Advances in Nanocellulose-Based Composites for Sustainable Food Packaging

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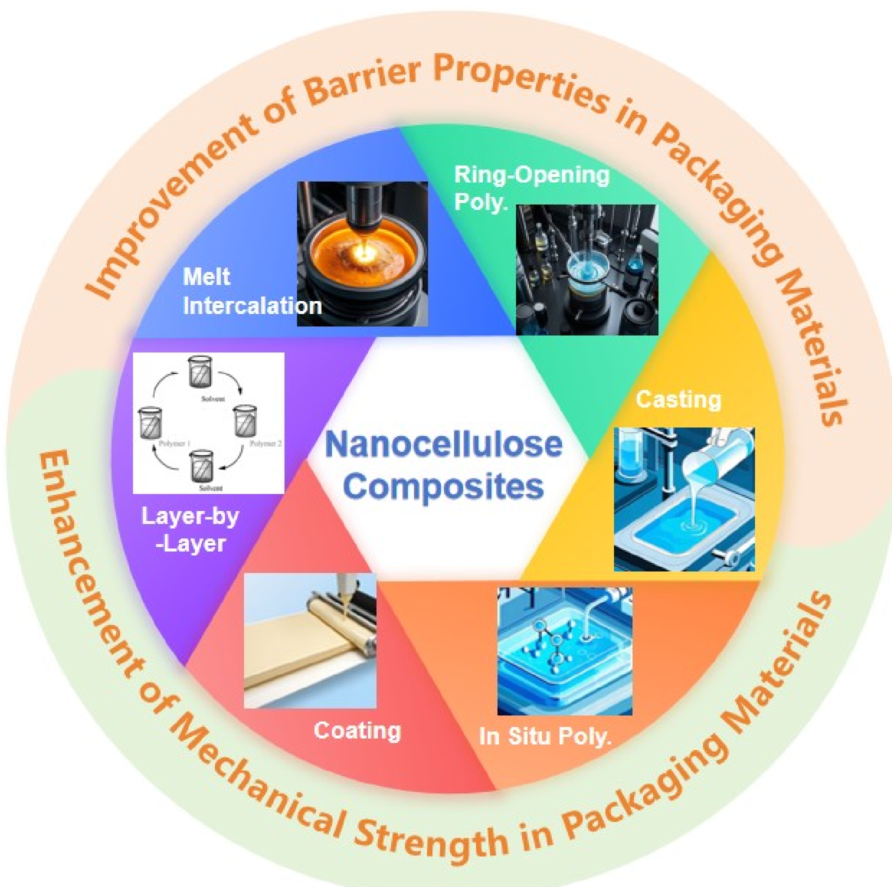
DOI: 10.15376/biores.20.3.Shi

GRAPHICAL ABSTRACT



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Nanocellulose, a sustainable and versatile nanomaterial derived from abundant natural resources such as plants and bacteria, has emerged as a promising candidate for advancing eco-friendly food packaging. This review summarizes recent advancements in nanocellulose composites, focusing on their preparation methods, enhanced mechanical and barrier properties, applications in food preservation, safety profiles, and biodegradability. Nanocellulose composites, synthesized *via* techniques such as solution casting, melt intercalation, layer-by-layer self-assembly, *in situ* polymerization, coating, and ring-opening polymerization, can exhibit exceptional mechanical strength, oxygen and moisture barrier performance, as well as compatibility with active agents such as antioxidants and antimicrobials. Studies highlight the role of nanocellulose in reducing polymer composite permeability while maintaining biodegradability. Despite these advantages, challenges such as high production costs, energy-intensive methods (*e.g.*, sulfuric acid hydrolysis), and hydrophilic limitations hinder industrial scalability. Emerging strategies, including enzymatic processing and surface modifications (acetylation, oxidation), offer pathways to enhance hydrophobicity, dispersion, and thermal stability. Future research should prioritize scalable, low-cost production technologies and expanded applications in smart and active packaging systems. By addressing these challenges, nanocellulose composites hold significant potential to revolutionize sustainable packaging, aligning with global demands for reduced environmental impact and enhanced food security.

DOI: 10.15376/biores.20.3.Shi

Keywords: Nanocellulose; Composite materials; Food packaging; Biodegradability; Sustainable materials; Barrier properties

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INTRODUCTION

Over the past decades, petroleum-based materials have been widely utilized in food packaging due to their low cost, excellent mechanical and physical properties, and high plasticity (Zhao *et al.* 2020a; Shlush *et al.* 2022; Shi *et al.* 2024a). However, most petroleum-based materials are environmentally detrimental, posing risks to marine and terrestrial ecosystems and negatively impacting human health. With the growing emphasis on ecological protection and sustainable development, there has been a paradigm shift toward replacing petroleum-derived products with renewable and biodegradable natural alternatives (Wang *et al.* 2018; Zhao *et al.* 2020b; Taherimehr *et al.* 2021). Bioplastics derived from biopolymers, owing to their eco-friendliness, biodegradability, non-toxicity, and hydrophilicity, have emerged as promising candidates in food packaging and garnered significant attention in recent years (Jariyasakoolroj *et al.* 2020; Mellinas *et al.* 2020; Morales *et al.* 2021).

