



Cellulose nanofibers derived from elephant grass incorporating anthocyanin extract from red dragon fruit peel as a natural fish freshness sensor

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ABSTRACT

Background: This study presents the development of cellulose nanofibers (CNF) derived from elephant grass incorporated with anthocyanin extract from red dragon fruit peel as a natural fish-freshness sensor. The research is motivated by the increasing demand for eco-friendly, rapid, and practical freshness-detection technologies to address food-safety challenges associated with fish spoilage. **Methods:** A literature-based Research and Development (R&D) framework was employed to formulate extraction procedures, cellulose purification steps, and CNF–anthocyanin film fabrication. Anthocyanin was extracted using an ethanol–citric acid solvent system, while CNF was produced through deep eutectic solvent (DES) pretreatment, bleaching, and ultrasonic disintegration. **Findings:** The resulting CNF anthocyanin films demonstrated pH-sensitive color transitions associated with volatile nitrogenous compounds released during fish spoilage, indicating their potential application as visual freshness sensors. **Conclusion:** The study concludes that integrating CNF with natural anthocyanins provides a stable, renewable, and environmentally friendly approach suitable for smart packaging applications. **Novelty/Originality of this article:** The novelty of this work lies in the utilization of elephant-grass-derived CNF combined with red dragon fruit peel anthocyanins to create an innovative natural sensor material for monitoring fish freshness.

KEYWORDS: cellulose nanofibers; elephant grass; red dragon fruit peel.

1. Introduction

Fish are one of the primary sources of animal protein for the Indonesian population and play an essential role in national food security (Rahma et al., 2024). According to data from the Kementerian Kelautan dan Perikanan (KKP), national fish consumption increased from 25.07 kg/capita in 2023 to 25.31 kg/capita in 2024. This upward trend reflects the community's strong dependence on fish but also presents potential risks to food quality and safety due to the widespread contamination of microplastics in aquatic environments. Microplastics can transport hazardous chemicals that subsequently accumulate in fish tissues, potentially causing oxidative stress and posing health risks to humans (Senathirajah et al., 2023). Furthermore, reports from the Central Java Provincial Marine and Fisheries Agency (2024) documented cases of fish poisoning resulting from inadequate quality control, while consumers continue to experience difficulties in distinguishing fresh fish from spoiled fish based solely on odor or color.

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These issues stem from the highly perishable nature of fish. Its high water and protein content accelerates chemical and microbiological reactions after harvest, causing rapid deterioration in quality (Tavares et al., 2021). Conventional freshness assessment methods, such as microbiological and chemical analyses, are indeed accurate; however, they are costly, time-consuming, and impractical for direct application in distribution and retail settings (Cheng et al., 2021). Therefore, simple, rapid, and environmentally friendly technological innovations are urgently needed to support consumers and industry stakeholders in verifying fish freshness more effectively.

Globally, the development of smart packaging and intelligent freshness sensors has advanced rapidly and has become a significant trend within the modern food industry. Such technologies enable real-time food quality monitoring through colorimetric or sensory responses without requiring laboratory instruments (Schaefer & Cheung, 2018). Recent reviews have highlighted the widespread application of colorimetric food freshness indicators (CFFI) in high-protein foods, including fish, which produce volatile amines and experience pH shifts as primary indicators of spoilage (Zhai et al., 2025). These innovations are highly relevant for enhancing food safety, improving distribution efficiency, and reducing food loss at the global scale.

In the fisheries sector both in Asia and international markets the need for rapid and practical freshness sensors is becoming increasingly urgent due to the high perishability of fish along the supply chain. Fish products are highly vulnerable to temperature fluctuations, distribution delays, and variations in storage conditions. As a result, colorimetric sensors offer a promising solution for producers, distributors, and consumers (Yang et al., 2025). Sensors capable of detecting volatile amines and pH elevation are widely recognized as the most relevant indicators for assessing fish freshness (Zhai et al., 2025).

Despite the progress in freshness-indicator technologies, most commercially available indicators still rely on synthetic dyes or reagents. While these synthetic indicators provide high stability, they may leave toxic residues, are not always safe for direct food contact, and are non-biodegradable, contributing to environmental burdens (Schaefer & Cheung, 2018). Conversely, natural pigments especially anthocyanins are considered safer alternatives due to their non-toxic nature, pH sensitivity, biodegradability, and antioxidant properties (Zhai et al., 2025). However, these natural pigments often face limitations in stability, particularly when exposed to light, oxidation, and temperature fluctuations. Incorporating natural pigments into biopolymer matrices such as nanocellulose has been identified as an ideal strategy to enhance stability and indicator performance while addressing sustainability concerns.

