LNPs are considered essential for antimicrobial properties (Behera et al., 2024). Another antimicrobial mechanism of lignin nanoparticles is related to polyphenols. By lysis of polyphenols, lignin nanoparticles lead to damage to the bacterial cell wall, resulting in leakage of the internal fluid. In addition, reactive oxygen species absorbed by polyphenols and accumulated on the surface of lignin nanoparticles can lead to oxidative stress in the bacterial cell. This mechanism suggests that the antioxidant function of lignin nanoparticles is consistent with its antimicrobial function by the production of reactive oxygen species. In addition, lignin nanoparticles, due to their small size, can facilitate the penetration of microorganisms into the microorganism cell by a Trojan horse mechanism and escape from the cell membrane. In this reaction, monophenolic compounds such as cinnamaldehyde, which are derived from lignin, penetrate into the bacterial cell, leading to a decrease in intracellular pH and ATP leakage, and ultimately the bacteria die (Fig. 3.) (Yang et al., 2018b).

4.2. Antioxidant function

As previously demonstrated, lignin possesses the ability to scavenge radicals due to its abundant functional groups and complex chemical structure. Functional groups such as hydroxyl and phenolic methoxy in lignin nanoparticles neutralize the oxidative release reaction by donating hydrogen, so it is considered natural antioxidants. The antioxidant activity of lignin can be enhanced by the presence of more low-molecular-weight groups, phenolic hydroxyl groups, and narrowly dispersed groups. Also, the large number of aromatic compounds present in the three types of phenylpropane monomers, including phenolic hydroxyl groups and numerous benzene rings, leads to increased antioxidant properties of LNPs (Santo Pereira et al., 2022). However, studies have shown that when lignin is converted into nanoparticles, its antioxidant function is enhanced. This phenomenon is justified due to the nanoscale size, as lignin exhibits a smaller volume and a larger specific surface area at this scale, leading to an increase in surface functional

sites. On the other hand, the surface of lignin nanoparticles contains a large number of phenolic hydroxyl groups, which neutralize the DPPH radical. Additionally, the hydroxyl and carboxyl functional groups on the surface of lignin nanoparticles contribute to their solubility in water, thereby increasing their bioavailability. As a result, lignin nanoparticles can be used to enhance the oxidation resistance of composite films and hydrogels (Wang et al., 2022).

5. The effect of loading LNPs in food packaging matrix

Research on the effect of lignin nanoparticles on the properties of composites and packaging films is reported in Table 2.

5.1. Mechanical properties

Biodegradable films and composites used for packaging should have adequate flexibility and mechanical strength against external stress and be able to maintain the integrity of packaged food during transportation/handling and storage. Most studies investigate elongation at break (EAB), tensile strength (TS), and Young's modulus (YM) of biodegradable films. Factors such as the nature of the biopolymer and the additive type affect the tensile properties of FPFs (Bakhshizadeh et al., 2023). This part investigated the effect of adding LNPs on the tensile properties of different polymers. For example, Sun et al. (2023) found that adding 1–5 % LNPs increased the starch film's elastic modulus and TS, which were at their highest values at concentrations of 2 and 3 %. The authors attributed this improvement in mechanical properties to the reinforcing effect of LNPs in the starch film, which makes the starch film compatible by creating hydrogen bonds. However, the YM and TS in 4 and 5 % concentrations of LNPs were lower than in other concentrations because LNPs in high concentrations cause particle accumulation, which has a negative effect on mechanical properties (Fig. 4b). In addition, the structure created between LNPs and starch molecules reduced the starch film's molecular chain mobility and the EAB (Fig. 4a) (Sun et al., 2023). In another study, Zou et al. (2023) reported that increasing the lignin nanoparticle content from 0 to 5 % increased the TS of chitosan (CS) film from 37.29 to 43.59. In addition, the EAB increased from 3.33 to 7.87. The LNPs, which are uniformly distributed in the CS film, affect the tension in the CS film and improve its mechanical properties. In addition, the electrostatic interaction between lignin and CS NPs has increased the mechanical properties (Zou

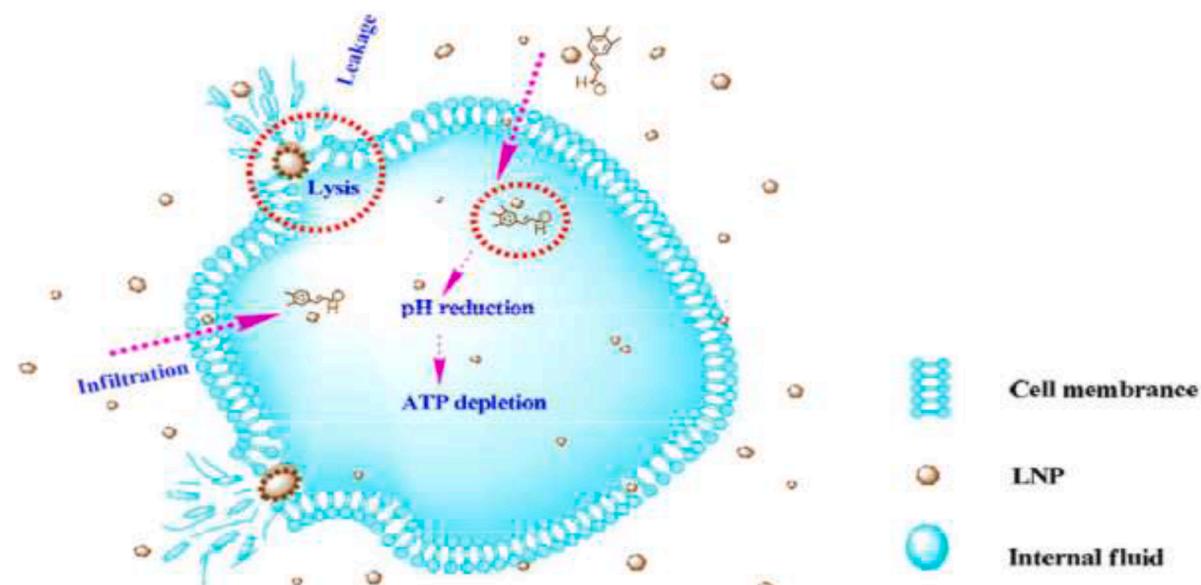


Fig. 3. . Antimicrobial mechanism of lignin nanoparticles, Ref. (Yang et al., 2018b).

Table 2

The effect of LNP on the physical, mechanical, and functional properties of packaging films.

Film base		Key observations				Ref.
Polymer	Additives	Film characterization		Functional properties		
		Physical properties (Thickness; mm, MC, WS, SI; %, WVTR; GGGG, g/(m ² ·24 h), WVP; g mm/m ² h kPa, OTR; cm ³ /(m ² ·24 h MPa), OP; cm ³ /m ² h)	Mechanical properties (TS and YM; MPa, EAB; %,)	Antioxidant ability/ Method	Antimicrobial ability (IZ; (mm) or IR; (%))	
CS	LNPs and ASPNG	WS (↑; 33.12 → 18.33), WVTR (↓; 1987.33 → 1784.67), OTR (↑; 5.73 → 4.25)	TS (↑; 37.29 → 43.59), EAB (↑; 3.33 → 7.87)	NS	<i>E. coli</i> (↓; up to 10 log CFU/mL)	(Zou et al., 2023)
PVA/CS and PVA/chitin Starch	LNPs	Thickness (↑; 0.22 → 0.39), MC (↓; 16.33 → 5.79), WS (↓; 100.0 → 13.74),	TS (↑; 23.40 → 36.82), EAB (↑; 121.6 → 121.2)	DPPH; 88.74 %	<i>E. coli</i> (IZ; 24), <i>K. pneumonia</i> (IZ; 21), <i>S. aureus</i> (IZ; 24.5), and <i>S. epidermidis</i> (IZ; 25.5)	(Worku et al., 2024a)
CS	LNPs	NS	TS (↑; 12.01 → ~ 48.8), YM (↑; 581.8 → ~ 1400)	DPPH; 70.8 %	NS	(Sun et al., 2023)
CS	LNPs	SI (↓; 20.05 → 17.02), WVP (↓; ~ 20 → ~ 17), WCA (↑; 95.06 → 110.1),	TS (↑; 7.09 → ~ 48.8), EAB (↑; 109.71 → 332.58)	DPPH; 80.8 % and ABTS; 90.00 %	<i>S. aureus</i> (IZ; NS) and <i>E. coli</i> (IZ; NS)	(Zhang, W. et al., 2023)
CS	LNPs	WVP (↓; 1.92 → 1.29),	TS (↑; 21.5 → ~ 30.5), YM (↑; 23.6 → 185.7)	NS	NS	(Vijayakumar et al., 2022)
PVA	LNPs	Thickness (↑; 0.89 → 0.91), WVP (↓; 22.51 → 14.22), WCA (↑; 38.9 → 78.43),	TS (↑; ~ 40 → ~ 60), EAB (↑; ~ 140 → ~ 150), YM (↑; 700 → ~ 1200)	DPPH; 74.18 %	<i>S. aureus</i> (IR; 99.26) and <i>E. coli</i> (IR; 95.79)	(Zheng et al., 2024)
Pectin	LNP@PDA	WCA (↑; 62.06 → 77.68), WVP (↓; ~ 9.0 → ~ 6.0), OP (↓; ~ 19.0 → ~ 5.0)	TS (↑; 13.81 → 26.47), EAB (↑; ~ 5 → ~ 14)	DPPH; 65.00 %	<i>S. aureus</i> (IZ; NS) and <i>E. coli</i> (IZ; NS)	(Zhang et al., 2024)
PVA/CNFs	LNPs	WVTR (↓; 103.05 → 58.36), WVP (↓; 2.45 → 1.42), WCA (↑; 20 → 46),	TS (↑; 28.7 → 26.3), EAB (↑; 262.11 → 163.83)	NS	NS	(Zhou et al., 2022)
PVA/TA	LNPs-PS	Thickness (↓; 0.089 → 0.072), WCA (↑; 35.9 → 81.43), MC (↓; 20.33 → 6.79), WVP (↓; 10.2 → 4.54)	TS (↓; 74.51 → 32.15), EAB (↓; 257.97 → 97.16)	NS	<i>S. aureus</i> and <i>E. coli</i>	(Zeng et al., 2024)
PLA	LNPs	NS	TS (↓; 28 → 17.09), EAB (↓; 1.8 → 8.16), YM (C 0.7 → ~ 3.56)	DPPH; 60.00 %	NS	(Daassi et al., 2023)
PVA-GD	LNPs	WVTR (↓; 10 → 4.01), WCA (↑; 53 → 73),	TS (↑; 26.0 → 35.02), EAB (↓; 232 → 207)	NS	NS	(Yang et al., 2020)
PVA	LNPs	WCA (↑; 52 → 80),	TS (↑; 26.0 → 38.1), EAB (↓; 229 → 237)	NS	<i>S. aureus</i> (0.25 × 10 ⁶ CFU/mL) and <i>E. coli</i> (1.0 × 10 ⁶ CFU/mL)	(Yang et al., 2021)
PBS	Thymol and LNPs	Thickness (↑; 0.29 → 0.33), WVP (↓; 1.54 → 1.09), OP (↑; 2.28 → 2.74),	TS (↓; 34.3 → 30.0), EAB (↓; 11.6 → 10.6), YM (↓; 593.4 → ~ 486.7)	NS	<i>C. gloeosporioides</i> (IZ; up to 100 %) and <i>L. theobromae</i> (IZ; up to 100 %)	(Basbasan et al., 2023)
PBS	CIN and LNPs	Thickness (↑; 0.33 → 0.342), OP (↓; 5.24 → 4.36), WVP (↑; 1.70 → 1.75), WCA (↑; 63.18 → 76.08)	TS (↓; 27.2 → 26.00), EAB (↓; 10.92 → 9.22), YM (↓; 536.22 → ~ 528.92)	NS	<i>Penicillium</i> spp (IZ; up to 60 %)	(Moe et al., 2023)