Cellulose, the most abundant biopolymer on Earth, is ubiquitously sourced from natural plants, wood, agricultural residues, industrial waste, bacteria, and algae (Ahmad-Khorairi *et al.* 2023; Kaczmarek and Białkowska 2025; Li *et al.* 2025). Nanocellulose, which can be regarded as a product of cellulose, exhibits exceptional attributes such as high tensile modulus, superior strength, large surface area, and high aspect ratio, thus positioning it as an attractive emerging nanomaterial (Yi *et al.* 2020; Hu *et al.* 2021; Du *et al.* 2023; Shi *et al.* 2024a). Recent efforts have focused on integrating nanocellulose with biopolymers to develop nanocomposites. The incorporation of nanocellulose enhances the mechanical strength and barrier properties of biopolymers, thereby improving their suitability for food packaging applications.

This paper summarizes the sources and characteristics of nanocellulose, discusses the preparation methods for nanocellulose composites and the effects of nanocellulose incorporation on composite performance, evaluates the safety and biodegradability of nanocellulose composites, and outlines future development trends. The aim is to provide insights for advancing the utilization of nanocellulose and the development of novel packaging materials, with an emphasis on food packaging.

NANOCELLULOSE

Nanocellulose, a nature-sourced polymer with nanostructures, has garnered extensive attention from researchers worldwide due to its exceptional mechanical properties, barrier performance, biocompatibility, and biodegradability (Zinge and Kandasubramanian 2020). Nanocellulose is primarily prepared from two major sources: plants (*e.g.*, cell walls of wood, cotton, and wheat straw) and microorganisms (*e.g.*, metabolic byproducts of *Gluconacetobacter xylinus*, kombucha cultures, and *Komagataeibacter* spp.) (Das *et al.* 2024). Nanocellulose is produced by processing cellulose into single linear fibers with diameters below 100 nm. While retaining the fundamental properties of cellulose, its distinctiveness lies in its nanoscale dimensions (Hubbe *et al.* 2017). Similar to cellulose, nanocellulose is insoluble in water or common organic solvents at room temperature. Its thermal stability depends on factors such as size, crystallinity, polymerization degree, and functional groups, with rapid degradation occurring above 220 °C.

Based on isolation methods and sources, nanocellulose is classified into three categories: cellulose nanocrystals (CNCs), cellulose nanofibers (CNFs), and bacterial nanocellulose (BNCs). CNCs are predominantly synthesized *via* inorganic strong acid hydrolysis or enzymatic treatment, CNFs *via* physical-mechanical methods, and BNCs through biosynthetic processes (Ferrer *et al.* 2016).

Plant-Based Nanocellulose

Plants serve as the primary source of cellulose. Plant cells are predominantly composed of fibrous cells interconnected with other non-fibrous cells *via* the middle lamella. Plant fibers refer to the residual fibrous cells obtained after removing non-fibrous components through physical, chemical, or biological treatments (Yang *et al.* 2025). Figure

1 illustrates the hierarchical structure of cellulose from fibers to nanostructured cellulose. Within plant cell walls, cellulose nanofibrils—also termed nanocellulose—are processed into cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs) (which are traditionally called nanofibrillated cellulose) *via* chemical or mechanical methods.

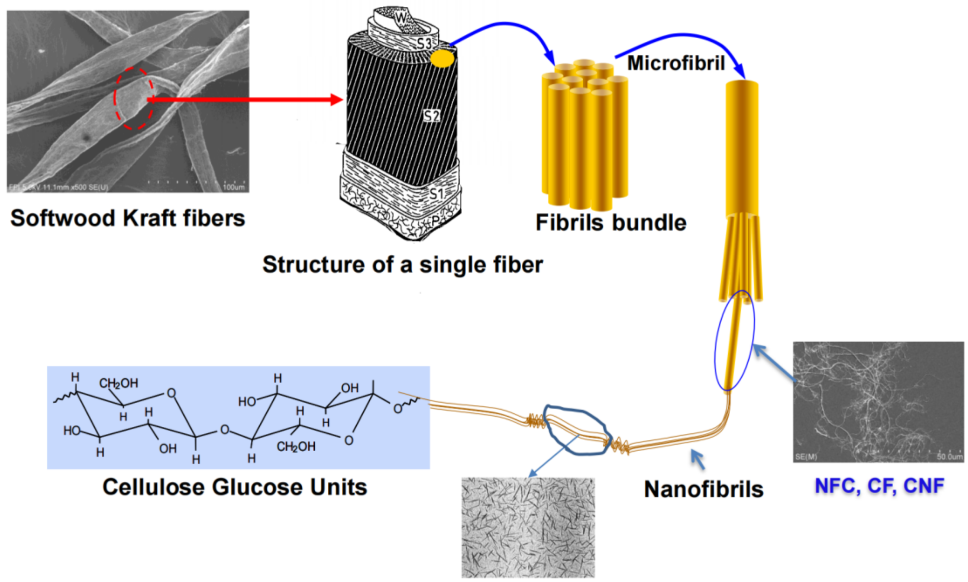

Fig. 1. Hierarchical structure of cellulose from fibers to nanostructured cellulose

CNCs are short rod-shaped microfibrils extracted from plant fibers, with lengths generally below 500 nm, widths ranging from 3 to 10 nm, and elastic moduli of 130 to 150 GPa (Habibi *et al.* 2010). Chemical methods, such as acid hydrolysis, alkaline hydrolysis, TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl) oxidation, enzymatic hydrolysis, and hydrogen peroxide oxidation, remain the most widely used approaches for CNC production due to their efficiency and simplicity. Among these, acid hydrolysis is the most prevalent (Zhang *et al.* 2024).