One promising approach is the use of Cellulose Nano Fiber (CNF) as a base material for pouch-type packaging equipped with natural colorimetric indicators. CNF is a biopolymer with high mechanical strength, large surface area, and excellent barrier properties against water vapor and oxygen, making it an effective matrix for supporting freshness indicators (Xu et al., 2024). Elephant grass is a promising CNF precursor because it contains a high cellulose content of 40.85% (Puspita, 2018) and demonstrates good water resistance, making it a sustainable raw material.

To achieve freshness-sensing functionality, CNF is combined with anthocyanin pigments extracted from red dragon fruit peel. Anthocyanins are natural, water-soluble colorants highly sensitive to pH changes, allowing them to detect volatile compounds released during fish spoilage through easily observable color shifts (Yessica, 2023). Anthocyanin-based indicators are effective in assisting the identification and monitoring of food quality during distribution (Zhao et al., 2022).

However, most previous studies have focused primarily on modifying CNF to enhance mechanical properties or antibacterial activity for packaging applications (Sun et al., 2024) rather than developing CNF–anthocyanin systems as practical fish-freshness sensors. This indicates a research gap in formulating natural-material-based indicators that are both functional and sustainable. Therefore, the novelty of the present study lies in the utilization of CNF derived from elephant grass combined with red dragon fruit peel anthocyanins as a freshness indicator in a user-friendly and environmentally friendly pouch format.

The development of CNF–anthocyanin-based packaging offers a relevant solution to current food safety and sustainability challenges. This innovation provides a rapid, practical, and eco-friendly method for assessing fish freshness while contributing to plastic waste reduction through the use of natural materials. This sensor technology is expected to enhance consumer protection, improve the quality of fishery products, and support the achievement of Sustainable Development Goal (SDG) 12 on responsible consumption and production.

The objective of this study is to develop a CNF pouch combined with anthocyanin as a responsive, effective, and stable indicator of fish freshness during storage. Conceptually, it is hypothesized that the intensity of the color response in the CNF–anthocyanin material will increase proportionally to the concentration of volatile basic compounds generated as fish freshness declines.

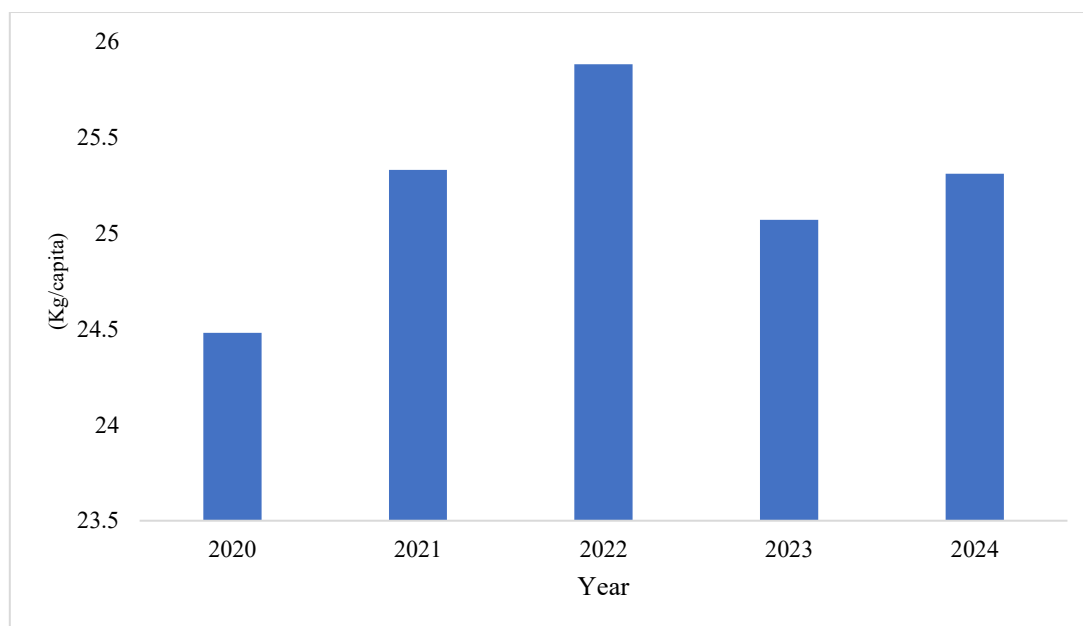


Fig. 1. Fish Consumption of the Community by Year (Kg/capita)
(Kementerian Kelautan dan Perikanan Republik Indonesia, 2024)

2. Methods

2.1 Research design

This study employed a Research and Development (R&D) approach to develop an intelligent packaging system based on Cellulose Nano Fiber (CNF) and anthocyanin for fish freshness detection. According to Waruwu (2024), R&D is a systematic method aimed at producing innovative products through sequential stages ranging from literature review, design, experimentation, and validation. This approach was selected because the development of a smart packaging system requires the integration of material engineering, extraction technology, and chemical characterization to ensure that the resulting product is not only theoretically feasible but also functionally applicable.