Abbreviation; NS; not stated, ASPNG; acylated soy protein isolate nanogel, WVTR; Water vapor transmission rate, OTR; oxygen transmission rate, PDA; polydopamine, CNFs; chitin nanofibers, TA, tannin acid, PS; potassium sorbate, PLA; polylactic acid, GD; Glutaraldehyde, PBS; Polybutylene Succinate, CIN; cinnamaldehyde, CS; chitosan, IZ; inhibition zone, IR; inhibition rates, MC; moisture content, WS; water solubility, WVP; water vapor permeability, OP; oxygen permeability, WCA; water contact angle, TS; tensile strength, EAB; elongation at break, YM; young's modulus, SI; swelling index., (↑); increase, (↓); decrease, (↑↓); variable, (↔); no significant change.

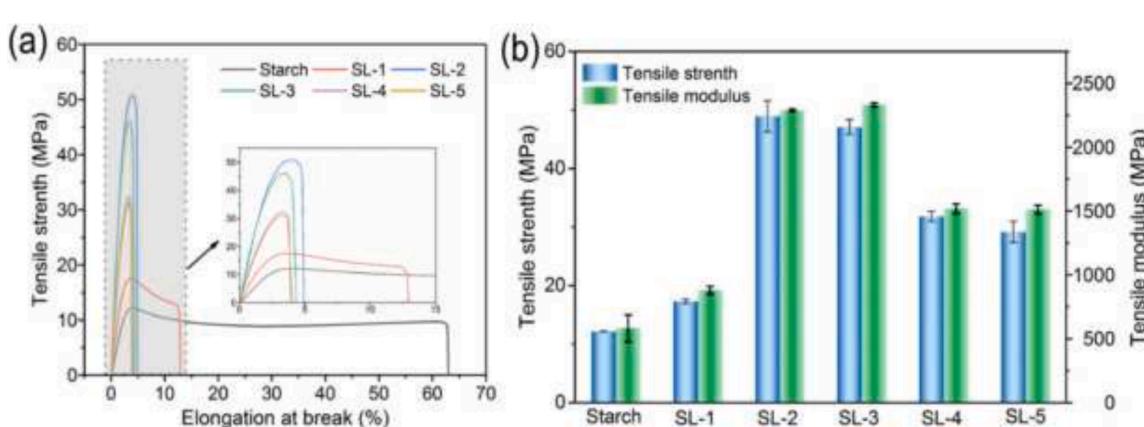


Fig. 4. Stress-strain curves (a) and TS and YM (b) of starch film and starch film containing 1–5 % LNPs, Ref. (Sun et al., 2023).

et al., 2023). Worku et al. (2024) showed that by increasing the content of LNPs from 0 to 3 %, the TS of polyvinyl alcohol/CS (PVA/CS) film increased from 31.28 to 36.82. In addition, the TS of PVA/chitin film increased from 18.85 to 36.40. Also, the EAB for PVA/CS film increased from 70.0 to 121.2, and in PVA/chitin film from 90.9 to 110.6. Because benzene is in the structure of LNPs and softens the films (Worku et al., 2024a). In another study, Vijayakumar et al. (2022) found that increasing the content of LNPs from 0 to 15 % increased the TS from 21.5 MPa to 30.5 MPa, and YM increased from 894 MPa to 1814 MPa. The results show that adding NPs up to 15 % to the CS film increased due to compatibility with the TS matrix and YM. The TS and YM of the CS film in 30 % concentration, compared to the film containing 15 % concentration of NPs, decreased to 23.6 MPa and 185 MPa, respectively. At 30 % concentrations of LNPs, it causes the accumulation of NPs and their non-uniform distribution, increases the uneven tension between CS and LNPs, and decreases their mechanical properties (Vijayakumar et al., 2022). In addition, Zheng et al. (2024) found that adding LNPs improved the mechanical properties of PVA film. The TS of PVA film increased by increasing the content of LNPs. Also, the elongation of the PVA film containing LNPs increased, and the best performance was obtained at a concentration of 0.5. Also, the elongation of the PVA film containing LNPs increased, and the best performance was obtained at a concentration of 0.5. These results show that adding LNPs can improve the flexibility and plasticity of PVA film. In addition, YM of the PVA film with different amounts of LNPs fluctuated, but it was increased compared to the pure film. This shows that LNPs bring excellent deformation resistance to PVA films (Zheng et al., 2024).

5.2. Oxygen permeability and water vapor permeability

Factors such as water vapor permeability (WVP) and oxygen permeability (OP) are used to determine the barrier properties of the packaging film. These two factors in biodegradable films should be as minimal as possible because the presence of water and oxygen affects the chemical, physical, and microbial properties and reduces the stability of packaged food (M. Tavassoli et al., 2023b). The researchers reported that the addition of LNPs can reduce the WVP and OP of the films. In their study of 2023, Sun and co-workers reported that the OP of the starch film decreased with the increase in the concentration of LNPs. LNPs prevent oxygen absorption and consumption by the oxidizer by increasing the twisting of the oxygen distribution paths in the film and acting as a barrier against oxygen (Sun et al., 2023). In addition, the study by Zou et al. (2023) found that the addition of 3 % LNPs resulted in decreases of 10 % and 20.1 % in WVP and OP, respectively. LNPs have

reduced the mobility of CS molecule chains and acted as a barrier against water and oxygen penetration. LNPs have reduced the mobility of CS molecule chains and acted as a barrier against water and oxygen penetration. In addition, LNPs have increased the tortuous path for the distribution of water vapor and oxygen and have reduced WVP and OP (Zou et al., 2023). In another 2023 study, the authors reported that with the increase in LNPs from 1 to 10 %, WVP decreased, especially at a concentration of 5 %. LNPs increase the tortuosity of the matrix for the passage of steam and reduce the permeability of water vapor. However, at a concentration of 10 % LNPs, the WVP increased compared to the 5 % concentration because the LNPs accumulated with increasing content, which affected their ability to intercept water and compress the film (Fig. 5a) (Zhang, W. et al., 2023). Vijayakumar et al. (2022) observed that with the increase in the content of LNPs from 0 to 15 %, the WVP of CS film decreased from 1.92 to 1.29 g/m²/day. The reduction of this factor due to LNPs has created a winding path for water vapor. However, at 30 % concentration of LNPs, WVP increased to 1.84 g/m²/day compared to the treatment containing other NPs. However, at concentrations of 30 %, these particles create voids in the CS film through agglomeration, allowing water vapor to quickly pass through these voids, and thus increasing WVP (Vijayakumar et al., 2022). In this context, Zheng et al. (2024) found that by increasing the content of LNPs from 0 to 5 %, the WVP of PVA film decreased from 1.12×10^{-10} g m⁻¹.Pa⁻¹.s⁻¹ to 0.55×10^{-10} g m⁻¹.Pa⁻¹.s⁻¹. By adding LNPs, the empty spaces in the PVA film were filled, a strong hydrogen bond was formed, and the film's structure became more compact, resulting in a decrease in WVP (Fig. 5b) (Zheng et al., 2024).

5.3. Water solubility and moisture content

One of the influential factors in evaluating the physical properties of biodegradable films is water resistance, which is evaluated by water solubility (WS) and moisture content (MC). These factors play a significant role in the packaging of food sensitive to humidity or high humidity (Tavassoli et al., 2025). Finally, the researchers noted that adding NPs can reduce the biodegradable films' WS and MC. For example, Zou et al. (2023) reported that as the content of LNPs increased from 0 % to 5 %, WS decreased from 33.12 % to 18.33 %. The hydrophobic and hydrogen bonding interactions between CS molecules and LNPs have reduced the movement of CS molecule chains and the solubility of CS films (Zou et al., 2023). In another study, Worku et al. (2024) found that with the increase in the concentration of NPs from 0 to 3 %, the MC of PVA/CS film decreased from 1.11 % to 1.81 %, respectively. Additionally, the water content of the PVA/chitin film decreased from 13.32 % to

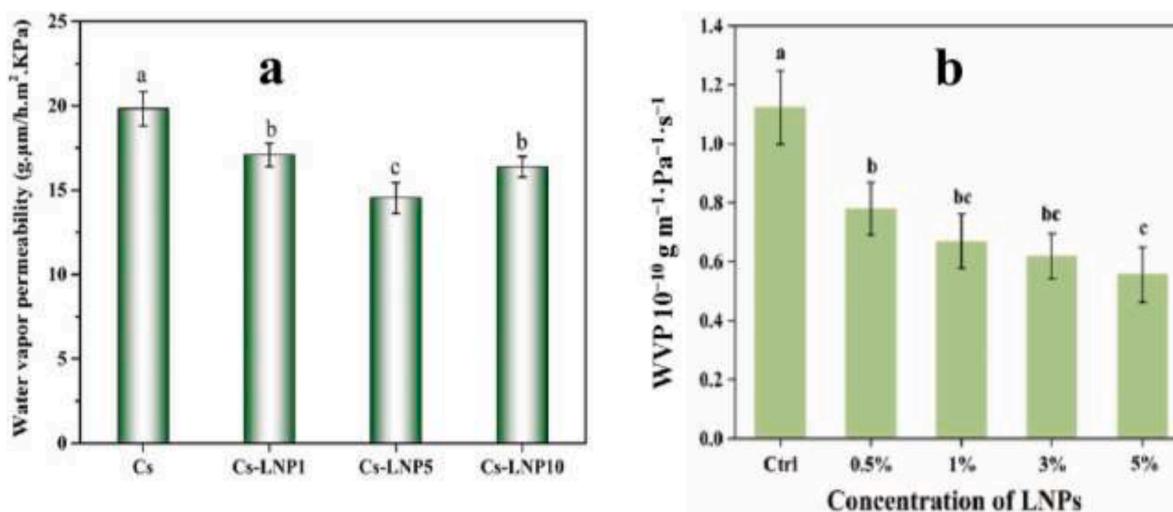


Fig. 5. Results of WVP of chitosan(a) and polyvinyl alcohol, Ref. (Zhang, W. et al., 2023), (b) films containing LNPs, Ref. (Zheng et al., 2024).

