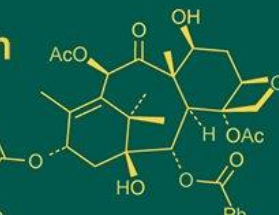


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Rice straw-derived nanocellulose and pomegranate peel polyphenols for active biodegradable food packaging: A review

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Abstract

The growing concern about the environmental impact of petroleum-based plastics have accelerated the development of sustainable packaging options made from renewable resources. Agricultural by-products and waste from food processing have been explored as potential sources for creating biodegradable and functional food packaging systems. Rice straw is one of the most widely available agricultural wastes globally and serves as a valuable source of cellulose and nanocellulose. Similarly, pomegranate peel is rich in phenolic compounds, which exhibit strong antioxidant and antimicrobial properties. Rice straw-derived nanocellulose is known for its excellent mechanical strength, barrier characteristics, biodegradability, and compatibility with biopolymer matrices. Likewise, the polyphenols found in pomegranate peel can serve as active components in packaging to reduce microbial growth and prevent oxidative damage to food. The utilisation of both rice straw and pomegranate peel together is being examined, with emphasis on their physical and chemical attributes, effectiveness in food preservation, environmental benefits and future research directions.

Keywords: Agricultural waste, bioactive compounds, biodegradable packaging, nanocellulose, pomegranate peel, rice straw, valorisation

Introduction

The persistent presence of conventional plastic packaging in the environment and its role in global pollution has become a major issue. Increased awareness of sustainability has led to the creation of biodegradable packaging systems using renewable resources. Agricultural residues represent an appealing source of biopolymers (Mohanty *et al.*, 2002; Santhosh *et al.*, 2021; Ali *et al.*, 2024) [2, 24, 33]. Because they are inexpensive, available in abundance, and environmentally friendly. Rice is one of the most produced agricultural by products worldwide. However much of it is burned after harvest, leading to significant air pollution and greenhouse gas emissions (Islam *et al.*, 2022; Ren *et al.*, 2024) [11, 35]. Recently it has been proven to be an excellent source of cellulose and nanocellulose for biodegradable packaging applications. Nanocellulose is known for its high tensile strength, biodegradability, low density, and good barrier properties, making it an effective reinforcing agent in packaging materials. (Klemm *et al.*, 2011; Moon *et al.*, 2011; Perumal *et al.*, 2022) [3, 16, 25]. Pomegranate peel constitutes about one-third to one half of the fruit's weight and is usually discarded during the processing of pomegranate juice (Akhtar *et al.*, 2015; Singh *et al.*, 2018; Ramos *et al.*, 2022) [1, 23, 42]. Despite being considered waste, it contains high levels of polyphenols, tannins, flavonoids, and phenolic acids which have strong antioxidants and antimicrobial activity (Kumar *et al.*, 2022) [18]. Rice straw mainly consists of cellulose, hemicellulose, lignin and silica, with cellulose content typically ranging from 35% to 45%, making it suitable for nanocellulose production. (Islam *et al.*, 2022; Lu and Hsieh, 2012) [11, 22]. Open field burning of rice straw causes environmental pollution and results in the loss of valuable biomass resources. Therefore, the transformation of rice straw into nanocellulose-based materials has attracted considerable scientific attention. (Bangar *et al.*, 2023; Ren *et al.*, 2024) [5, 35]. Common methods used for extracting nanocellulose include alkali treatment, bleaching and acid hydrolysis. Alkali treatment removes hemicellulose and waxes, the bleaching process removes lignin, and cellulose nanocrystals are obtained through sulfuric

acid hydrolysis. Other methods such as enzymatic hydrolysis and ultrasonication have also been studied for their potential to enhance sustainability and reduce usage. (Trache *et al.*, 2017; Lu and Hsieh, 2012; Oun and Rhim, 2016) [6, 22, 30]. Nanocellulose has favourable properties such as high crystallinity, a large surface area, good mechanical properties, and biodegradability. (Klemm *et al.*, 2011; Moon *et al.*, 2011) [16, 25]. The purified BNC free of lignin or hemicellulose is composed of an interwoven network of nanofibers (20-100 nm in diameter) with extremely high properties. These properties allow its incorporation in starch, protein and polysaccharide-based packaging films, which results in enhanced strength and barrier properties. (Rhim *et al.*, 2013; Jadaun *et al.*, 2023) [12, 36]. Nanocellulose based packaging materials are one of the most promising reinforcing agents for biodegradable food packaging. Its high aspect ratio and nanoscale dimensions allow for strong interactions with polymer matrices, resulting in improved tensile strength and film integrity. Research has shown that incorporating nanocellulose into biodegradable films improves their mechanical properties, increases thermal stability, and reduces oxygen permeability. (Rhim *et al.*, 2013; Perumal *et al.*, 2022; Ren *et al.*, 2024) [3, 35, 36]. Additionally, these films are flexible, transparent and environmentally friendly. These advantages make nanocellulose a viable replacement for synthetic packaging materials. (Siracusa *et al.*, 2008; Sharma *et al.*, 2017) [41, 43]. Recent studies have focused on active packaging systems where nanocellulose serves as a carrier for antioxidant and antibacterial compounds in addition to providing structural support. (López-Rubio *et al.*, 2006; Primožič *et al.*, 2021) [21, 32]. These versatile materials are being explored more extensively for their application in food preservation.