The initial phase of the study focused on identifying the requirements for a rapid, visually observable, and environmentally friendly freshness indicator. Fish spoilage occurs rapidly due to proteolytic reactions and microbial activity that produce volatile basic compounds such as ammonia and trimethylamine. These compounds increase the pH level of fish tissue, thereby creating the need for a pH-responsive indicator capable of providing visual color changes during spoilage.

A comprehensive literature review was conducted to examine anthocyanin extraction techniques, cellulose delignification and purification methods, and nanocellulose-based film

fabrication. The review incorporated studies from natural product chemistry, food technology, and recent developments in sustainable smart packaging systems. Based on the reviewed literature, the anthocyanin extraction procedure adopted in this study followed the method proposed by Meganingtyas and Alauhdin (2021), while the production of CNF was adapted from Deep Eutectic Solvent (DES)-based techniques developed by Sun et al. (2024). These methods were selected due to their efficiency, environmental compatibility, and ability to preserve the stability of active compounds essential for intelligent packaging applications

2.2 Anthocyanin extraction and characterization

The first experimental stage involved the extraction of anthocyanins from red dragon fruit peel, which served as the primary chromatic indicator in the freshness sensor system. The fruit peel was air-dried for one week in a shaded environment to minimize pigment degradation caused by ultraviolet exposure. Natural drying was preferred over high-temperature drying techniques because it better preserves anthocyanin stability. The dried material was then ground into fine powder to increase the contact surface area between the material and solvent during extraction.

Anthocyanin extraction was conducted through a 24-hour maceration process using a material-to-solvent ratio of 1:5 (w/v). Three solvent systems were evaluated: (1) distilled water, (2) distilled water–citric acid 10% (5:1, v/v), and (3) ethanol 96%–citric acid 10% (5:1, v/v). Previous studies reported that ethanol–citric acid provides superior extraction efficiency and color stability because ethanol effectively dissolves polar and semi-polar pigments, while citric acid maintains acidic conditions that stabilize anthocyanin structures.

The resulting filtrate was concentrated using a rotary vacuum evaporator at 40°C to remove solvents while preventing thermal degradation of the pigments. The concentrated extract was subsequently partitioned using an ethyl acetate–water system (1:1) to eliminate non-polar impurities and enrich the anthocyanin fraction. The aqueous layer was then evaporated to obtain purified anthocyanin extract, which was stored in amber vials under refrigerated conditions to minimize oxidation. Anthocyanin presence was confirmed through qualitative flavonoid testing using hot ethanol, 2 M HCl, and magnesium ribbon, which generated characteristic color changes indicating flavonoid compounds. Further characterization was conducted using Fourier Transform Infrared (FT-IR) spectroscopy and UV-Visible spectroscopy. FT-IR analysis identified functional groups including O–H stretching, aliphatic C–H, carbonyl C=O, aromatic C=C, and C–O vibrations, all characteristic of anthocyanin structures. UV-Vis analysis demonstrated a maximum absorbance at 498.6 nm, which is typical of betacyanin-type anthocyanins found in red dragon fruit peel. Stability testing showed that the ethanol–citric acid extract exhibited the highest resistance to degradation, making it suitable as a pH-responsive indicator for intelligent packaging applications.

2.3 Preparation of cellulose nanofiber (CNF) and film fabrication

The subsequent stage involved the production of Cellulose Nano Fiber (CNF) from elephant grass as the primary film matrix. This stage consisted of DES synthesis, cellulose extraction and purification, and film fabrication. Two types of Deep Eutectic Solvents (DES) were synthesized. DES-1 was prepared by heating a mixture of choline chloride and glycerol (1:2) at 90°C for 60 minutes until a homogeneous solution was formed. DES-2 was synthesized from choline chloride and oxalic acid dihydrate (1:1) at 60°C for 60 minutes. Both DES systems functioned as environmentally friendly solvents capable of selectively dissolving lignin and hemicellulose while preserving cellulose structures.

Dried elephant grass (1 g) was treated with 20 g of DES-1 at 140°C for 30 minutes to initiate lignocellulosic breakdown. A solid acid catalyst, SC-SO₃H (0.3 g), was added to enhance delignification, and the mixture was stirred for 3 hours. After cooling, a 1,4-dioxane–water mixture (4:1) was added to a total volume of 50 mL, followed by decantation

to separate the catalyst. Filtration produced a pale-yellow cellulose fraction, which was subsequently bleached using 7% NaClO₂ at 90°C for 4 hours. The material was washed with deionized water and dried at 60°C for 24 hours, resulting in white cellulose fibers. Further purification was performed using DES-2 in a 1:1 mass ratio at 80°C for 3 hours, producing purified cellulose after filtration and drying.