3.32 %. Because LNPs have an aromatic superhydrophobic structure and repel water, creating hydrogen bonds between polymers and LNPs can be another reason for reducing the MC. In addition, with the increase in the concentration of LNPs from 0 to 3 %, the WS of the PVA/CS film decreased from 44.98 % to 13.74 %. Also, the WS of PVA/chitin film decreased from 51.66 to 32.90 %. A strong connection between LNPs and the polymer matrix was established, resulting in decreased displacement of the polymer chains through hydrogen bonding, which limits the free hydroxyl groups that can interact with water (Worku et al., 2024a).

5.4. Water contact angle

The water contact angle (WCA) is an important factor that shows the film's hydrophobic and hydrophilic properties. A contact angle greater than 65° indicates a hydrophobic surface, while a contact angle less than 65° indicates a hydrophilic surface (Tavassoli et al., 2024b). In this context, Zhang et al. (2024) found that adding LNPs coated with poly-dopamine (PDA) to the pectin film increased the WCA. However, when the content of LNPs coated with PDA exceeded 1 %, the WCA of the pectin film was greater than 65° (72.66–77.85°) for 360 s, indicating the film's hydrophobic stability. The authors attributed the increase in the WCA to the film's compact structure and uneven surface on the nanoscale. Furthermore, the addition of LNPs coated with PDA to pectin has led to the formation of hydrogen bonds, inhibited the interaction between water and hydrophilic groups, and restricted the binding of hydrophilic groups to water (Zhang et al., 2024). Zhang et al. (2023) reported that the WCA of CS film increased from 96.06° to 110.1°, increasing the content of LNPs from 0 to 10 %. LNPs create hydrophilic groups on the outside and hydrophobic groups on the inside, providing more opportunities to interact with hydrophilic and amino groups (Fig. 6a) (Zhang, W. et al., 2023). Zhou et al. (2022) reported that the WCA of PVA/chitin nanofiber (PVA/CNFs) film was 38°, but by adding 1, 3 %, and 5 % LNPs, it became 63°, 65°, and 46°, respectively. This shows that with the increase in the content of LNPs, the contact angle has increased compared to the pure film, which was due to the increase in the film's roughness with the addition of these nanoparticles. At a concentration of 5 %, the contact angle of water decreased due to the

increase in the pores created by these NPs in the film (Zhou et al., 2022). In another study, Zheng et al. (2024) reported that with the increase in the content of LNPs from 0 to 5 %, the WCA of PVA film increased from 36.8° to 75.1°. Because LNPs are inherently hydrophobic, the roughness of the film increases with the addition of LNPs, and the contact angle of water also increases (Fig. 6b) (Zheng et al., 2024). Zeng et al. (2024) demonstrated that by incorporating LNPs loaded with potassium sorbate (PS) into the PVA/tannic acid (PVA/TA) film, the contact angle increased to 80°. This is because the structure of LNP@PS contains aliphatic hydrophobic groups (Zeng et al., 2024).

5.5. Morphological and microstructural properties

The morphology of biodegradable films is evaluated through atomic force microscopes, scanning electron microscopes, and confocal laser scanning microscopes. Usually, pure and clean films have a uniform, non-porous, and homogeneous surface (Bahramian et al., 2025). However, adding LNPs to the film matrix can change the morphology of the film. For example, in the study of Sun et al. (2023), the surface of the pure starch film was smooth and uniform, but with the addition of 2 % LNPs, the surface of the film became slightly uneven. However, it was evenly distributed in the film. However, when the LNPs were increased to 5 %, the film's surface was uneven, and a slight accumulation of particles was seen (Fig. 7A). This is because LNPs with hydroxyl groups create intermolecular hydrogen bonds, and as a result, NPs accumulate (Sun et al., 2023).

In another study, Zou et al. (2023) found that the addition of 3 % LNPs to the CS film surface resulted in a rough surface due to the accumulation of LNPs. In contrast, the surface of the pure CS film was homogeneous, smooth, and corrosion-resistant (Zou et al., 2023). Zhang et al. (2023) demonstrated that the addition of LNPs rendered the CS film rougher. However, the morphology of the CS composite containing LNPs was relatively rough. The morphology of the CS film revealed that more regular nanoparticles were uniformly observed on the surfaces of Cs-LNP1 and Cs-LNP5, while cracks appeared in the cross-sections. In addition, the surface of the CS film with an increasing content of LNPs compacted with multiple agglomerates was coarse, without holes and cracks. This is due to the good compatibility resulting from hydrogen

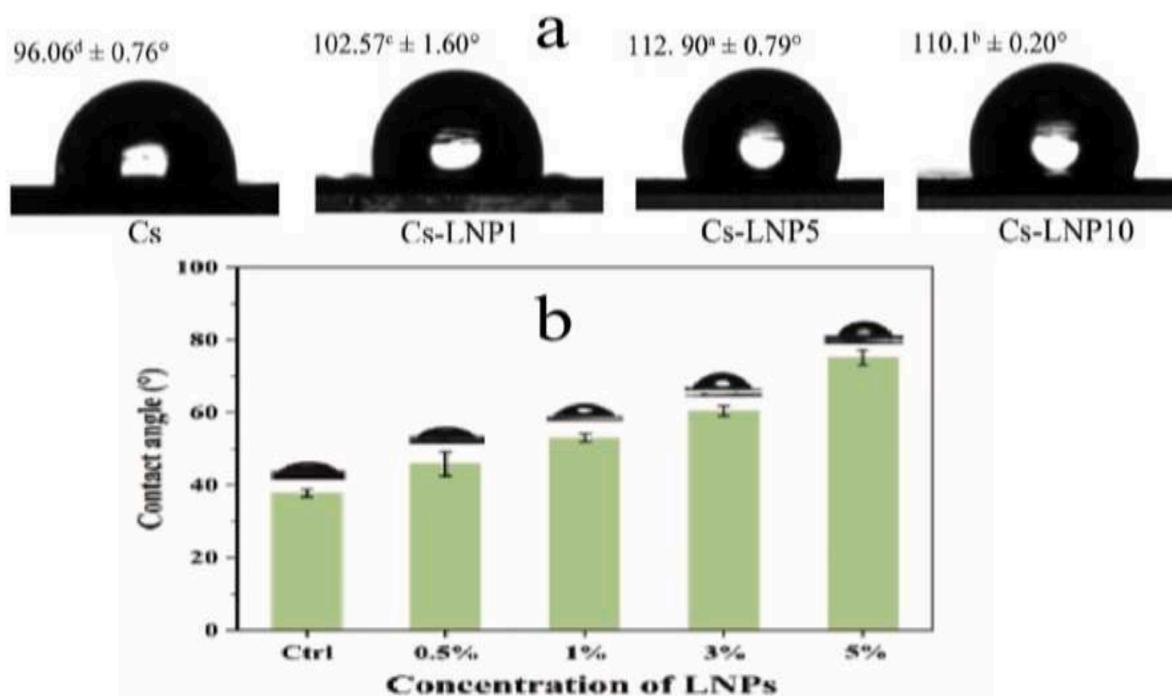


Fig. 6. Results of WCA of chitosan(a) and polyvinyl alcohol, Ref. (Zhang, W. et al., 2023), (b) films containing lignin nanoparticles, Ref. (Zheng et al., 2024).

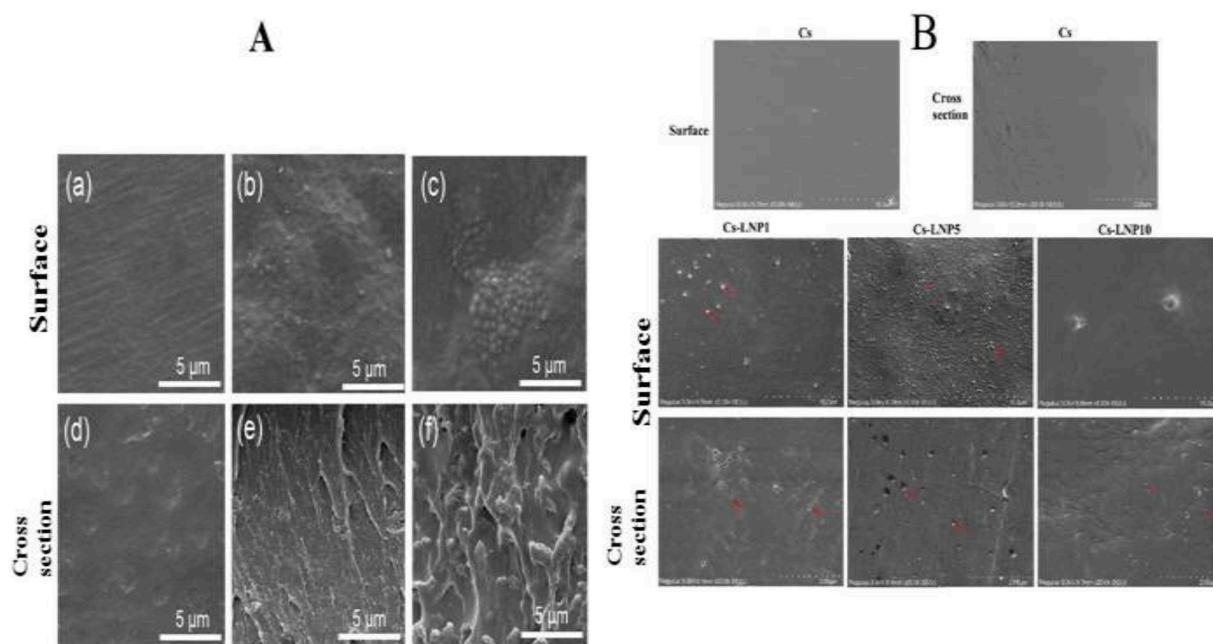


Fig. 7. SEM images of the surface and cross-section of starch/LNPs (A) (starch film (a, d) 2 % (b, e) and 5 % (c, f) LNPs) and Cs, Ref. (Sun et al., 2023) (B) (1,5,10 % LNPs) film containing LNPs, Ref. (Zhang, W. et al., 2023).

bonding between LNPs and the CS film (Fig. 7B) (Zhang, W. et al., 2023). In this context, Vijayakumar et al. (2022) found that LNPs of up to 15 % were uniformly distributed in the CS film. However, at a concentration of 30 %, the accumulation of NPs and non-uniform distribution were visible due to the high content of LNPs and particle-particle interaction. The particle increases, and accumulation takes place. In addition, the lack of interaction between NPs in high content and CS caused space in the CS film (Vijayakumar et al., 2022). These SEM changes indicate that at high concentrations of lignin nanoparticles, film cohesion is disrupted, and LNPs may have more particle-particle interactions, leading to aggregation. Furthermore, at high concentrations, these nanoparticles may not interact with the matrix, leaving voids during film drying. For these reasons, lignin nanoparticles at high concentrations can have negative effects on the mechanical and physical properties of the film. Therefore, LNPs need to be optimized to produce a film with desirable properties.