Rice straw: In the form of nanocellulose and nanocrystals

Rice straw is a significant agricultural by-product containing approximately 35% to 45% cellulose. The extraction of Rice Straw Nanocellulose (RSNC), usually in the form Cellulose Nanofibers (CNF), offers a sustainable pathway for certainly high value materials. (Lu and Hsieh, 2012; Islam *et al.*, 2022; Ren *et al.*, 2024) [11, 22, 35]. This material can be extracted from agricultural by-products such as rice straw, banana tree, or bagasse. (Johar *et al.*, 2012; Trache *et al.*, 2017) [6]. Rice straw was chosen as the raw material in this study.

Extraction and yield dynamics: to convert raw rice straw into nanocellulose, lignin and hemicellulose must be removed through bleaching and alkaline treatment, which is followed by mechanical or chemical disintegration (Lu and Hsieh, 2012; Trache *et al.*, 2017) [6, 22]. The percentage yield is commonly used to assess the effectiveness of the extraction process. Crystallinity is improved by removing amorphous areas through acid hydrolysis (using H₂SO₄), leading to an increase in the crystallinity index (CrI). (Lu and Hsieh, 2012; Oun and Rhim, 2016) [22, 30]. Crystallinity-index values for rice-straw nanocellulose commonly fall within the range of approximately 65% to 80%, although the exact value depends on the raw material, pretreatment conditions, acid concentration, hydrolysis time, and purification procedure (Islam *et al.*, 2022; Ren *et al.*, 2024) [11, 35].

Effect on mechanical properties and composite composition

Because of its high aspect ratio and large surface area, rice-straw nanocellulose is frequently used as a reinforcing agent in polymer matrices such as polylactic acid, polyvinyl alcohol, and starch (Bangar *et al.*, 2023; Perumal *et al.*, 2022) [3, 5]. Tensile strength can increase through hydrogen bonding and the formation of a continuous or percolating nanocellulose network within the polymer matrix (Moon *et al.*, 2011; Rhim *et al.*, 2013) [25, 36].

The theoretical Young's modulus of a composite can be estimated using the rule of mixtures:

$$E_c = V_f E_f + (1 - V_f) E_m$$

Where E_c is the composite modulus, E_f is the modulus of the nanocellulose reinforcement, E_m is the modulus of the polymer matrix, and V_f is the volume fraction of nanocellulose. The actual modulus may differ from this theoretical value because of fibre orientation, dispersion, interfacial adhesion, defects, moisture content, and processing conditions (Faruk *et al.*, 2012; Thakur and Thakur, 2014) [27, 47].

The reinforcing efficiency of rice-straw cellulose depends strongly on concentration and dispersion. In many biodegradable-film systems, low nanocellulose concentrations can improve tensile strength, whereas excessive concentrations may cause aggregation and reduce mechanical performance (Bangar *et al.*, 2023; Jadaun *et al.*, 2023) [5, 12].

Effect on barrier and thermal properties (WVP): Rice-straw nanocellulose can reduce water-vapour and gas permeability by creating a tortuous pathway through the polymer matrix. This pathway increases the distance that water vapour and gas molecules must travel through the film (Rhim *et al.*, 2013; Perumal *et al.*, 2022) [3, 36]. The magnitude of the improvement depends on nanocellulose content, dispersion, film structure, relative humidity, and the hydrophilicity of the matrix. Nanocellulose can also influence the thermal stability of biodegradable composites. Sulfuric-acid hydrolysis may introduce sulphate groups onto the cellulose surface, which can lower the onset temperature of thermal degradation. At the same time, removal of lignin and hemicellulose can alter the thermal behaviour of the purified cellulose fraction (Trache *et al.*, 2017; Islam *et al.*, 2022) [6, 11]. Reported maximum degradation temperatures vary according to the extraction and testing conditions; therefore, values such as $T_{max} = 320$ °C should be reported only when supported by experimental measurements or a directly comparable study.