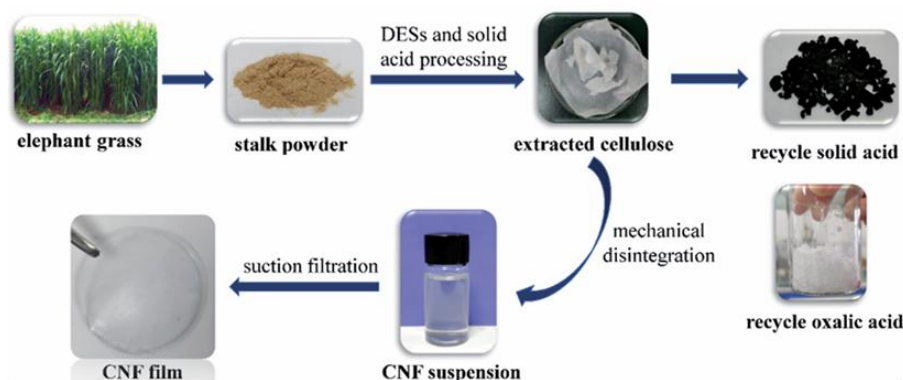


Fig. 2. Schematic illustration for the production of CNFs and films from elephant grass. (Wu et al., 2024)

The final stage involved the fabrication of anthocyanin-loaded CNF film. Purified cellulose (2 g) was dispersed in 80 mL of deionized water, followed by the addition of 2 mL anthocyanin extract. The mixture underwent probe ultrasonication for 3 hours at 4°C to produce a CNF suspension with a concentration of 0.025 wt% while preventing pigment degradation caused by heat. The suspension was vacuum-filtered through a 0.22 mm cellulose ester membrane and dried between filter paper and glass plates for 12 hours. The resulting CNF film, with a thickness of 43.2 μ m, functioned as the base material for the SINARA pouch and demonstrated visible color changes in response to pH variations associated with fish spoilage.

The selection of Deep Eutectic Solvents (DES) as the pretreatment strategy was based on several advantages reported in the literature. Compared with conventional methods such as acid hydrolysis, alkalization, steam explosion, TEMPO-mediated oxidation, and ozonation, DES offers lower toxicity, reduced chemical waste generation, and milder operating conditions. According to Li et al. (2023), DES selectively removes lignin and hemicellulose without causing excessive cellulose depolymerization. DES is also recyclable, energy-efficient, and compatible with green chemistry principles, making it highly suitable for food-related applications. Furthermore, DES pretreatment produces cellulose with higher crystallinity, lighter color, and improved yield while reducing the energy requirements associated with mechanical fibrillation processes. Therefore, DES represents a superior and sustainable approach for nanocellulose production in intelligent packaging systems.

3. Results and Discussion

3.1 Results of anthocyanin extraction from dragon fruit peel

The anthocyanin extraction process in this study was formulated based on the method reported by Meganingtyas and Alauhdin (2021), who successfully obtained a concentrated extract from red dragon fruit peel with high flavonoid, particularly anthocyanin, content. The resulting extract exhibited a purplish-red coloration, which is a typical visual characteristic of anthocyanin-rich extracts and indicates the predominance of flavylum cation structures under acidic conditions. Similar color characteristics of dragon fruit peel anthocyanin extracts have also been reported in previous studies, confirming the reliability of this pigment source for pH-responsive applications (Hidayat et al., 2022).

The effectiveness of acidified ethanol as an extraction solvent has been widely reported in the literature. Acidic conditions facilitate partial disruption of plant cell walls and membranes, promoting the release of intracellular pigments into the solvent phase while maintaining anthocyanin stability (Meganingtyas & Alauhdin, 2021). Lestari et al. (2022) further demonstrated that acidified solvents improve extraction yield and color intensity compared to neutral solvents, as anthocyanins are more stable in acidic environments. The maximum absorption wavelength of the extracted pigment, reported at approximately 498.6 nm, is consistent with the typical UV-Vis absorption range of anthocyanins derived from dragon fruit peel and other red-pigmented plant sources.

Anthocyanins are well known for their pH-sensitive color behavior, which arises from reversible structural transformations of their molecular forms. Under acidic conditions, anthocyanins predominantly exist as red flavylium cations, whereas increasing pH leads to the formation of quinonoidal bases and chalcone structures, resulting in purple, blue, and yellow color transitions (Zhao et al., 2022). This distinct and gradual color change makes anthocyanins highly suitable as visual indicators for monitoring food freshness, particularly in fish products where spoilage is associated with the release of volatile basic compounds such as ammonia and trimethylamine (Franceschelli et al., 2021).