5.6. Structural properties

Fourier-transform infrared (FTIR) spectral analysis investigates molecular interactions in different polymers and FPFs. IR spectra obtained from biodegradable films containing LNPs are different due to the participation of several functional groups (Abedi-Firoozjah et al., 2025a). For example, Sun et al. (2023) reported that the absorption peaks of starch film at 3434 cm^{-1} , 2920 cm^{-1} , and 1640 cm^{-1} correspond to O—H stretching vibration, C—H bond stretching vibration, and OH bending vibration, respectively. However, with the addition of 2 and 3 % LNPs, the characteristic peak changed from 3434 cm^{-1} to 3430 cm^{-1} and 3422 cm^{-1} , respectively (Fig. 8a), due to the interaction of hydrogen bonds between LNPs and starch molecules. As shown in Fig. 8b, LNPs have many hydroxyl groups that can cross-link with starch molecules through hydrogen bonding (Sun et al., 2023). Zhou et al. (2022) found that adding LNPs to the PVA/CNFs film caused a change in the film's C—O and O—H tension, which was due to the formation of hydrogen

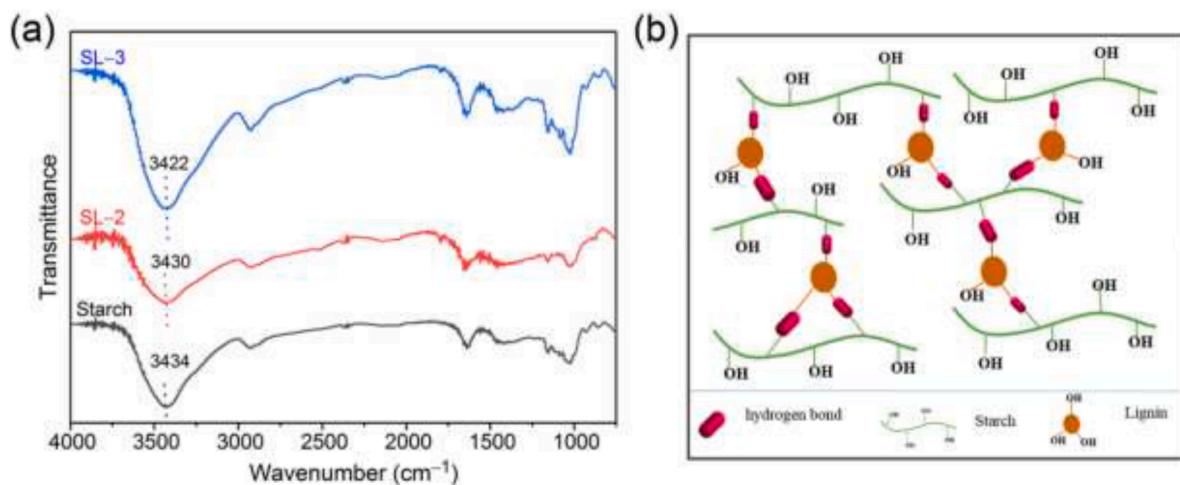


Fig. 8. IR spectra analysis of starch film loaded with 2 % and 3 % LNPs (a), and schematic illustration (b) of the interaction between polymer matrix and LNPs functional chain, Ref. (Sun et al., 2023).

bonds (Zhou et al., 2022). In another study, Zheng et al. (2024) reported that the hydroxyl (O—H) stretching peak changed from 3299 cm⁻¹ to 3321 cm⁻¹ by adding LNPs from 0 to 5 % to PVA film. In addition, the C—O stretch peak of PVA film increased from 1086 cm⁻¹ to 1096 cm⁻¹ by increasing the content of LNPs from 0 to 5 %. These results indicate a strong hydrogen bond between LNPs and PVA (Zheng et al., 2024).

5.7. Crystallinity analysis

X-ray Diffraction (XRD) patterns of biodegradable films are measured to evaluate crystal lattice structures and intermolecular interactions between film components (Javdani et al., 2025). Sun et al. (2023) showed that the pure starch film had two crystallization peaks at 23 ° and 17 °, which caused the emergence of type B starch. By adding LNPs, the diffraction peak of the starch film became sharper, and its intensity increased (at 17 °), creating B-type crystalline starch. This shows that adding LNPs enhances nucleation and increases crystallization (Fig. 9a) (Sun et al., 2023). Zhou et al. (2022) found that increasing the content of LNPs from 0 to 5 % decreased the crystallinity of the PVA/CNFs film from 45.43 to 42.33 %, which also reduced the peak intensity (Zhou et al., 2022). In another study, Zhang et al. (2023) reported that the addition of LNPs to the CS film reduced the intensity of the diffraction peak and increased the amorphous content of the crystal network. This indicates a homogeneous distribution in the CS film and a decrease in its crystallinity because the interaction between LNPs and hydroxyl groups of CS reduces chain mobility and crystallinity (Zhang, W. et al., 2023).

5.8. Thermal stability

Thermal stability of biodegradable films is essential for the performance of packaging materials and maintaining integrity during storage, processing, and distribution. Thermal stability of FPFs is measured using differential scanning calorimetry, thermal analysis, differential thermal analysis, and derivative thermogravimetry (Abedi-Firoozjah et al., 2025b). Studies have shown that the addition of LNPs to a film matrix has improved the thermal stability. In the study of Sun et al. (2023), they found that adding LNPs increased the thermal stability of the starch film. Thermal improvement is due to good compatibility and strong interaction between the starch film and LNPs. In addition, LNPs have prevented the thermal decomposition of the starch film and increased the thermal stability (Fig. 9b,c) (Sun et al., 2023). In another study, Zheng et al. (2024) reported that the thermal stability of PVA film increased with increasing concentration of LNPs. The authors attributed the increase in thermal stability of PVA film containing NPs to the strong hydrogen bond between PVA and LNPs. In addition, the homogeneous and uniform distribution of LNPs in the PVA film has also increased thermal stability (Zheng et al., 2024). In this context, Daassi et al. (2023) stated that adding LNPs increased the thermal stability of electrospun poly-lactic acid (PLA) fiber. The authors attributed the increase in thermal stability to the strong bond formed with PLA after adding LNPs (Yang

et al., 2020).

5.9. Optical properties

Optical properties, including color, transparency, and light transmission of biodegradable films, are important factors in the packaging of food products. This is due to customers' attention to the appearance of food products when buying and consuming them. The transparency of biodegradable films is obtained by dividing the absorbance at 600 nm by the thickness of the film, and the light transmission is evaluated using a UV-visible spectrophotometer at a wavelength of 200 to 800 nm (M. Tavassoli et al., 2023a). The researchers reported that using LNPs in FPFs reduces transparency and visible light but increases the UV-blocking properties of biodegradable films. For example, Sun et al. (2023) reported that adding LNPs to starch film decreased the L* (Fig. 10a) but increased the a* (Fig. 10b), b* (Fig. 10c), and total color difference (ΔE) (Fig. 10d). These results show that the brightness of the films after the addition of LNPs decreased, turning towards yellowish or reddish hues, which is caused by the color of the LNPs themselves. In addition, the clean starch film was transparent and colorless, while the films containing LNPs were brown (Fig. 10e). Also, as the content of LNPs increased, visible light transmission decreased, and at a concentration of 2 to 5 %, it blocked ultraviolet light transmission (Fig. 10f). The hydroxyl groups of LNPs, the conjugated double bond of the benzene ring, and the carbonyl group of the phenylpropane side chain absorb ultraviolet light. In addition, phenolic hydroxyl groups absorb photon energy, convert it into heat, and release it in the environment without photocatalytic destruction of the starch film (Sun et al., 2023). In another study, Zou et al. (2023) found that adding LNPs from 0 (pure film sample) to 5 % decreased the CS film's lightness (L value) from 90.96 to 79.10. In addition to the a* increased from -1.96 to 1.01, b* increased from 2.70 to 32.97, and ΔE increased from 4.71 to 36.71. The phenolic compounds in lignin absorb light or scatter light. In addition, the blocking property of ultraviolet rays in the content of 3 and 5 % LNPs was 71.4 % and 94.7 %, respectively, because the chromophores in lignin have the property of blocking ultraviolet rays (Zou et al., 2023). Zhou et al. (2022) demonstrated that incorporating 1 % LNPs into PVA/CNF film blocks 40 % of UVA (325–400 nm). In addition, adding 3 % and 5 % blocks 80 % and 90 % of UVA and 100 % of UVC and UVB. The authors attributed the UV blocking to the structure of LNPs containing phenolic hydroxyl and phenylpropane groups that block the passage of UV rays (Zhou et al., 2022). In this context, Zhang and colleagues found that as the content of LNPs increased, UV light transmission in CS film decreased, especially at 5 % and 10 %. LNPs prevented 100 % transmission of UV light through the CS film. Because in the structure of lignin, there are aromatic rings and chromophores that block UV rays (Zhang, W. et al., 2023).

5.10. Antioxidant activity

Because pure FPFs do not have antioxidant activity (AxAC), a

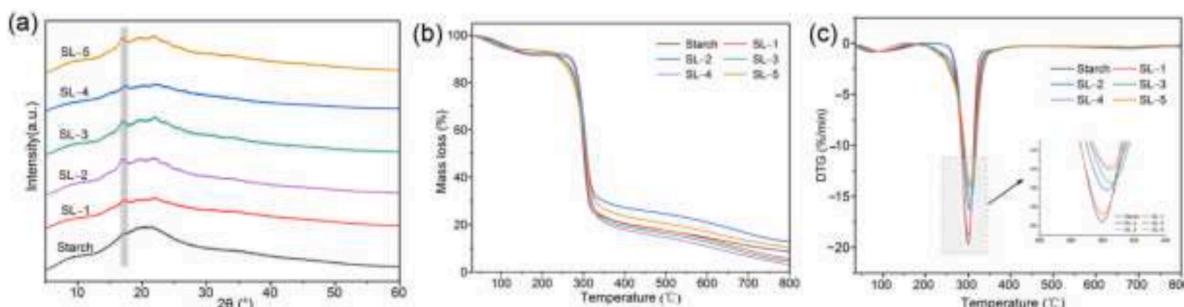


Fig. 9. XRD (a), TGA (b) and DTG (c) curves of starch/lignin nanoparticle (SL) composite films, Ref. (Sun et al., 2023).

