Preparation of a Bio-Based Coating Film Incorporation Nanocellulose and Carbon Dots for Extending Fruit Shelf Life

Piyatida Piachuad and Jidapha Tinoi
Division of Biochemistry and Biochemical Innovation, Department of Chemistry, Faculty of Science, Chiang Mai University, Thailand ; Corresponding author : jidapha.t@cmu.ac.th

Abstract

This research focuses on the preparation of a bio-based gel film for fruit packaging by incorporating nanocellulose and carbon dots (CDs) to enhance shelf life and reduce spoilage during transportation using eco-friendly natural materials. Nanocellulose was produced from sugarcane using enzymatic hydrolysis under certain conditions. The results showed that the granular nanocellulose was obtained approximately 40.70% yield and had a particle size of 320–450 nm with a polydispersity index (PDI) of 0.42, and a zeta potential of -35.2 mV. In addition, carbon dots were synthesized by a microwave digestion process using citric acid and urea as precursors. Negative-charged carbon dots were prepared, exhibiting particle size distributions in the ranges of 1–100 nm and 100–560 nm, with a PDI of 0.367 and a zeta potential of –46.60 mV. These results indicated that granular nanocellulose and carbon dots could be combined to formulate the coating film for extending fruit shelf life. The results demonstrated that the bio-based coating film derived from granular nanocellulose and carbon dots has potential as a protective wrap for preserving fruit freshness.

Introduction

Amidst the global environmental crisis and rising demand for sustainable materials, the massive surplus of sugarcane bagasse 50-100 million tons/year and significant fruit waste 27 million tons/year due to short shelf life have driven the development of nano-composite coating films. This innovation utilizes sugarcane bagasse, composed of cellulose 37.2%, lignin 26.5%, and hemicellulose 22.1% (Figure 1), which undergoes biomass pretreatment to extract nanocellulose (e.g., CNCs and CNFs).

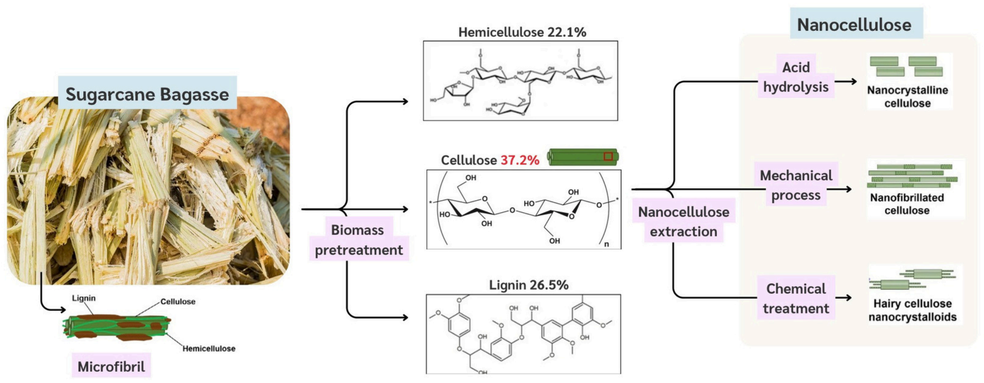


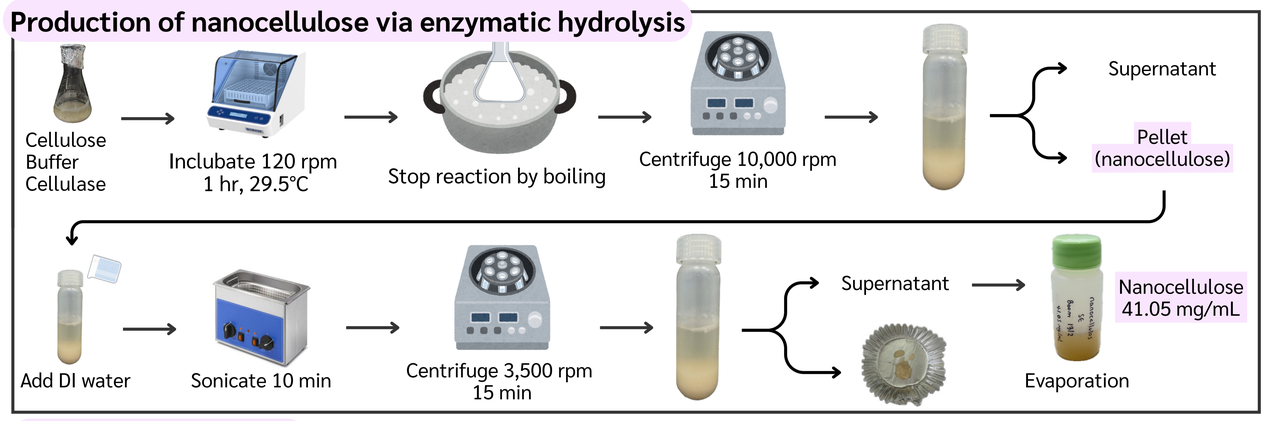
Figure 1. Sugarcane bagasse composition and nanocellulose production