Several studies have confirmed the applicability of dragon fruit peel anthocyanins for intelligent packaging systems. Hidayat et al. (2022) reported that films incorporating dragon fruit peel anthocyanins exhibited clear and easily distinguishable color changes during fish storage, enabling consumers to visually assess freshness. Similarly, Lestari et al. (2022) demonstrated that pH-sensitive films containing dragon fruit peel extract showed stable color responses over a wide pH range, highlighting their potential for real-time freshness monitoring.

Despite these advantages, free anthocyanin extracts are inherently sensitive to environmental factors such as light exposure, oxygen, temperature, and alkaline conditions, which can accelerate pigment degradation and reduce color intensity over time (Utama et al., 2018). Variations in fruit maturity and peel composition may also influence anthocyanin yield and stability. These limitations emphasize the importance of immobilizing anthocyanins within a protective matrix to enhance their durability and functional performance. Therefore, incorporation of anthocyanins into cellulose nanofiber matrices is proposed as an effective strategy to improve pigment stability while preserving pH responsiveness, as discussed in the following sections.

3.2 Results of CNF extraction from elephant grass

The production process of CNF from elephant grass exhibited clear physical changes at each treatment stage. After pretreatment using DES-1, the fiber structure began to experience lignin and hemicellulose removal, indicated by a darker color and a visibly swollen fiber morphology, consistent with the cell-wall softening mechanism in lignocellulosic biomass reported by Wu et al. (2021). This swelling behavior indicates enhanced penetration of the deep eutectic solvent into the plant cell wall matrix, leading to the partial disruption of intermolecular hydrogen bonding and weakening of lignin-carbohydrate complexes. Similar effects have been reported for DES-based pretreatments on various lignocellulosic biomasses, where solvent acidity and hydrogen bond donor-acceptor interactions play a crucial role in cell wall deconstruction (Abbott et al., 2011; Francisco et al., 2013).

The effectiveness of DES pretreatment is strongly associated with its selective dissolution capability toward amorphous components such as hemicellulose and lignin, while largely preserving the crystalline cellulose domains. According to Francisco et al. (2013), the tunable polarity and acidity of DES systems enhance fractionation efficiency without excessively degrading cellulose, making them suitable for sustainable nanocellulose production. In the present context, such selective removal facilitates fibril separation during subsequent mechanical treatments. During the bleaching stage, the material became visibly whiter and cleaner; FTIR analysis in the study by Yuan et al. (2024)

confirmed the effectiveness of this step by showing reduced intensities of aromatic lignin absorption bands, indicating successful delignification. Efficient lignin removal at this stage is critical because residual lignin can act as a physical barrier, preventing complete fiber fibrillation and reducing the homogeneity of cellulose nanofibrils (Siró & Plackett, 2010). Moreover, lignin residues may adversely affect the optical properties of CNF films, resulting in lower transparency and uneven surface morphology, which are undesirable for advanced packaging and sensor applications (Xu et al., 2024).

Subsequent treatment with DES-2 followed by ultrasonic disintegration produced finer and more homogeneous fibrils. Wu et al. (2021) reported that a similar combination of DES treatment and ultrasonic processing yielded nanofibrils with diameters in the range of 2–6 nm and a loosely entangled network morphology. Ultrasonication promotes nanofibril separation through cavitation-induced shear forces, which further disrupt interfibrillar hydrogen bonds and reduce agglomeration (Siró & Plackett, 2010). This mechanical disintegration step is particularly effective when combined with chemical pretreatments such as DES, which pre-soften the fiber structure and lower energy requirements compared to purely mechanical processes.

Comparable results have been reported in studies employing aluminum chloride-based DES systems, where elephant-grass-derived CNF exhibited an average nanofibril width of approximately 5.15 nm and a high crystallinity index of about 85.3% (Yuan et al., 2023). High crystallinity is a desirable characteristic, as it correlates with improved tensile strength, thermal stability, and moisture resistance of CNF-based films (Xu et al., 2024). These properties are especially relevant for packaging films and smart indicator substrates, where mechanical integrity and environmental stability are essential. The cellulose yield obtained from elephant grass through the applied extraction sequence was found to be within a competitive range. Wu et al. (2021) reported a cellulose yield of approximately 25.1%, demonstrating the effectiveness of combining DES pretreatment with solid acid catalysts to remove non-cellulosic components. This value is consistent with Yuan et al. (2024), who showed that the cellulose content of elephant grass can reach around 27.4%, depending on harvesting time and growth conditions.

Such yield values are comparable to or even higher than those reported for other agricultural residues, including rice straw and sugarcane bagasse, suggesting that elephant grass represents a promising low-cost and renewable feedstock for CNF production (Rantong et al., 2020). In addition to yield considerations, the physical characteristics of the resulting CNF indicate suitability for film-fabrication applications. The nanofibrils produced exhibited lengths of approximately 800–1000 nm and widths within the nanometer scale, as reported by Wu et al. (2021), forming interconnected fibrillar networks. The prepared CNF films appeared translucent to opalescent with smooth surface textures and uniform fibril distribution. Such optical and morphological characteristics are advantageous for applications requiring visual clarity, including intelligent packaging systems, where transparency is necessary to enable effective colorimetric signal observation (Xu et al., 2024).