CNFs are filamentous nanocellulose fibers extracted from plant fibers, characterized by lengths exceeding 500 nm, diameters below 100 nm, and high aspect ratios. In plant cell walls, cellulose macromolecular chains intertwine to form linear nanostructures. Physical methods, involving high-intensity mechanical processing of raw plant cellulose to achieve nanoscale dimensions, are typically employed for CNF preparation (Tyagi *et al.* 2021; Yao *et al.* 2023).

Bacterial Nanocellulose

Bacteria represent an alternative source of nanocellulose. Bacterial cellulose (BC), synthesized *via* microbial fermentation in specific bacterial strains through biofabrication techniques, refers to nanocellulose assemblies produced by these organisms. BC is composed of nanofibrils with diameters ranging from 20 to 100 nm, exhibiting a higher elastic modulus compared to plant-derived nanocellulose. In contrast to plant-based counterparts, BC demonstrates superior mechanical properties, enhanced biocompatibility, and higher crystallinity. However, due to its higher production costs, BC is primarily utilized in biomedical applications. Biological methods, such as static and agitated cultures, are the predominant approaches for BC synthesis. These cultivation techniques significantly influence the morphology and properties of BC (Fernandes *et al.* 2020).

PREPARATION OF NANOCELLULOSE COMPOSITES

Nanocellulose not only retains the renewable and biodegradable characteristics of natural cellulose but it also exhibits potential advantages such as a large specific surface area, high transparency, superior strength, low density, versatile chemical modification potential, and biocompatibility, making it an exceptional candidate for functional composite materials. Currently, most nanocellulose composites are applied in the form of composite films in fields such as food packaging and biomedicine. Significant progress has been made in nanocellulose composite film research, where researchers incorporate nanocellulose as a reinforcing phase in polymer matrices to develop novel composites through various methodologies.

Extrusion-blowing is a common method for producing food packaging films. However, nanocellulose composites face challenges in extrusion-blowing processes due to the material's hygroscopic nature (attributed to abundant hydroxyl groups on its surface), poor dispersion in solid resins, and rapid thermal decomposition above 220 °C. To address these limitations, existing preparation methods include: solution casting, layer-by-layer (LbL) self-assembly, *in situ* polymerization, coating, melt intercalation, and ring-opening polymerization.

Solution Casting

Solution casting is a straightforward processing method for nanocomposites. The principle involves dispersing nanocellulose in water or various organic media, followed by mixing with a polymer solution under mechanical stirring, ultrasonication, or high-temperature autoclave treatment to form a homogeneous suspension. The suspension is then cast onto a flat substrate, and the solvent is removed through evaporation drying, resulting in a uniform film.

Kang *et al.* (2021) incorporated natural antioxidants into nanocellulose and employed solution casting to fabricate food packaging films for extending raspberry shelf life. Similarly, Marand *et al.* (2021) prepared composite films by integrating nickel oxide nanoparticles into chitosan, demonstrating their potential for active food packaging or wastewater treatment.

In recent years, researchers have explored the potential of solution casting for specialized applications. For example, Kang *et al.* (2021) successfully incorporated natural antioxidants into nanocellulose to create food packaging films. This approach demonstrated the potential to extend the shelf life of raspberries, highlighting the practical use of solution-cast films in the food packaging industry. Similarly, Marand *et al.* (2021) took a different approach by integrating nickel oxide nanoparticles into chitosan to prepare composite films. Their study revealed the potential of these films for active food packaging as well as for wastewater treatment, showcasing the versatility of solution casting in producing materials with a wide range of applications.

However, solution casting suffers from drawbacks such as time-consuming processes, low nanocellulose loading capacity, and high energy consumption, rendering it unsuitable for large-scale production.

Layer-by-Layer (LbL) Self-Assembly

Layer-by-Layer (LbL) self-assembly is a well-established technique used to create nanostructured composite films. This method involves the sequential adsorption of complementary components onto a substrate, with each layer typically formed through electrostatic interactions between oppositely charged polyelectrolytes. The electrostatic forces drive the binding of the components, resulting in the formation of multilayered films. The LbL process is particularly useful for producing films that require precise control over their structure, as the individual layers can be adjusted to meet specific functional needs (Richardson *et al*. 2016; Zhang *et al.* 2022).

The classical LbL approach involves dipping a substrate into a solution containing one of the components, followed by rinsing to remove excess material. This process is repeated for each subsequent layer, ensuring that the films grow layer by layer with controlled thickness. The resulting multilayered films can be built up with a high degree of precision. This method allows for the fabrication of complex nanostructured films on solid supports, with layers being assembled from solutions or dispersions of the respective materials. This versatility makes it suitable for a variety of applications where precise material properties are required.