Environmental and adsorption effects: Because of its high density of hydroxyl (-OH) groups, RSNC is effective as an adsorbent for dyes and heavy metals in waste treatment.

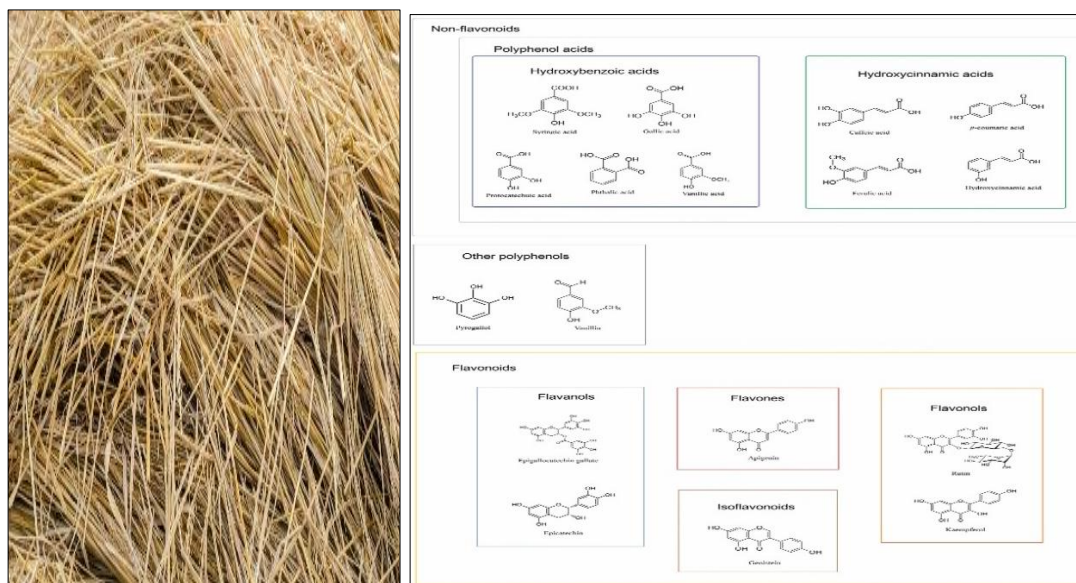
Adsorption capacity: The equilibrium adsorption capacity, denoted as q_e , can be calculated using:

$$q_e = \frac{(C_0 - C_e)V}{W}$$

$$q_e = W(C_0 - C_e)V$$

Where C_0 and C_e are the initial and equilibrium concentrations, respectively, in mg L^{-1} ; V is the

solution volume in LL; and W is the mass of rice-straw nanocellulose in gg



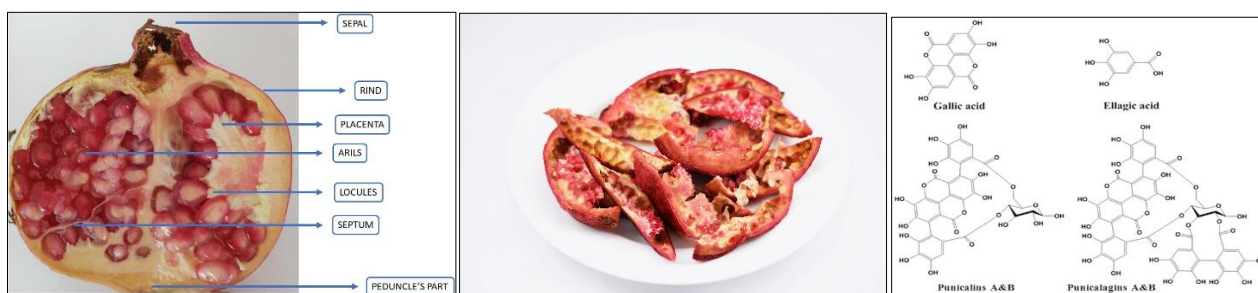
Source: Islam *et al.* (2022) ^[11] <https://DOI.org/10.1016/j.tifs.2022.11.020>