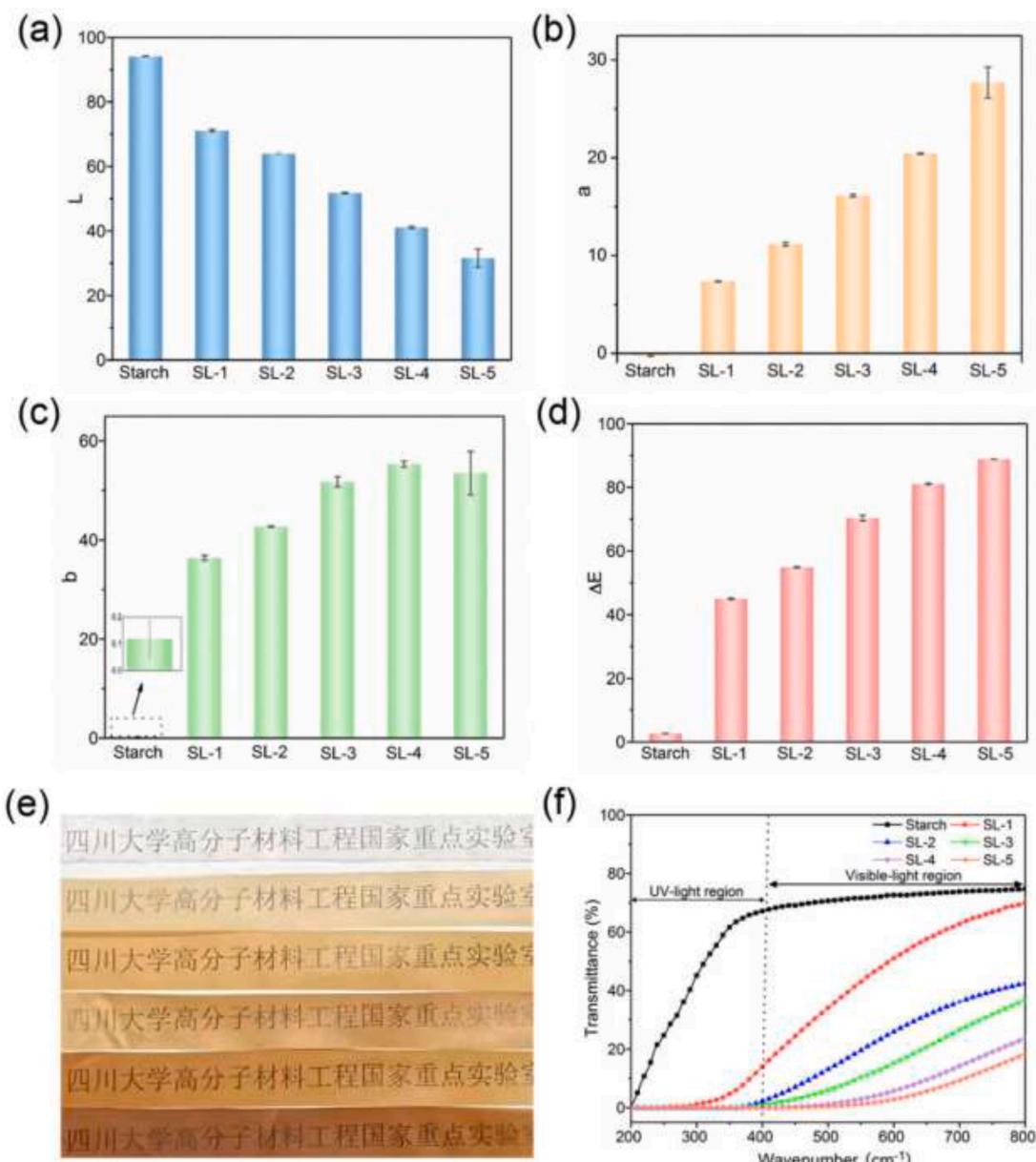


Fig. 10. Color index: (a) L (lightness), (b) a (red/green) value, (c) b (yellow/blue) value, and (d) ΔE (total color difference), and (e) digital photographs and (f) UV-vis light transmittance spectra of starch film and SL composite films containing 1 % to 5 % LNPs, Ref. (Sun et al., 2023).

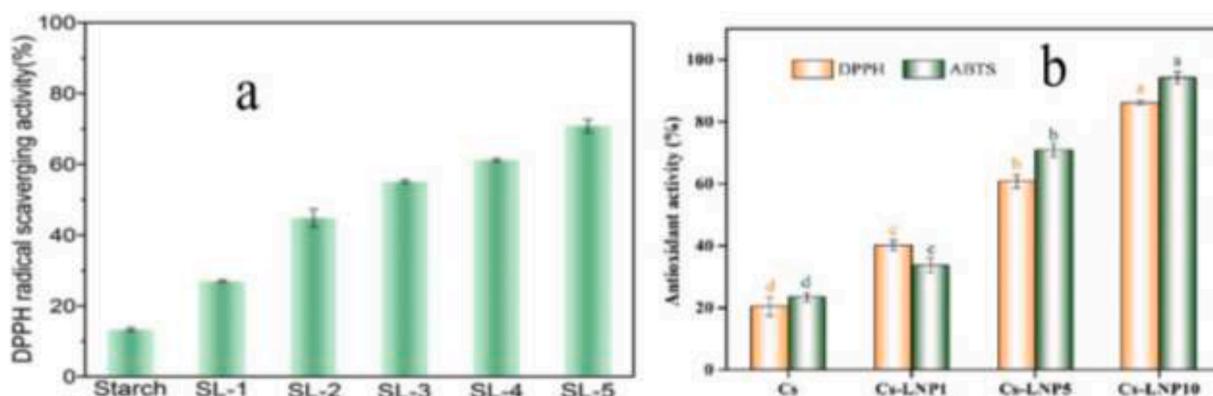


Fig. 11. Results of antioxidant properties of starch(a) and chitosan, Ref. (Sun et al., 2023), (b) films containing lignin nanoparticles, Ref. (Zhang, W. et al., 2023).

bioactive compound with AxAC must be added to the film. The oxidation of lipids alters their taste, structure, aroma, and nutritional value. Therefore, compounds that have AxAC in biodegradable films are required to reduce oxidation. Researchers have used lignin as an antioxidant compound in this field due to its hydroxyl and methoxy groups. However, researchers found that LNP s have more AxAC than lignin compounds (Worku et al., 2024a). For example, Sun et al. (2023) found that by increasing the concentration of LNPs from 0 to 5 %, the AxAC of starch film increased from 13.3 % to 70.8 %. The authors attributed the film's AxAC to the phenolic hydroxyl groups of LNPs because they destroy free radicals (Fig. 11a) (Sun et al., 2023). Zhang et al. (2023) reported that as the concentration of LNPs increased, the AxAC of CS film also increased. This is because more phenolic and hydroxyl groups are produced, and the AxAC increases (Zhang, W. et al., 2023). In another study, Yang and his research team reported in 2018 that PVA/CS hydrogels containing 1 and 3 % LNPs had AxAC of 74.3 % and 78.6 %, respectively (Yang et al., 2018a). In this context, Worku et al. (2024) observed that adding 3 % LNPs to PVA/CS and PVA/chitin films had AxAC of 87.4 and 88.74, respectively. The AxAC of LNPs is related to its free phenolic groups, which cause the formation of phenoxy radicals during inhibition. In addition, the phenolic groups of lignin with ortho substituents (methoxyl units) stabilize phenoxy radicals by preventing their propagation and intensification (Worku et al., 2024a). Zhang et al. (2024) found that the AxAC of CS film increased as the content of LNPs increased. By increasing the content of LNPs, more phenolic and hydroxyl groups are produced, increasing the AxAC activity (Fig. 11b) (Zhang, W. et al., 2023).

5.11. Antimicrobial activity

Pure FPFs generally do not have antimicrobial activity (AmAC), so adding antimicrobial compounds to the film matrix is necessary. Using antimicrobial compounds such as LNPs can reduce or even eliminate the growth of microorganisms and spoilage, thus improving food products' quality, microbial safety, and shelf life. For example, Worku et al. (2024)

investigated the AmAC of PVA/CS and PVA/chitin films containing LNPs. They reported that the zone of inhibition of PVA/CI/3 % LNPs for *S. aureus*, *S. epidermidis*, *K. pneumoniae*, and *Escherichia coli* was 25, 26, 22, and 24 mm, respectively. In addition, the inhibition zone of PVA/CH/3 % LNPs for *S. aureus*, *S. epidermidis*, *K. pneumoniae*, and *E. coli* was 22, 19, 23, and 21 mm, respectively. The results show that LNPs were more effective against Gram-positive than Gram-negative bacteria. This is because the cell wall of gram-positive bacteria contains more lipoproteins and phospholipids than that of gram-negative bacteria, which increases the permeability of hydrophobic substances. Therefore, the AmAC of NPs is due to hydrophobicity, lipophilicity, and binding to the proteins of microorganisms (Worku et al., 2024a). In another study in 2021, Yang and his group reported that the colony count of PVA film for *S. aureus* and *E. coli* was 1.5×10^7 CFU/ml and 5.0×10^7 CFU/ml, respectively. However, by adding 3 % LNPs to PVA film, the colony counts of *S. aureus* and *E. coli* decreased to 0.25×10^6 and 1.0×10^6 CFU/ml. The authors attributed the AmAC to the phenolic groups of LNPs because it exerts its AmAC by producing active oxygen species. In addition, functional groups and side chains of phenolic compounds of LNPs have AmAC (Yang et al., 2021). LNPs penetrate bacteria, disrupting bacterial membranes and interacting with lipids and proteins, thereby disrupting the membrane and inhibiting the respiratory chain. In addition, lignin nanoparticles lead to the formation of reactive oxygen species, which in turn cause oxidative damage to cellular components and inhibit bacterial proliferation (Li, H. et al., 2025). In this context, Zheng et al. (2024) reported that the AmAC of PVA film increased with the increase in the content of LNPs. PVA film containing 5 % LNPs showed 99.26 % and 95.79 % AmAC against *S. aureus* and *E. coli*, respectively (Fig. 12). LNPs create a low pH environment around the cell membrane and cause lysis and rupture of the cell membrane, which leads to the death of the microorganism (Zheng et al., 2024). Zhang et al. (2024) found that the addition of LNPs increased the AmAC of CS film against *S. aureus* and *E. coli*. In addition, with increasing content of LNPs, the AmAC of CS film did not increase, and no visual difference was observed between CS film containing 5 % and 10 % LNPs (Zhang, W. et al., 2023).