Recent studies have further demonstrated that DES-treated CNF exhibits enhanced dispersion stability and reduced fibril aggregation, attributed to the introduction of surface charges and increased surface accessibility (Wu et al., 2024). Improved dispersion stability facilitates homogeneous film formation and consistent physicochemical properties across the material. However, it should be noted that variations in cultivation conditions, plant maturity, and pretreatment parameters can significantly influence lignocellulosic composition and, consequently, CNF yield and quality (Sun et al., 2024). Therefore, careful optimization of extraction conditions is necessary for achieving reproducible material performance at an industrial scale. Overall, the observed physical transformations, favorable cellulose yield, high crystallinity index, and nanoscale fibril dimensions collectively indicate that elephant grass is a viable and effective raw material for the sustainable production of high-quality CNF suitable for advanced film-based applications.

3.3 Characterization of CNF–anthocyanin films

Characterization of CNF–anthocyanin films is a crucial step in evaluating their suitability as intelligent packaging materials, as both structural integrity and functional responsiveness determine sensor performance. The incorporation of natural pigments into biopolymer matrices has been widely explored due to the ability of such systems to provide visible indicators of food quality changes. Among various pigments, anthocyanins have attracted significant interest because of their pH-sensitive color behavior and compatibility with biodegradable polymer matrices.

Several studies have demonstrated the effectiveness of anthocyanin-based films as freshness indicators. Safitri et al. (2023) reported that starch/cellulose/anthocyanin indicator films were capable of responding to ammonia vapor released during food spoilage. Utama et al. (2020) further showed that the stability of color in anthocyanin-based biodegradable films is influenced by thermal processing, highlighting the importance of processing conditions in sensor reliability. Reinforcement of polymer matrices using cellulose nanofibrils has also been shown to improve mechanical properties while maintaining functional responsiveness, as demonstrated by Chen et al. (2021).

Recent developments have focused on improving the practical applicability of pigment-based indicator films under real packaging environments. Cai et al. (2025) reported that hydrophobic cellulose composite films functionalized with anthocyanins exhibited clearer color transitions and improved performance in monitoring beef freshness. Collectively, these studies indicate that CNF–anthocyanin composite films possess considerable potential for intelligent packaging applications. Therefore, characterization of mechanical, optical, and pH-responsive properties is essential to assess the performance of CNF–anthocyanin films developed in this study.

3.3.1 Mechanical properties

Mechanical properties are critical parameters in determining the suitability of CNF anthocyanin films for intelligent packaging applications, as packaging materials must withstand mechanical stress during handling, transportation, and storage. The incorporation of cellulose nanofibrils into polymer matrices is widely reported to improve tensile strength and flexibility through the formation of dense hydrogen-bonding networks among nanofibers (Siró & Plackett, 2010). Chen et al. (2021) demonstrated that CNF-reinforced films exhibited enhanced mechanical performance while maintaining functional responsiveness, highlighting the reinforcing role of CNF at the nanoscale.

In CNF–anthocyanin composite films, mechanical performance is influenced by the balance between nanofibril reinforcement and pigment incorporation. Excessive anthocyanin loading may disrupt the continuity of the CNF network and reduce stress transfer efficiency, whereas insufficient pigment content can limit sensor visibility. Therefore, optimization of CNF content and anthocyanin concentration is essential to achieve films that exhibit both adequate mechanical integrity and effective sensing functionality.

3.3.2 Optical and color response properties

Optical properties play a crucial role in the effectiveness of intelligent packaging films, as color changes must be clearly visible and easily interpreted by consumers. Anthocyanins are widely recognized for their strong chromatic response and visible color transitions resulting from structural changes in different environmental conditions, particularly pH variations (Castañeda-Ovando et al., 2009). Previous studies have emphasized that homogeneous pigment distribution within polymer matrices is necessary to ensure consistent color development and minimize visual irregularities.

The incorporation of anthocyanins into a CNF matrix can improve color uniformity due to the high surface area and interconnected nanofibrillar structure of CNF. Cai et al. (2025)

reported that cellulose-based films with well-dispersed anthocyanins exhibited clearer and more distinguishable color transitions during food spoilage monitoring. Furthermore, appropriate control of film thickness and CNF concentration is important to balance transparency and color intensity, ensuring reliable visual detection in practical packaging applications.

3.3.3 pH Sensitivity and freshness indication performance

The pH-responsive behavior of anthocyanins is the primary mechanism enabling CNF–anthocyanin films to function as freshness indicators. Anthocyanins undergo reversible molecular transformations under different pH conditions, resulting in distinct and visually observable color changes (Castañeda-Ovando et al., 2009). This characteristic makes anthocyanins suitable for monitoring food spoilage processes that involve the release of volatile basic compounds.