The properties of the films produced through LbL self-assembly are diverse and can be tailored for different purposes. For example, films can be engineered to exhibit characteristics such as enhanced gas barrier properties, anti-fog capabilities, superhydrophobicity, antimicrobial activity, or the ability to deliver bioactive compounds. These features are particularly useful in the field of packaging, where such properties are in high demand for improving the performance of packaging materials (Fotie *et al.* 2020; Nguyen *et al.* 2021; Thuy *et al.* 2021; Ahmad *et al.* 2025; Li *et al.* 2025).

In packaging applications, the LbL technique is often employed to create films using layers of polyelectrolytes and nanocellulose. Cellulose nanocrystals (CNCs), which are derived from natural cellulose, are commonly used as one of the components. These can be alternately deposited with cationic polyelectrolytes, such as chitosan (Li *et al.* 2015), poly(ethyleneimine), poly(allylamine hydrochloride) (Marais *et al.* 2014), or poly(diallyldimethylammonium chloride) (Foster *et al.* 2018). The electrostatic attraction between these oppositely charged components results in the formation of multilayered films, where each layer adheres to the previous one due to these interactions.

One of the key advantages of the LbL technique is its simplicity and versatility. The process allows for precise control over the thickness of the films, which can be adjusted at the nanoscale. This level of control is critical for applications that require films with specific properties, such as optimal mechanical strength, flexibility, or barrier functions. Additionally, LbL self-assembly can be used to coat complex three-dimensional objects, such as small bottles, cups, and trays, which broadens its potential applications in various industries.

Despite its many advantages, the LbL self-assembly process is not without its limitations. One of the main challenges associated with this technique is that it is time-consuming and complex. The need for multiple dipping and rinsing steps, as well as the precise control over each layer's deposition, makes the process slower compared to other methods of film production. This limitation makes it less suitable for large-scale industrial production, where speed and efficiency are often paramount. Nevertheless, the LbL technique remains highly valuable for creating high-performance coatings and films for specialized packaging applications. In these cases, where precise control over the material's properties is essential, the benefits of LbL self-assembly outweigh the challenges associated with its use.

In Situ Polymerization

In situ polymerization has become a highly effective strategy for fabricating nanocellulose-reinforced polymer composites. This method involves synthesizing polymer matrices *via* controlled chain propagation reactions within a composite system that contains nanocellulose fillers. The technique differentiates itself from conventional methods, which typically blend pre-formed polymers with nanocellulose. Instead, *in situ* polymerization allows monomers or prepolymers to undergo polymerization directly in contact with nanocellulose surfaces. This process creates an intimate connection between the polymer and nanocellulose, which promotes stronger interfacial interactions.

These interfacial interactions are achieved through hydrogen bonding and mechanical interlocking between the polymer and nanocellulose. The presence of nanocellulose acts as nucleation sites, guiding the polymer chain assembly as it forms. This intimate contact is particularly beneficial in ensuring that the nanocellulose is effectively incorporated into the polymer matrix. The polymerization process creates a stronger bond between the components, enhancing the overall properties of the composite material (Attia *et al.* 2021; Feng *et al.* 2021; Nepomuceno *et al.* 2021).

The *in situ* approach offers several advantages for nanocellulose incorporation in polymer composites. First, the fluid monomer medium enables uniform dispersion of the nanocellulose prior to polymerization. This addresses the aggregation issues commonly encountered in melt-blending systems, where nanocellulose particles tend to clump together, resulting in an uneven distribution. Second, as the polymer chains grow during the polymerization process, they can establish molecular-level interactions with the hydroxyl groups present on the nanocellulose surface. This strengthens the interaction between the two materials, contributing to the overall integrity of the composite. Third, the *in situ* polymerization environment naturally promotes adhesion between the matrix and filler without the need for chemical modification of the nanocellulose. This feature simplifies the fabrication process while still achieving strong matrix-filler bonding.

A notable application of this technique is demonstrated by Clarke *et al.* (2019), who explored the dispersion of nanocellulose in poly(ethylene succinate) (PESu) during *in situ* polycondensation. Their study showed that the nanocellulose fibers acted as heterogeneous nucleating agents, significantly accelerating the crystallization kinetics of PESu even at low nanocellulose loading levels. This result underscores the important role that nanocellulose plays in modifying the polymer matrix. Specifically, the physical presence of nanocellulose altered the polymer chain dynamics, as evidenced by reduced molecular weights and increased melt viscosity with higher nanocellulose content. These changes were not the result of chemical bonding but rather stemmed from the physical confinement of the polymer chains by the nanocellulose, highlighting the unique advantage of *in situ* polymerization in creating nanocomposite architectures with constrained polymer chains.

In contrast to traditional cellulose polymerization methods, the *in situ* polymerization of nanocellulose maintains the chemical integrity of the nanocellulose phase, which acts purely as a reinforcement material. The polymer matrix is formed around the nanocellulose through controlled chain growth, ensuring that the reinforcing phase remains intact and functional. This approach has led to the development of composite films that exhibit synergistic properties derived from both components. The nanocellulose network contributes to enhanced biodegradability, while the *in situ*-formed polymer matrix offers improved moisture resistance. These complementary properties make such systems particularly promising for applications in sustainable packaging, where the nanocellulose provides structural reinforcement, and the polymer matrix governs the barrier properties essential for packaging performance.