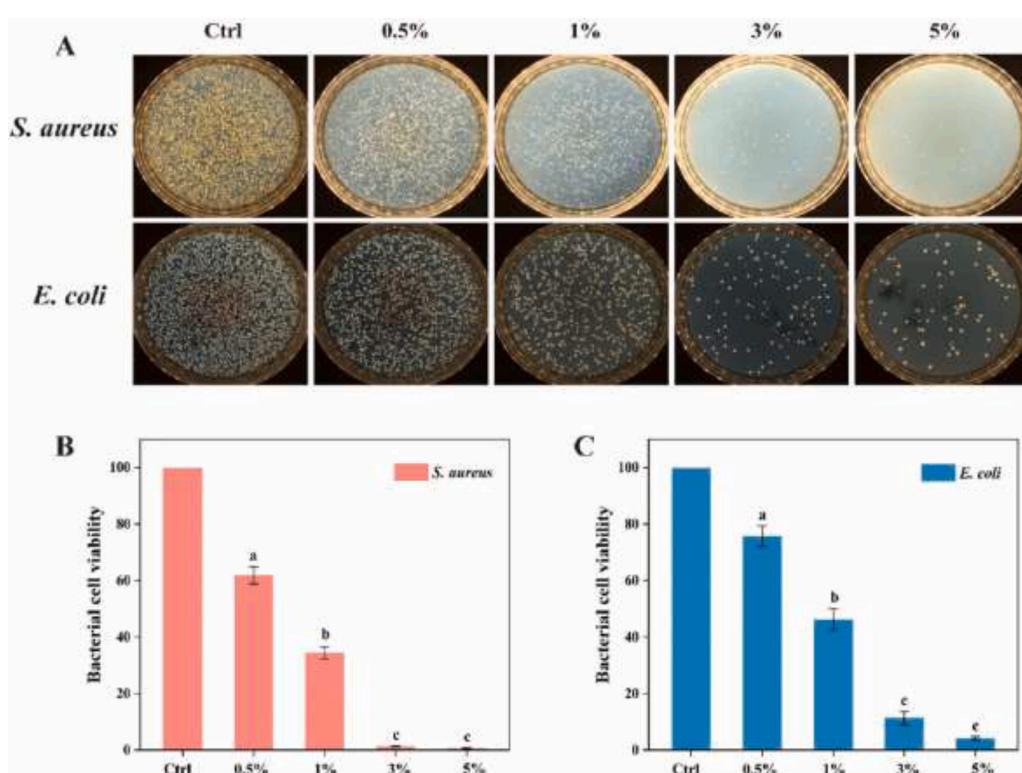


Fig. 12. Antimicrobial activity of PVA film containing different concentrations of LNPs, Ref. (Zheng et al., 2024).

In addition, Zeng et al. (2024) reported that adding LNP@PS loaded by PS (LNP@PS) to PVA/TA film showed AmAC against *E. coli* and *S. aureus*. It was also observed that LNP@PS up to a concentration of 3 % (LNP@PS-3-TA-0) caused a two-fold reduction in *S. aureus* and a three-fold reduction in *E. coli* activity compared to pure PVA film. The AmAC is due to the synergistic effect of LNP@PS and PS. The hydroxyl groups of the phenolic compounds of LNP@PS inhibit bacteria. Also, PS contains carboxyl groups and conjugated double bonds that bind to the sulphydryl group of the bacteria's enzyme system, disrupting the enzyme system and, as a result, reducing the growth of bacteria. In addition, the conjugated double bond in PS oxidizes the carboxyl group and further disrupts the bacterial enzyme system. Also, adding TA to the film containing LNP@PS increased the AmAC. LNP@PS-1-TA-5 treatment showed 100 % AmAC against *S. aureus* and *E. coli* (Zeng et al., 2024). In addition, LNP penetrates the cell wall through a Trojan horse mechanism, causing damage to the bacterial cell wall and membrane, protein synthesis in ribosomes, which leads to the leakage of bacterial bio-compounds to the outside, ultimately disrupting bacterial metabolism and causing the death of the bacteria (Li et al., 2023). Also, because particles smaller than 2 μm can enter the cell through various endocytosis processes, the size of lignin nanoparticles in food packaging studies is approximately less than 500 nm, which is easily ingested into cells due to their small size and destroys the interior of the cell (Ali et al., 2024).

6. Application of LNP-rich composite films

Recently, researchers have been paying attention to LNP as an active ingredient in food packaging. Unlike mineral or metal fillers that pose health and environmental risks, LNP are biocompatible, have AmAC and AxAC, and reduce health risks even if they migrate to food. The applications of lignin nanoparticles in packaging films are reported in Table 3. In this context, Sun et al. (2023) investigated the effect of a

starch film containing LNP on the oxidation of soybean oil. Indicators such as saponification, peroxide, and acid values are used to evaluate fat and oil oxidation. The saponification value shows the molecular weight of the fatty acid in the oil, and if it is high, it indicates the oil's rancidity. The peroxide value (PV) of oils shows the degree of oxidation, and the acid value of oils shows the free acid content produced by the oxidation of oil triglycerides. As illustrated in Fig. 13, the saponification value, PV, and acid value have increased with the increase in the storage time of soybean oil. The control sample, sealed without film, had the highest index compared to other treatments, while soybean oil treated with starch/5 % LNP, starch/2 % LNP, and pure starch, respectively, had the lowest index. Therefore, the index of saponification value, PV, and acid value of the control sample on day 24 were 196.2 mg/g, 75.9 meq/kg, and 1.80 mg/g, respectively, because they were directly exposed to oxygen. However, soybean oil sealed with neat starch film was 194.8 mg/g, 47.4 meq/kg, and 1.55 mg/g, respectively, and soybean oil sealed with starch film/2 % LNP was 196.2 mg/g, 75.9 meq/kg, and 1.80 mg/g. These results show that starch films containing LNP were more effective in delaying the oxidation of soybean oil. However, there were no significant changes between the starch films containing 2 % and 5 % LNP in this regard. LNP absorb photon energy and convert it into heat, and the corresponding hydrophilic chromophores, which are phenolic hydroxyl groups, block UV rays. In addition, chromophores have the ability to quench the radicals produced during oxidation by transferring electrons to them (Sun et al., 2023).

Zhang et al. (2023) packed fish fillets with CS film containing LNP in another study. They found that fish fillets that were not wrapped (control samples) were sticky, yellow, and wet, indicating spoilage. However, the fish fillet packed with CS film and CS/LNP had a dry and relatively white surface, indicating that the fish fillet had preserved its freshness (Fig. 14a-e). Due to the presence of lipids, fish is susceptible to oxidation, which reduces its nutritional value. Here, the thiobarbituric

Table 3
Application of LNP-based films in packaging of real food samples.

Film base	Preparation		Packaging in vivo/in vitro application		Ref.
	Polymer	Functional additives/ LNP content	Food model	Remarks	
CS	LNP/0, 1, 5, and 10 wt % based on chitosan	Dried at 40 °C for 20 h, peeled and heated at 90 °C for 2 h, and finally equilibrated at 25 °C and 50 % RH for 72 h	Fish	Refrigerated grass fish wrapped in films showed improved quality, with an extended shelf life of 10 days.	(Zhang, W. et al., 2023)
Starch	LNP/ 1 %, 2 %, 3 %, 4 %, and 5 % (w/w)	Dried at 45 °C for 20 h, and then conditioned at room temperature and relative humidity of 55 % for 24 h	Soybean oil	Decline peroxide value, saponification value, and acid value to delay oxidation process of oil sample during storage	(Sun et al., 2023)
CS	ASPNG (3 %, 5 %, 7 %) and LNP/1 %, 3 %, and 5 % (w/w)	Solution (30 g) cast on a plastic Petri dish (14 × 14 mm ²) and dried at 22 °C with 54 % relative humidity for 2 days at constant temperature.	NS	NS	(Zou et al., 2023)
PVA	LNP/0.5 %, 1 %, 3 %, and 5 %	Mixture poured into plastic Petri, dried and equilibrated at 40 % humidity and 25 °C for 12 h	NS	NS	(Zheng et al., 2024)
Pectin	LNP/0.5 %, 1.0 %, 5.0 % and 10.0 %, w/w	Pouring the mixture onto an acrylic plate, followed by drying at 25 °C for 48 h	Banana and milk	Effectively delay the spoilage of food sample up to 7 days	(Zhang et al., 2024)
PVA/CNFs	LNP/1, 3, 5 %	Dried at 40 °C for 12 h to produce films, which were then kept in a desiccator under conditions of 67 % RH and 25 °C	NS	NS	(Zhou et al., 2022)
PVA/TA	LNP-PS/2 mg/mL	A mixture at 90 °C maintained for 60 min for blending and then poured into molds and drying at 25 °C.	Strawberry	Strawberry preservation with an extension of 3 days	(Zeng et al., 2024)
PVA-GD	LNP/ 2.0 %	Dried in the oven at 50 °C for 12 h, with peeling completed prior to storage under conditions of 53 % RH and 25 °C.	NS	NS	(Yang et al., 2020)
PVA	LNP/ 1, 2 and 3 wt %	Dispersion casting in Petri dishes, oven drying at 50 °C for 24 h, film removal, and storage at 53 % relative humidity and 25 °C	Shrimp	Shrimp packaged in LNP containing PVA nanocomposites films were less spoiled	(Yang et al., 2021)
PBS	Thymol and LNP/ 1 % (w/w)	Rotor speed of 0.038 g-force; temperature of the mixing chamber at 120 °C	Mango	Maintaining mango freshness up to 6 days	(Basbasan et al., 2023)
PBS	CIN and LNP/2 %	Gradual loading into an extruder (with a screw speed of 100 rpm and barrel temperatures of 110, 130, 140, 150, 154, 155, 155, and 160 °C, from the feeding zone to the die zone.	Bread	PBS's potential in extending bread shelf life, with possible applications to other food items vulnerable to fungal spoilage.	(Moe et al., 2023)

Abbreviation; NS; not stated, ASPNG; acylated soy protein isolate nanogel, CNFs; chitin nanofibers, TA, tannin acid, PS; potassium sorbate, GD; Glutaraldehyde, PBS; Polybutylene Succinate, CIN; cinnamaldehyde, CS; chitosan.