Several studies have demonstrated the effectiveness of anthocyanin-based films in responding to spoilage-related pH changes. Safitri et al. (2023) showed that anthocyanin-containing films exhibited a clear response to ammonia vapor generated during food deterioration. The presence of CNF in the composite film contributes to enhanced structural stability and limits pigment migration, thereby supporting consistent color response over time. These properties indicate that CNF–anthocyanin films possess strong potential as biodegradable and consumer-friendly freshness indicators for intelligent food packaging systems.

3.4 Results of fish freshness sensor testing

Anthocyanin extract from red dragon fruit peel incorporated into a cellulose nanofiber (CNF) matrix exhibits characteristic pH-dependent color changes corresponding to the flavylium structure of anthocyanins (Prमितasari et al., 2022). Under highly acidic conditions, the indicator appears red to pink; near neutral pH it shifts to purple; and under alkaline conditions it transitions toward blue/green or becomes faded (Hidayat et al., 2022). This consistent color variation within the pH range of 1–11 enables CNF–anthocyanin films to function as clear visual pH indicators, allowing the development of pH–color reference charts (Lestari et al., 2022). This behavior aligns with previous studies evaluating the pH-sensitive characteristics of anthocyanins and the application of dragon fruit peel anthocyanins as indicator dyes (Arghavani et al., 2023).

Previous research has demonstrated that although dragon fruit peel anthocyanins serve as effective pH indicators, the performance of the resulting films depends greatly on the matrix used. Prमितasari et al. (2022) reported that cassava starch–chitosan films displayed distinct color transitions from red to purple and then blue-green as pH increased, making them suitable for monitoring shrimp freshness. However, their mechanical properties were limited, and color stability declined during storage. Similarly, Azlim et al. (2021), who used gelatin as the matrix, observed comparable color-change behavior, but anthocyanin degradation occurred more rapidly under alkaline conditions, leading to reduced long-term stability. These findings indicate that while anthocyanins possess excellent pH sensitivity, simple biopolymer matrices still lack the mechanical strength and pigment stability required for reliable indicator films.

Studies using cellulose nanofiber-based matrices have shown substantially improved performance. Arghavani et al. (2023) found that incorporating anthocyanins into bacterial cellulose nanofibers resulted in films with enhanced pigment retention and minimal color migration. This improvement is attributed to the high surface area of the nanofiber network, which promotes stronger and more stable interactions with anthocyanins. Supporting this, Wagh et al. (2023) reported that CNF increases the mechanical strength of the films, maintains homogeneous pigment distribution, and improves resistance to moisture and light. These results confirm that BCNF and CNF matrices outperform starch or gelatin in terms of stability, color intensity, and durability.

Further strengthening these observations, Remedio et al. (2024) explained that anthocyanin stability is highly dependent on anthocyanin–polymer interactions. Polymers with dense structures and high mechanical integrity, such as cellulose nanofibers, are more capable of reducing pigment degradation caused by light, oxygen, and alkaline pH. This highlights the importance of selecting an appropriate matrix for smart packaging and food-freshness sensor applications. Therefore, using cellulose nanofiber (CNF) as a matrix for immobilizing anthocyanins from red dragon fruit peel is considered the most optimal approach for creating stable, sensitive, and durable fish-freshness sensors.

The stability of anthocyanins within the CNF matrix is further influenced by environmental factors such as light, oxygen, temperature, and pH. According to Khoo et al. (2017), the flavylium structure that is stable under acidic conditions can transform into carbinol or quinoidal base forms at higher pH levels, resulting in pigment fading or a shift toward blue-green coloration. In addition, Liu et al. (2018) reported that anthocyanins are highly susceptible to oxidative degradation upon exposure to oxygen and light, necessitating the use of matrices with strong barrier properties. The dense fibrillar structure of CNF can reduce oxygen and light permeability, thereby preserving pigment intensity for a longer period compared with conventional biopolymers. Oliveira et al. (2020) further emphasized that anthocyanin stability can be enhanced through hydrogen bonding interactions with polymers possessing a highly compact network, such as cellulose nanofibers.

In the broader context of smart packaging development, anthocyanin-based indicators have been widely utilized to monitor pH changes caused by volatile basic compounds produced during spoilage of perishable foods. Yin et al. (2021) noted that anthocyanin-based films provide strong color responsiveness, though their long-term applicability is highly dependent on matrix mechanical strength, stability, and water resistance. Meanwhile, Prietto et al. (2017) demonstrated that although chitosan–anthocyanin films effectively respond to pH variations, their pigment stability during storage remains a significant limitation. Incorporating anthocyanins into CNF matrices addresses these challenges by enhancing mechanical properties, improving pigment protection, and slowing degradation. Thus, CNF–anthocyanin films offer improved sensitivity and accuracy for freshness detection, making CNF a highly promising material for next-generation smart food packaging systems.