Coating Method

The coating method involves applying nanocellulose coatings to various substrates such as paper, cardboard, or other materials used in packaging. This process significantly enhances the properties of the packaging, particularly in food-related applications. Specifically, it improves moisture resistance, gas barrier properties, and oil repellency, which are crucial for maintaining food freshness and extending shelf life. These coatings offer a sustainable alternative to traditional packaging solutions, which often rely on petroleum-based products.

During the coating process, a solid film layer adheres to the substrate surface, while residual liquid media evaporate. The high dispersibility of nanocellulose in water facilitates the formation of thin coatings, either alone or in combination with other polymers. For example, Spieser *et al.* (2020) deposited an active ink composed of cellulose nanofibrils and silver nanowires onto flexible transparent polymer films using a bar-coating technique, achieving precise control over film thickness and significantly improving the antimicrobial and barrier properties of the base film. Jin *et al.* (2021) utilized nanocellulose as a coating for paper-based materials to enhance the overall performance of food packaging paper, investigating its effects on mechanical and barrier properties. Wang *et al.* (2022) developed a nanocellulose-coated paperboard incorporating carboxymethyl chitosan/carboxymethyl cellulose and polylactic acid/zinc oxide nanocomposites. Their study demonstrated excellent barrier and antimicrobial performance, highlighting its potential as a biodegradable material for fast-food packaging.

Melt Intercalation Method

Melt intercalation has demonstrated significant potential for fabricating nanocellulose-reinforced thermoplastic composites, particularly for industrial-scale production. This technique involves thermomechanically dispersing nanocellulose within a molten polymer matrix through high-shear mixing, followed by extrusion to create homogeneous nanocomposites. The absence of solvents makes this method inherently compatible with nanocellulose’s hydrophilic nature, as it avoids the interfacial incompatibility issues often encountered in solvent-based systems. By promoting interfacial interactions between the polymer matrix and nanofillers, melt intercalation minimizes nanomaterial leaching during processing, thereby improving the mechanical properties of the resulting composites.

Given nanocellulose’s high aspect ratio, renewable nature, and tunable surface chemistry, melt intercalation represents an attractive approach for its incorporation into polymer matrices. The technique’s energy efficiency and scalability make it particularly suitable for nanocellulose, which often requires high-shear processing to maintain dispersion. Additionally, melt intercalation preserves nanocellulose’s crystalline structure better than solvent-based methods, which can degrade cellulose chains.

To date, this method has been employed to synthesize polyvinylidene fluoride/organic montmorillonite (Tong *et al.* 2021), heterometallic/chitin (Emam *et al.* 2021), and nanosheet hydroxyapatite-reinforced polylactic acid nanocomposites (Huang *et al.* 2020), which show promising applications in biomedicine. Extending this approach to nanocellulose would address current limitations in cellulose composite processing, particularly for applications requiring high-throughput manufacturing. Preliminary studies suggest that melt intercalation could enhance nanocellulose dispersion in thermoplastics like polyethylene and polypropylene, which constitute ~50% of global polymer production, thereby expanding sustainable material options for packaging sector.

Ring-Opening Polymerization

Ring-opening polymerization (ROP) is a reaction type used to synthesize aliphatic polyesters and epoxy resin networks. Due to its mild reaction conditions and absence of small-molecule byproducts, ROP yields products with high molecular weights and narrow distributions, making it suitable for thermosetting polymer-based composites.

The ROP process involves the polymerization of cyclic monomers, such as lactones and lactides, using specific initiators to trigger the reaction. These initiators can vary, with common examples including alcohols, amino alcohols, amino acids, and amines. By carefully choosing the appropriate initiator, researchers can control the polymerization process to achieve the desired polymer characteristics. This level of control over the polymerization allows for the creation of materials with tailored properties, such as improved mechanical performance, which is particularly useful in the development of composite materials for advanced engineering applications.

Incorporating nanocellulose into the polymer matrix opens up exciting opportunities for the development of nanocomposites. Nanocellulose, with its exceptional strength and biocompatibility, can enhance the overall properties of the polymer, offering improved mechanical strength, stiffness, and durability. By grafting polymers onto the surfaces of nanocellulose, researchers can further enhance these properties, creating nanocomposites with superior performance compared to conventional materials. This approach allows for the development of materials that are not only stronger but also lighter and more sustainable, making them ideal for a wide range of applications, from packaging to construction materials.

Lalanne-Tisné *et al.* (2020) conducted ROP of nanocellulose and polyesters using N,N-dimethylaminopyridine (DMAP) as an initiator under mild conditions, investigating parameter interactions and their effects on cellulose modification. The resulting bio-nanocomposites exhibit potential applications in medicine, automotive engineering, and packaging.