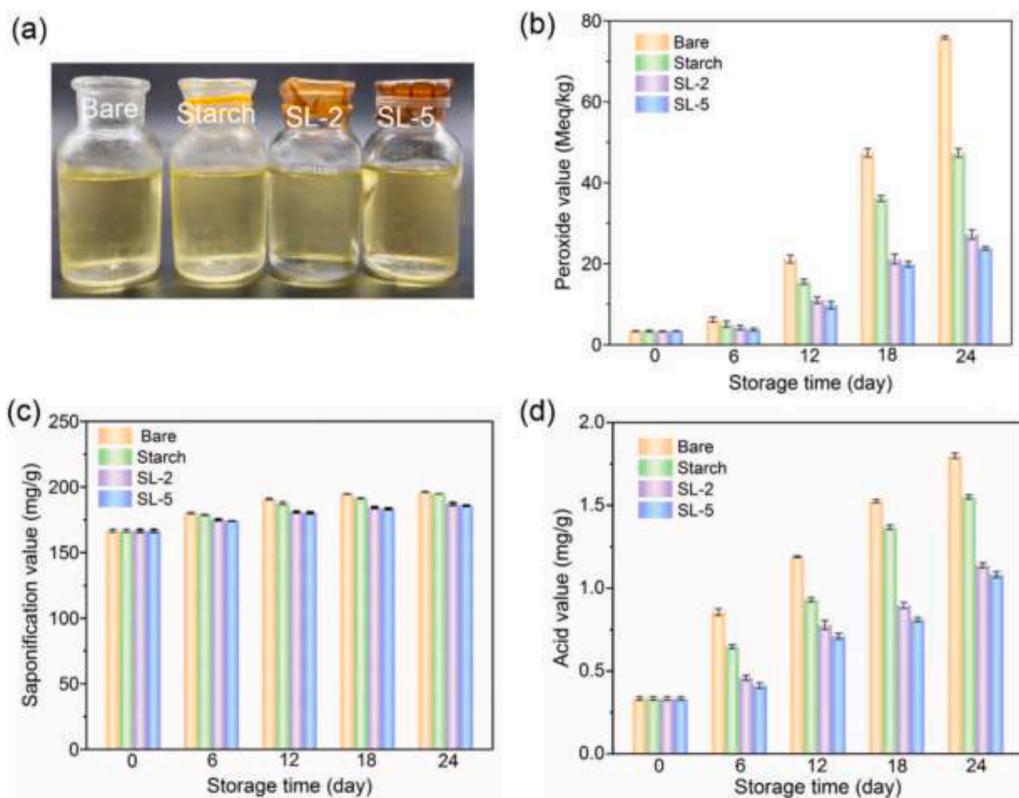


Fig. 13. Soybean oil packed with control treatment, starch film and starch loading with 2 and 5 % LNPs (a), changes in peroxide value (b), saponification value (c), acid value (d) of soybean oil samples. Reproduced from Ref. (Sun et al., 2023) with permission.

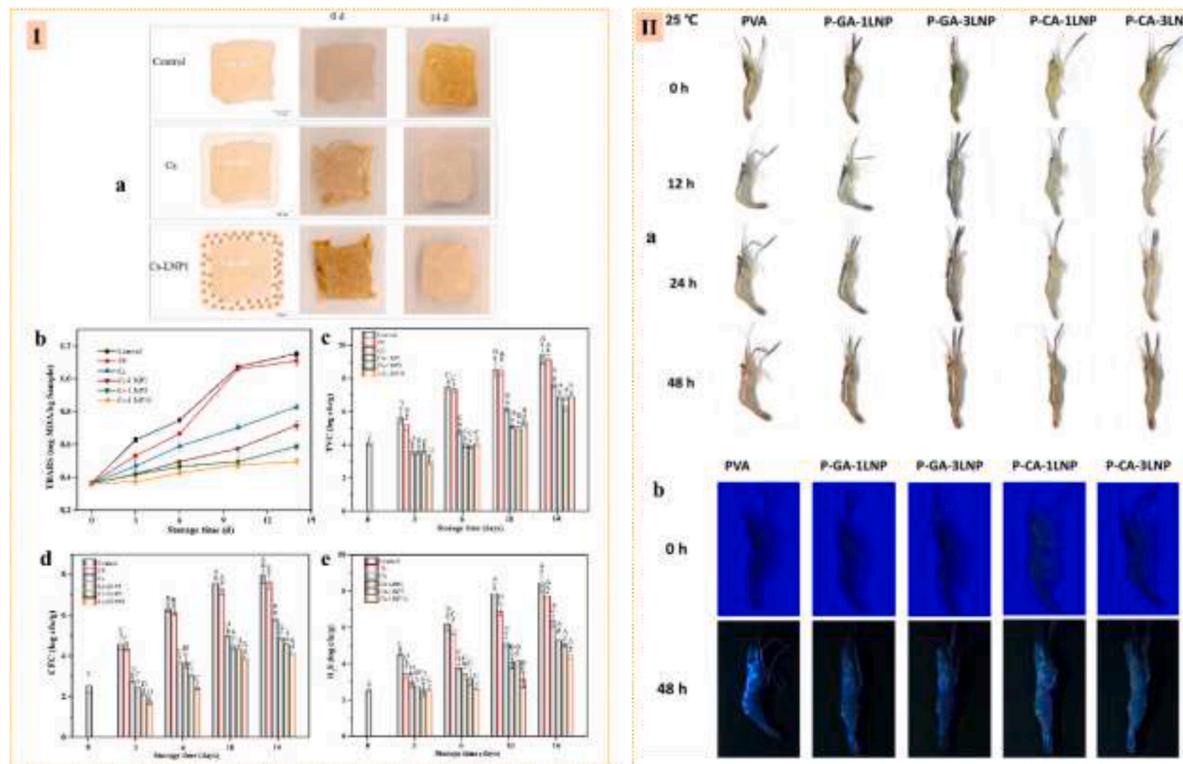


Fig. 14. (I) Packed fish fillets (a), TBARS (b), TVC (c), CFC (d), H2S (e) with different treatments during 14 days' storage period; reproduced from Ref. (Zhang, W. et al., 2023) with permission. (II) Monitoring shrimp freshness wrapped with PVA film loaded with LNPs at a temperature of 25 °C (a) and monitoring sample freshness packaged with PVA film loaded with LNPs at different times based on the fluorescent effect of shrimp (b); Reprinted from Ref. (Yang et al., 2021) with permission.

acid reactive substances (TBARS) of fish fillets packaged with different treatments over 14 days. By increasing the content of LNPs, the amount of thiobarbituric acid reactants decreased. The amount of TBARS in fish fillets packed with CS containing 0.0 and 10 % LNPs was 0.82 and 0.49 MDA/kg, respectively. However, it was almost 1.2 MDA/kg in the control and polyethylene samples (Fig. 14I-b). The AxAC of CS and LNPs

decreased TBARS. The authors evaluated the microbial spoilage of fish fillets using total viable count (TVC), *Pseudomonas* count (CFC), and H₂S-producing bacteria count (H₂S). The primary H₂S, CFC, and TVC values were 2.49, 2.51, and 4.16 CFU/g, respectively. As the storage time increased, bacteria increased in all treatments. The TVC of fish fillet packed with control, polyethylene, CS, CS /1.5, and 10 % LNPs after 14

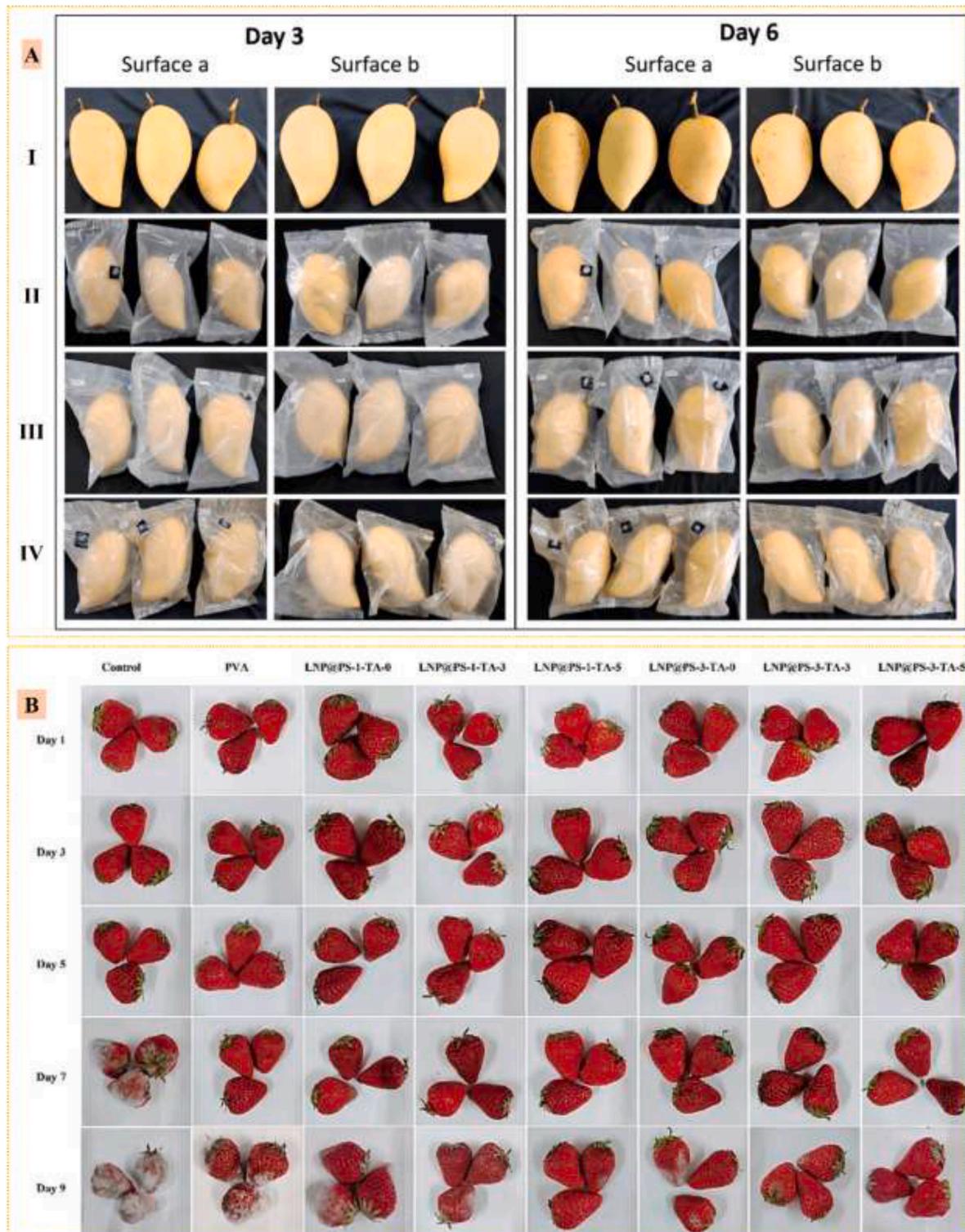


Fig. 15. (A) Mango fruit wrapped with (I) control, (II) neat PBS, (III) PBS/ 10 %Thymol, and (IV) PBS/ 10 %Thymol/1 % LNPs on days 3 and 6 at 12 °C and RH of 90 %; Reprinted from Ref. ([Basbasan et al., 2023](#)) with permission. (B) Strawberry samples status wrapped with PVA/LNPs loaded with potassium sorbate and tannin acid during storage at 25 °C; Reprinted from Ref. ([Zeng et al., 2024](#)).

days of storage were 9.38, 9.13, 7.65, 6.86, 6.36, and 6.92 log CFU/g, respectively. The limit of the TVC for fish is 7 log CFU/g, but according to the results of the TVC of fish fillets packed with CS film containing LNPs, it was less than 7 log CFU/g, which indicates the AmAC of LNPs. In addition, similar results were observed in *Pseudomonas* and H₂S-producing bacteria. In general, films developed with LNPs showed more AmAC than other treatments and increased the shelf life of fish fillets (Zhang, W. et al., 2023).