Fig 1: Rice straw and its chemical composition

Pomegranate peel: An important polyphenol source

Pomegranate peel contains various bioactive compounds such as punicalagin, ellagic acid, gallic acid, catechins, and anthocyanins (Singh *et al.*, 2018; Marina Ramos *et al.*, 2022) ^[23, 42]. These compounds are known for their strong anti-inflammatory, antibacterial, antioxidant, and free radical scavenging effects. ((Akhtar *et al.*, 2015) ^[1]. The antioxidant activity of pomegranate peel is typically higher than that of the edible arils. Therefore, it has become a

valuable ingredient in food systems and a natural preservative. (Akhtar *et al.*, 2015; Kumar *et al.*, 2022) ^[1, 18]. Typically, ethanol-water mixtures, methanol, ultrasound-assisted extraction, microwave-assisted extraction, or other eco-friendly extraction methods are used to extract polyphenols. (Akhtar, S.*et al.*, 2015; Loizzo and Silva, 2021) ^[1, 20]. Extraction conditions strongly affect antioxidant capacity and phenolic yield. ((Loizzo and Silva, 2021; Rodrigue z, *et al.*, 2025) ^[20, 37].



Source: (Singh *et al.*, 2018) ^[42]

Fig 2: Structure and composition of pomegranate peel

Polyphenols from pomegranate peels in active packaging

Active packaging is designed to interact with food and its surroundings to improve quality and extend shelf life (Realini and Marcos, 2014; Suneetha *et al.*, 2018; Kopjar *et al.*, 2026) ^[34, 45]. Due to the growing demand for clean-label food preservation, natural polyphenols are increasingly used as active ingredients. Starch, chitosan, gelatine and polylactic acid films have successfully incorporated pomegranate peel extract. (Kumar, N. *et al.*, 2022; Soleimanzadeh *et al.*, 2024) ^[18, 44] These films offer enhanced food preservation, increased antioxidant activity, improved antibacterial properties, and better UV protection. (Suneetha, Jessie *et al.*, 2018) ^[45] Pomegranate peel extract has been found to inhibit common foodborne pathogens like *Staphylococcus aureus* and *Escherichia coli* (Kumar *et al.*, 2022; Singh *et al.*, 2018) ^[18, 42]. The antibacterial action is

mainly due to phenolic compounds that disrupt microbial cell membranes and alter cellular metabolism.

Potential synergy between pomegranate peel polyphenols and rice straw nanocellulose

The combination of pomegranate peel polyphenols with rice straw nanocellulose. The combination of pomegranate peel polyphenols with rice straw nanocellulose offers a unique opportunity to develop versatile active packaging materials. (Dufresne, Alain 2012) ^[12] pomegranate peel polyphenols provide antibacterial and antioxidant properties, while nanocellulose offers structural support. (Anand Babu Perumal 2022, Primožič, *et al.*, 2021) ^[3, 32] Adding polyphenols to nanocellulose-reinforced films can improve:

- Tensile strength
- Oxygen barrier properties

- Antioxidant capacity
- Antimicrobial activity
- Shelf-life extension

Such as dual functional packaging technologies align with the principles of circular bioeconomy by simultaneously utilizing agricultural by products and food processing waste. (López-Rubio, *et al.*, 2006) [21].

Uses for food preservation

Active biodegradable packaging that uses natural bioactive compounds can be used to preserve fruits, vegetables, meat products, dairy items, and baked goods (Appendini, Realini and Marcos, 2014) [34]. Films enhanced with pomegranate peel extract have shown potential in reducing lipid oxidation, inhibiting microbial growth, and preserving sensory quality over time (Kumar *et al.*, 2022; Soleimanzadeh *et al.*, 2024) [18, 44]. The use of nanocellulose improve the durability and barrier performance of the packaging, making it more suitable for commercial food applications (Perumal *et al.*, 2022; Ren *et al.*, 2024) [3, 35].

Possible applications include

- Fresh fruit packaging
- Vegetable packaging
- Meat packaging
- Ready-to-eat foods
- Useful food packaging

Summary of properties

Table 1: Comparative effects of rice straw nanocellulose and pomegranate polyphenols on the functional properties of biodegradable food packaging films

Property	Effect of Rice Straw Nanocellulose	Effect of Pomegranate Polyphenols
Mechanical	Increases Tensile Strength	Plasticizing effect (at high conc.)
Barrier	Lowers Gas Permeability	Minimal effect
Optical	Increases Opacity	UV radiation absorption
Biological	Structural bio-scaffold	Antimicrobial/Antioxidant activity

Conclusion

Overall, rice-straw nanocellulose and pomegranate-peel polyphenols provide complementary functions. Nanocellulose primarily contributes structural and barrier properties, while pomegranate polyphenols provide biological activity. Their combination may therefore support the development of biodegradable active-packaging films based on agricultural and food-processing by-products. Further research should evaluate film formulation, component compatibility, migration behaviour, mechanical performance, barrier properties, antimicrobial activity, antioxidant capacity, biodegradability, and food-contact safety.

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