These bio-nanocomposites, made from renewable resources, offer potential solutions to challenges in industries that require materials with both high strength and sustainability. In the medical field, for example, the biocompatibility of the materials makes them suitable for use in medical devices, drug delivery systems, and tissue engineering. In automotive engineering, these materials can contribute to lighter, more fuel-efficient vehicles without compromising on strength or durability. Similarly, in packaging, the enhanced mechanical properties of these bio-nanocomposites can help create more efficient, eco-friendly packaging solutions that reduce waste and improve sustainability. Thus, ROP offers a powerful method for developing materials with wide-ranging applications across various industries.

FUNDAMENTAL PROPERTIES OF NANOCELLULOSE COMPOSITES

Nanocellulose, as a reinforcing phase, can enhance the mechanical strength and barrier properties of polymer matrices, enabling the development of advanced packaging materials. Additionally, nanocellulose can serve as a carrier for active substances such as antioxidants and antimicrobial agents, which synergize with the polymer matrix to extend food shelf life.

Enhancement of Mechanical Strength in Packaging Materials

Numerous studies have reported significant improvements in the mechanical properties of nanocellulose-reinforced composites. Eichers *et al.* (2022) enhanced the mechanical performance of polylactic acid (PLA) composites using nanocellulose alongside distillers' dried grains with solubles (DDGS) as reinforcing agents, polyethylene glycol (PEG) as a plasticizer, and maleic anhydride (MA) as a coupling agent *via* melt blending. Their results demonstrated a marked increase in Young's modulus and a slight improvement in tensile strength, indicating that the incorporation of cellulose nanocrystals (CNCs) effectively enhances the physical properties of PLA composites. Similarly, Gond *et al.* (2022) prepared bio-nanocomposites by integrating nanocellulose extracted from sugarcane bagasse with PLA through extrusion-injection molding. They observed notable increases in tensile strength, flexural strength, fracture toughness, and impact resistance with higher nanocellulose content. Nair *et al.* (2019) developed composites of cellulose nanofibers (CNFs) and bio-based epoxy resin, revealing that adding 18 to 23 wt% CNFs significantly improved the modulus, strength, and strain performance without compromising the epoxy resin's high thermal stability.

Improvement of Barrier Properties in Packaging Materials

The barrier performance of packaging materials is influenced by three sequential processes involved in gas or water vapor transmission: dissolution, diffusion, and desorption (Revathi *et al.* 2025). Each of these processes plays a vital role in determining how effectively a material can act as a barrier to gas or moisture. Initially, when gas molecules come into contact with the composite film, a fraction of these molecules dissolves into the film's matrix. This dissolution is the first step, where the gas molecules become integrated into the material. Once dissolved, the gas molecules begin to diffuse through the film, which is the second process. Driven by a concentration gradient, they move from regions of high concentration to regions of low concentration, gradually spreading throughout the material. This diffusion process continues until equilibrium is reached, meaning the concentration of gas molecules becomes uniform across the material. The third process, desorption, occurs when the gas molecules exit the film and are released into the surrounding environment. Together, these three stages—dissolution, diffusion, and desorption—are crucial for determining the overall barrier properties of the packaging material. The transport mechanism of oxygen or water vapor in nanocellulose composites is illustrated in Fig. 2.

In order to enhance the barrier performance of packaging materials, it is essential to control these three stages effectively. Specifically, managing the dissolution, diffusion, and desorption processes can lead to improved resistance against gas and moisture transmission. One way to achieve this is through the use of nanocellulose, a material known for its high crystallinity and ability to enhance the properties of composites. Nanocellulose is widely utilized in various composite materials due to its ability to impede gas transmission. Its inclusion in films and coatings can significantly improve their barrier performance, making it a promising candidate for use in packaging materials.

In research by Faraj *et al.* (2022), the gas barrier properties of PLA composites modified with three types of grafted CNCs (cellulose nanocrystals) were explored. Their study demonstrated that even with a relatively high loading of 30 wt% modified CNCs, the particles dispersed uniformly within the matrix. This uniform distribution of CNCs led to a significant improvement in the gas barrier performance of the composites, highlighting the potential of using modified nanocellulose to enhance packaging materials. Li *et al.* (2021) utilized free radical polymerization to hydrophobically modify nanocellulose, which was then compounded with organic montmorillonite and PLA. The resulting composite was used to coat paper substrates, and the performance of the coated paper was compared to uncoated substrates. The study found that the coating with this composite, which contained just 0.2 wt% nanocellulose, resulted in a dramatic reduction in water vapor transmission rate (WVTR) and moisture permeability. Specifically, the WVTR was reduced by 88.2%, and the moisture permeability decreased by 26.0%, demonstrating the effectiveness of nanocellulose-based composites in enhancing barrier properties.