3.5 Challenges and future perspectives

Despite the promising results demonstrated in the preparation and application of anthocyanin–CNF composite films, several challenges remain before practical implementation and large-scale commercialization can be achieved. One of the major challenges originates from the inherent variability of natural raw materials used in the fabrication of CNF- and anthocyanin-based films (Sun et al., 2024). Elephant grass–derived cellulose nanofibers are influenced by plant maturity, cultivation conditions, and harvesting time, which can lead to variations in fiber morphology and crystallinity (Yuan et al., 2024). Similarly, the anthocyanin concentration and color intensity obtained from dragon fruit peel extracts may vary depending on cultivar differences and post-harvest handling methods (Castañeda-Ovando et al., 2009). Such variability can result in inconsistent film properties and reduced reproducibility of sensor performance.

Another important challenge concerns the long-term stability of anthocyanins incorporated within the CNF matrix (Yousuf et al., 2022). Although CNF provides a hydrophilic network capable of immobilizing pigment molecules, anthocyanins remain sensitive to environmental factors such as light, temperature, oxygen, and moisture (Castañeda-Ovando et al., 2009). Prolonged exposure to these conditions may lead to pigment degradation, color fading, and reduced pH responsiveness over time. From a processing perspective, scalability of CNF production remains a key limitation for industrial application (Wu et al., 2021). In addition, mechanical and ultrasonic disintegration

processes require relatively high energy input, which may limit economic feasibility at larger production scales (Francisco et al., 2013).

The functional performance of anthocyanin–CNF films under real packaging conditions also requires further investigation. Mechanical stress during handling and transportation can compromise film integrity and lead to microstructural damage (Siró & Plackett, 2010). Exposure to high humidity environments may accelerate moisture absorption and pigment migration, thereby decreasing sensor accuracy (Xu et al., 2024). Despite these challenges, anthocyanin–CNF composite films show strong potential for application in intelligent food packaging systems. The incorporation of calibrated color reference scales onto CNF films has been proposed as an effective strategy to improve visual interpretation and reduce subjectivity in freshness assessment (Yousuf et al., 2022).

Furthermore, multifunctional smart packaging systems that combine pH-sensitive films with gas-responsive sensors may enhance spoilage detection accuracy in protein-rich foods (Sun et al., 2024). Advances in digital sensing technologies further broaden the application scope of anthocyanin–CNF systems. Integration with smartphone-based image analysis has been reported to improve signal reliability and enable real-time monitoring across the food supply chain (Wu et al., 2024). Overall, although challenges related to material variability, pigment stability, and process scalability persist, continued interdisciplinary research and system optimization are expected to support the development of anthocyanin–CNF composite films toward commercially viable intelligent packaging applications.

4. Conclusions

This study successfully demonstrated the potential of dragon fruit peel-derived anthocyanins and elephant grass-derived cellulose nanofibrils (CNF) as sustainable components for intelligent food packaging applications. Anthocyanin extraction using acidified ethanol produced a pigment with characteristic color properties and pH-sensitive behavior, confirming its suitability as a natural indicator material. Meanwhile, CNF extracted from elephant grass through a deep eutectic solvent (DES)-assisted process exhibited nanoscale fibril dimensions and favorable structural characteristics, supporting its function as a reinforcing biopolymer matrix.

The integration of anthocyanins into the CNF matrix resulted in composite films with promising mechanical stability, optical clarity, and functional responsiveness. CNF played a key role in enhancing film integrity and pigment dispersion, which contributed to uniform color distribution and consistent visual response. The fabricated CNF–anthocyanin films exhibited distinct pH-dependent color changes, indicating their ability to function as freshness indicators by responding to spoilage-related environmental changes such as the release of volatile basic compounds.

Overall, the findings highlight the feasibility of utilizing agricultural and food-processing waste as value-added materials for biodegradable and intelligent packaging systems. The combination of natural pigments and nanocellulose from renewable resources offers an environmentally friendly alternative to conventional synthetic indicators. Future research should focus on improving long-term stability, scaling up film production, and evaluating real-food packaging performance to further enhance the practical application of CNF–anthocyanin films in commercial intelligent packaging.

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Author Contribution

The authors contributed to the data acquisition, analysis, and interpretation in this study. Conceptualization: Deuriya R. Rahma A.; Methodology: Rahma A.; Data Curation: ; Writing –Original Draft Preparation: Deuriya R. Rahma A. Aurelia G.; Writing –Review & Editing: Rahma A. Deuriya R. Aurelia G.

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During the preparation of this work, the author(s) used Chat GPT to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and took full responsibility for the content of the publication.

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