Yang et al. (2021) also packed shrimp in a PVA film containing 1 % and 3 % LNPs and kept them at 25 °C for 48 hours. When shrimp are spoiled, they turn red and fluoresce if exposed to UV light. The results showed that after 12 hours, the packaged shrimp maintained its freshness. However, after 48 hours, shrimp packed in pure PVA film began to produce red fluorescence under UV light (Fig. 14II-a, b). However, shrimps packed with films containing LNPs were less spoiled due to the AmAC and AxAC of LNPs (Yang et al., 2021). Basbasan et al. (2023) designed an active packaging based on polybutylene succinate (PBS)/thymol-containing LNPs to increase the storage of mango fruit. The authors found that on days 3 and 6, no disease was observed in the mango fruit, as shown in Fig. 15A. After 33 days, the control fruits wrapped with PBS contained black-brown sunken circular spots, indicating mango anthracnose disease caused by *Colletotrichum gloeosporioides*. In addition, a brown area was observed around the base of the mango fruit's stem end, indicating stem end rot caused by *Lasiodiplodia theobromae*. The decay of the whole mango fruit during 33 days of storage in the control treatment, PBS film, PBS film/10 % thymol, and PBS film/10 % thymol/1 % LNPs was 16.0, 17.2, 5.2, and 1.1 cm², respectively. The presence of LNPs in the film has exerted its AmAC because phenolic hydroxyl groups, which are responsible for the AmAC of LNPs, damage microorganisms' cell membranes and lead to their destruction (Basbasan et al., 2023). In another study, Zeng et al. (2024) evaluated the effect of PVA/LNP@PS/TA film on weight loss, freshness retention, and strawberry appearance. As shown in Fig. 15B, weight loss in all strawberry fruit samples increased with increasing storage time. After the end of the seventh day, the weight loss of strawberries packed with PVA/3 % LNP@PS /5 % TA was approximately 8.99 %, which was significantly less than that of strawberries packed with PVA film and the control. Also, visually, strawberries packed with PVA/3 % LNP@PS /5 % TA treatment remained fresh and intact (Zeng et al., 2024).

In another study by Zhang et al. (2024), the effect of pectin coating containing LNPs coated with PDA on bananas was investigated. After 7 days of storage, the uncoated bananas (control) had a completely brown surface, while the surface of the coated bananas was slightly brown. This indicates that the pectin coating containing LNPs coated with PDA increases the shelf life of bananas, which is due to the coating's AmAC and AxAC. In addition, this pectin coating contains LNPs coated with PDA as a barrier and physical layer that prevents bacteria or other substances from sticking to the banana surface. Zhang et al. (2023) investigated the effect of pectin film containing LNPs on increasing the shelf life of strawberries. They found that strawberries packaged with pure pectin film and plastic wrap showed slight spoilage for 7 days. However, strawberries packaged with pectin/LNPs (except 1 % LNPs) retained their original shape. The good barrier properties, AxAC, and AmAC of pectin film containing LNPs increased the shelf life of strawberries. The weight loss rate of packed strawberries in different pectin/lignin nanoparticle treatments was significantly lower than that of pure pectin film due to the decrease in water vapor transfer rate. The soluble solid content and hardness of strawberries packaged with clean pectin and plastic packaging decreased, consistent with reduced strawberry quality. In contrast, the hardness and soluble solid content of strawberries packed with pectin film containing LNPs were maintained at up to 72.08 % and 89.29 % of their initial content, respectively. These results confirm the promising role of pectin film/ LNPs in increasing the shelf life of strawberries (Zhang, S. et al., 2023).

In an interesting work, Moe et al. (2023) investigated using PBS packaging containing LNPs for bread. The authors reported that the total

yeast and mold counts of bread packaged with PBS treatment on days 7 and 14 were 2.7 and 2 log CFU g⁻¹, respectively. The total yeast and mold counts of bread packaged with PBS/5 % cinnamaldehyde (CIN)/1 % LNPs treatment were < 1.0 log CFU g⁻¹ on days 7 and 14. The increased AmAC of PBS is related to lignin and CIN NPs. Adding LNPs to a PBS /5 % CIN film stabilizes CIN, increasing its efficient release and AmAC. The water content and water activity of packaged breads with different treatments. The results showed that the water content and water activity decreased with increasing storage. The minimum water activity required for the growth of fungi and bacteria is 0.6 and 0.91, respectively. On the 14th day, the water activity of packaged bread with different treatments was less than the optimal value for the growth of fungi and bacteria. The hardness and cohesion of samples packaged with different treatments increased and decreased, respectively, with increasing storage time due to the decrease in bread moisture during storage. The oxygen level was low in the PBS headspace, indicating that there are more microorganisms because they consume oxygen. The highest level of CO₂ in the upper space of PBS until day 10 was among the treatments, which shows that microorganisms produce CO₂ as a byproduct. Conversely, CO₂ in the headspace of PBS/1 % LNPs /5 % CIN treatment was low. These results show that yeast and mold consume O₂ and produce CO₂ (Moe et al., 2023).

Milk light spoilage causes nutrient loss, so milk packaging is very important. PDA's structure contains catechol groups that can stick to organic and inorganic surfaces. Therefore, the pectin film solution containing LNPs coated with PDA was attached to the milk packaging surface, and the milk's pH changes during storage were investigated. One of the critical factors of milk spoilage is pH, because a pH below 6.4 causes milk spoilage. The results showed that the pH of pectin-coated and uncoated milk after 7 days of storage was less than 6.4, indicating the milk spoilage of these two treatments. Decreasing milk pH causes lactose decomposition, followed by the production of lactic acid, and light accelerates this process. The pH of milks coated with pectin solution containing 0.5 and 1 % LNPs coated with PDA was higher than 6.4 after 7 days, and the pH changes were insignificant in the first 5 days, but the decrease in pH was noticeable on the seventh day. In contrast, the pH of milk coated with a pectin solution containing 5 % and 10 % LNPs coated with PDA remained stable after 7 storage days without a significant decrease. These results show that LNPs, containing 5 % and 10 % lignin, increased the shelf life of milk through AmAC and blocking ultraviolet rays. Vitamins B and C degraded quickly in uncoated and pectin-coated milk, but it was even faster in milk coated with pectin/ LNPs coated with PDA. Especially in pectin/10 % LNPs coated with PDA, the remaining vitamins B and C were 58.74 % and 72.58 %, respectively. In addition to their UV-blocking properties, LNPs contain PDA, which increases their stability against light (Zhang et al., 2024).

7. Conclusion remarks and future demands

LNPs derived from industrial and agricultural wastes have become a practical approach for active packaging. This approach aims to achieve a green and bio-circular economy and reduce food waste, potentially revolutionizing food packaging. LNPs are a promising natural alternative to metal and chemical nanomaterials for enhancing the safety and quality of food products in biodegradable food packaging. Several studies have demonstrated the potential of LNPs in active food packaging composites. Composites containing LNPs showed strong AxAc and AmAc, making them a promising bioactive compound for active packaging. Studies show that adding LNPs in composites and films improves physical properties such as moisture content and solubility. Furthermore, incorporating LNPs improved the films and composites' thermal stability, hydrophobic properties, and mechanical strength. Bio-composites containing LNPs provide a means to enhance the safety and shelf life of food products by reducing lipid oxidation and inhibiting microbial growth. Therefore, Films and composites containing LNPs for active packaging are a promising and ideal solution in the food

packaging sector. This approach not only increases the shelf life of food products but also improves their safety and quality standards. However, various methods have been reported for the synthesis of LNPs; however, LNPs extracted by different methods will have different properties and structures, which leads to inconsistencies in their use for packaging applications.

Strategies aimed at standardizing LNP structures critically tackle the inherent variability found in lignin, which results from differences in biomass feedstock types and various extraction methods used. A key issue in this standardization endeavor is the careful selection of suitable biomass sources and extraction techniques aimed at reducing the molecular diversity of lignin. The structural characteristics of lignin are significantly affected by the species from which it is sourced as well as the specific isolation or purification methods applied. The process of transforming lignin into LNPs, known as nanotransformation or nanoformulation, is important as it produces nanoscale units that exhibit enhanced reactivity and uniformity compared to bulk lignin. This transformation increases their compatibility with different polymer matrices. Moreover, chemical modifications, such as acetylation, are utilized to enhance the dispersion and uniformity of LNPs within composite materials, ultimately improving their functional performance in industrial uses.

Techniques involving hybridization are crucial for adjusting the properties of lignin, where lignin is combined with metals, metal oxides, or natural phenolic compounds. This method enables the tuning of biological activities and physicochemical properties, leading to the development of reproducible, multifunctional nanoparticles that can meet diverse industrial requirements. In food packaging applications, lignin structures specifically designed to improve antioxidant, antibacterial, and UV-resistance properties must contain a high concentration of phenolic hydroxyl groups. These groups are essential, enabling the proton-coupled electron transfer mechanisms that drive antioxidant activity. The existence of aromatic and aliphatic hydroxyl groups, along with carboxylic, carbonyl, and methoxyl functionalities inherent in lignin, further enhances its antibacterial effectiveness and UV-blocking ability. Incorporating LNPs rich in phenolic moieties into polymeric films, such as starch-PVA or PLA matrices, not only strengthens the mechanical properties of these materials but also boosts their antioxidant inhibition, particularly illustrated through DPPH radical scavenging activity. Additionally, these alterations enhance UV-barrier properties and introduce antibacterial characteristics, making them particularly suitable for food packaging applications.

Research has indicated that nanoformulated lignin particles, particularly when uniformly dispersed and occasionally treated with chemical modifications such as acetylation, consistently perform as effective UV shields and antimicrobial agents, while ensuring that food safety is not compromised (Cavallo et al., 2021; Wang et al., 2024). In summary, the successful production of lignin nanoparticles with a standardized size distribution and a high density of phenolic hydroxyl groups and aromatic structures is crucial for achieving improved antioxidant, antibacterial, and UV-resistance features. These attributes are vital in the development of high-performance, biodegradable food packaging materials. Utilizing optimal extraction methods, precise nanoformulation techniques, and targeted surface functionalization are essential strategies that promote reproducible and efficient industrial applications.

Ethical statement - studies in humans and animals

The authors clarify that the current research does not involve any human participants or animal subjects. Instead, it is categorized as an experimental study, focusing on controlled conditions and variables to gather data without direct interaction with living beings.

CRediT authorship contribution statement

Behnam Bahramian: Writing – review & editing, Writing – original

draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Narges Kiani-Salmi:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Reza Abedi-Firoozjah:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Milad Tavassoli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Danial Dehnad:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Asghar Azizian:** Writing – review & editing, Methodology, Investigation, Data curation. **Mitra Rezaie:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Roshanak Hasani:** Writing – review & editing, Software, Methodology, Investigation. **Sajad Ghaderi:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Majid Majlesi:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Ali Ehsani:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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