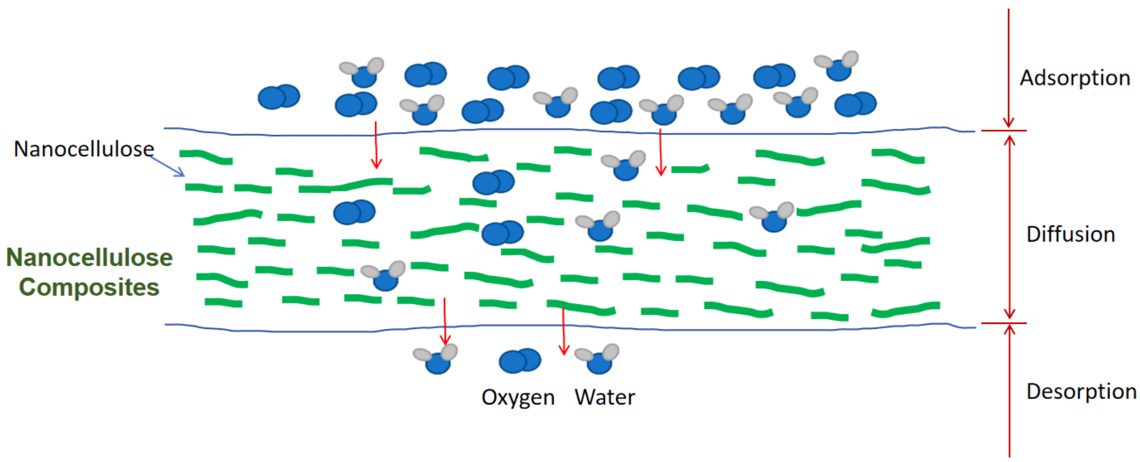

Fig. 2. Transport mechanism of oxygen or water vapor in nanocellulose composites

APPLICATION OF NANOCELLULOSE COMPOSITES IN FOOD PRESERVATION

Given the potential of nanocellulose in food packaging, film-forming biopolymers with antibacterial activity and biodegradability have attracted significant interest, and the application of nanocellulose in food preservation has garnered widespread attention. Most food products require days to months to reach consumers, making the extension of shelf life a critical necessity. Table 1 summarizes selected applications of nanocellulose composites in food preservation.

Nanocellulose composites are typically applied *via* spraying, coating, or wrapping to preserve food. These composites enhance oxygen barrier properties, reduce water vapor transmission rates, and improve mechanical strength to mitigate external physical impacts on food, thereby effectively extending the shelf life of food products. While oxygen blocking is consistently recognized as a major contributor, the cited authors suggest that synergistic effects of multiple barrier properties and mechanical reinforcement provide comprehensive protection. This multifunctionality makes nanocellulose composites particularly effective for diverse food preservation challenges.

Table 1. Application of Nanocellulose Composites in Food Preservation

Composite Composition	Food Type	Preservation Method	Preservation Effect	References
CNF-thyme essential oil (EO) slow-release system	Fresh beef	Wrapping fresh beef with foam plastic	Extended beef shelf life by 5 days	Zhang *et al*. 2020
Composite film composed of gelatin, bacterial cellulose, and magnesium oxide	Preserved eggs	Forming preservation coating on egg surfaces	Reduced weight loss and total volatile basic nitrogen (TVB-N) content, maintained sensory quality	Wang *et al*. 2021
Composite film blended with chitosan, nanocellulose, and tea polyphenol nanoliposomes	Silver carp fillets	Wrapping treated fish fillets with composite film	Inhibited TVB-N value increase (indicating protein and lipid decomposition) and extended storage time	Zhou *et al.* 2022
Starch film prepared by mixing nanocellulose, glycerol, polyvinyl alcohol, and additives	Edible oil	Using film as packaging for edible oil	Effectively preserved edible oil for over 3 months under ambient conditions	Patil *et al.* 2022
CNF colloidal suspension	Early-ripening apples	Spraying on apple surfaces	Inhibited respiration rate and ethylene production; intact appearance after 10 days of ambient storage	Wang *et al*. 2022
Composite film prepared by blending nanocellulose, hemicellulose, montmorillonite, and alkyl ketene dimer	Fresh asparagus	Forming preservation coating on green asparagus surfaces	Delayed nutrient loss, extended shelf life from 4 to 7 days	Lei *et al*. 2022
Preservation coating prepared by grafting enzyme-like metal-organic frameworks onto carboxymethyl cellulose nanofibers	Mango, Banana	Spraying preservation coating on fruit surfaces	Delayed appearance of black spots, reduced weight loss by 3.08% and 2.97%, significantly improved hardness	Huang *et al*. 2023
Biocomposite coating based on chitosan (CS) as the bio-based film forming material, CNC as the reinforcement and sodium tripolyphosphate (TPP) as the crosslinking agent.	Banana	Dipping the Biocomposite coating on fruit surfaces	Extended the shelf life of bananas from 5 days to 11 days at room temperature	Du *et al.* 2023
Nisin/cellulose nanofiber/protein bio-composite antibacterial coating	Cherry Tomato, Banana	Dipping the Biocomposite coating on fruit surfaces	Prolonged the shelf life of the fruits by over 6 days under 20℃, preserving their appearance, hardness, and nutrient content during storage.	Shi *et al.* 2024b

Composite Composition	Food Type	Preservation Method	Preservation Effect	References
Acidic sophorolipid-enhanced cellulose nanofiber-based coconut wax Pickering emulsion	Cherry tomatoes	Spraying preservation coating on fruit surfaces	Cherry tomatoes coated with ASL-CDPE remained fresh for at least 12 days at room temperature.	Li *et al.* 2025

SAFETY AND BIODEGRADABILITY OF NANOCELLULOSE COMPOSITES

The safety, biodegradability, and sustainability of nanomaterials in food packaging have been extensively studied (Bai *et al.* 2021; Deng *et al.* 2022). The safety of nanocellulose depends on factors such as raw material sources, particle size, morphology, and agglomeration. Notably, the U.S. Food and Drug Administration (FDA) has classified cellulose and its derivatives, including bacterial cellulose, as Generally Recognized As Safe (GRAS) substances. This GRAS status is particularly advantageous in the food packaging industry, where safety is a paramount concern. For bacterial cellulose, which may have a higher production cost compared to some alternative materials, this regulatory recognition can play a crucial role. It can potentially offset its cost disadvantage by providing assurance of safety to consumers and manufacturers, thereby facilitating its adoption in various food packaging applications. The specific regulatory approval granted by the FDA for bacterial nanocellulose for direct food contact applications, such as functional barrier layers in packaging materials, further underscores its suitability and safety for use in food packaging. Researchers have assessed the cytotoxicity, genotoxicity, and ecotoxicity of nanocellulose (Ingole *et al.* 2020; Lopes *et al.* 2020). Pinto *et al.* (2022) compared cellulose micro/nanomaterials (CMNMs) with multi-walled carbon nanotubes (MWCNTs) in terms of cellular internalization, in vitro cytotoxicity, and genotoxicity using micronucleus assays in human lung adenocarcinoma (A549) cells. Their results showed that CMNMs did not induce cytotoxic effects, suggesting that despite similarities in bio-persistence and high aspect ratios, CMNMs do not elicit toxicological responses akin to MWCNTs in human cells. However, comprehensive safety assessments require additional data, such as DNA damage and mutagenesis potential.

Nanocellulose, derived from plants, exhibits excellent biodegradability. The biodegradability of nanocellulose composites depends on the polymer matrix. Arun *et al.* (2022) prepared composite films by blending nanocellulose from coconut husk waste with linseed oil, lemon oil, and polyvinyl alcohol (PVA). Biodegradation studies over 45 days revealed a degradation extent of 91%. Similarly, Tian *et al.* (2022) fabricated transparent films from partially dissolved cellulose, demonstrating exceptional stability and mechanical properties. These films degraded almost completely within 19 days when buried in soil, highlighting their strong biodegradability.

CONCLUSIONS AND FUTURE PERSPECTIVES

Abundant, non-toxic, and biocompatible biopolymers are ideal alternatives to petroleum-based synthetic materials, with cellulose being the most abundant biopolymer on Earth. As a derivative of cellulose, nanocellulose is a pivotal emerging biomaterial that can be extracted from diverse biological resources. Leveraging its superior properties, novel packaging materials with enhanced performance have been developed. Extensive studies confirm that nanocellulose incorporation reduces oxygen permeability in polymer composites, extends food shelf life, improves mechanical, thermal, and barrier properties, and minimizes packaging waste. Thus, nanocellulose as a reinforcing phase in polymer matrices addresses critical challenges in the packaging industry.

In the field of sustainable food packaging, nanocellulose composites demonstrate significant potential. However, achieving their large-scale application faces multiple challenges. On the one hand, scalability and cost control remain critical bottlenecks. While current methods for nanocellulose production are diverse, many technologies remain confined to laboratory settings and struggle to meet industrial-scale demands. For instance, certain chemical treatment methods can effectively extract nanocellulose but require expensive reagents and complex processing, resulting in low production efficiency. These limitations severely hinder the feasibility of large-scale manufacturing and practical implementation.

On the other hand, smart and active packaging systems impose higher requirements on nanocellulose composites. Smart packaging must monitor and display food quality information, while active packaging needs to actively regulate the internal environment. To achieve broader applications in these areas, nanocellulose composites require enhanced functional properties such as gas barrier performance, antibacterial efficacy, and preservation capabilities to meet diverse food packaging needs.

To address these challenges, future research should prioritize the following directions:

First, developing scalable and cost-effective production technologies. This includes exploring green and sustainable processes like biosynthesis, optimizing existing chemical and physical treatment methods to improve efficiency, and reducing costs for industrial-scale adoption.

Second, advancing functional modification of nanocellulose composites tailored for smart/active packaging systems. By incorporating functional additives or hybridizing with other materials, their gas barrier properties, antibacterial activity, and freshness preservation can be enhanced. Concurrently, compatibility with intelligent components (e.g., sensors, indicators) must be ensured to enable real-time monitoring and active protection.

Third, fostering interdisciplinary collaboration across materials science, food science, and chemical engineering. Material scientists can innovate novel materials and refine production processes, food scientists can define functional requirements for specific applications, and chemical engineers can optimize manufacturing workflows to reduce costs. Such synergistic efforts will accelerate the integration of nanocellulose composites into intelligent and active packaging systems.

ACKNOWLEDGEMENTS

We would like to thank our supporters from Science Project of Tianjin Municipal Science and Technology Bureau (Grant number: 22YDTPJC00860).

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Article submitted: February 13, 2025; Peer review completed: April 12, 2025; Revised version received and accepted: May 11, 2025; Published: May 20, 2025.
DOI: 10.15376/biores.20.3.Shi