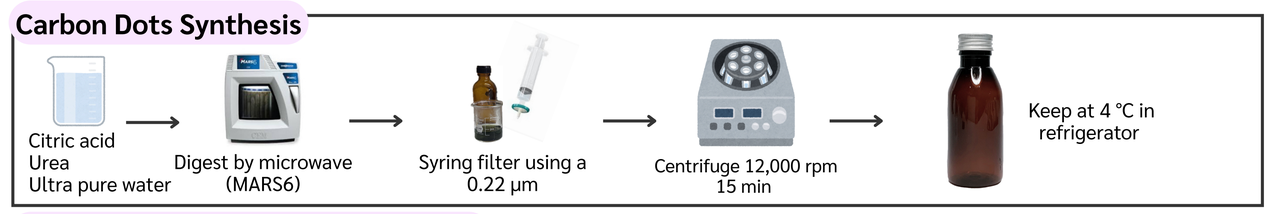
These materials offer superior mechanical properties and biocompatibility. By integrating photoluminescent Carbon Dots (CDs), the films achieve active packaging capabilities, providing potent antioxidant and antimicrobial activities. This research represents a synergistic integration of nanotechnology and bio-based materials to create low-toxicity, cost-effective, and eco-friendly smart packaging that extends food shelf life and promotes a circular economy.

Objectives

1. To produce and characterize granular nanocellulose (GNC) from sugarcane bagasse via enzymatic hydrolysis
2. To synthesize negative-charged carbon dots (CDs) via microwave digestion using citric acid and urea as precursors
3. To develop and evaluate a bio-based coating film incorporating GNC and CDs for enhancing antibacterial activity and fruit shelf life

Methodology





Results and Discussion

The nanocellulose was successfully produced from sugarcane using enzymatic hydrolysis, achieving a yield of approximately 40.70%. Figure 2 show DLS analysis revealed that the synthesized nanocellulose particles had a diameter ranging from 220 to 458 nm with a Zeta potential of -35.2 mV (PDI = 0.42), indicating good stability. In comparison, the carbon dots (CDs) were significantly smaller, ranging from 28 to 396 nm with a high negative surface charge of -46.6 mV (PDI = 0.367).

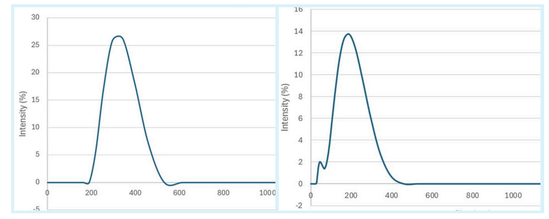


Figure 2. The particle size distribution of GNC and carbon dots particles.

This high surface charge is crucial as it prevents aggregation and ensures even distribution within the film matrix. To further characterize the chemical properties, the UV-Vis absorption spectrum of the CDs was analyzed. Figure 3 show distinct absorption peaks at 240 nm, corresponding to the π to π^* transition of aromatic C=C bonds, and 332 nm, representing the $n \rightarrow \pi^*$ transition of C=O surface functional groups. These oxygen-containing groups are vital as they facilitate the formation of hydrogen bonds with the nanocellulose matrix. Examination of the photoluminescence properties revealed a characteristic excitation-dependent emission. The CDs emit a strong blue light under a 365 nm UV lamp(Figure 4), with a maximum emission peak at 432 nm shown in Figure 5. This behavior is primarily attributed to the distribution of different surface states and functional groups on the carbon core, and the intense blue fluorescence confirms that the CDs possess the high optical sensitivity required for functional applications.

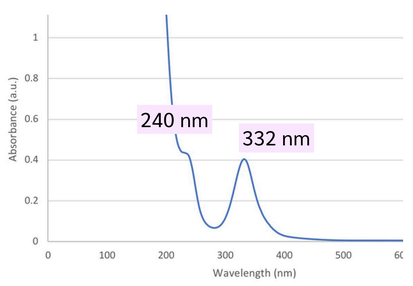


Figure 3. UV-vis absorption spectrum

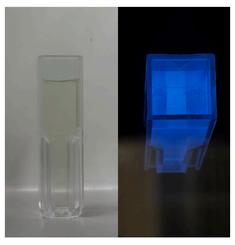


Figure 4. Photographs of CDs under daylight and a UV lamp.

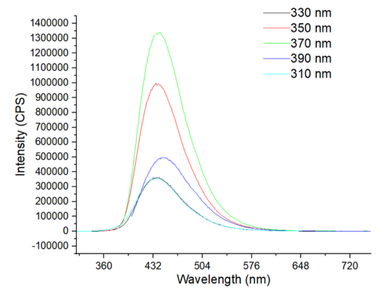


Figure 5. Fluorescence emission spectra

Finally, the antimicrobial activity was evaluated at 18 hours, where the synthesized CDs demonstrated significant antibacterial effectiveness. A high zone of inhibition of 35.27 mm was observed against *S. aureus* (Gram-positive) and 9.56 mm against *P. aeruginosa* (Gram-negative). The higher effectiveness against Gram-positive bacteria is due to the more complex cell wall structure of Gram-negative strains; regardless, these results prove that our CDs can effectively inhibit spoilage-causing bacteria.

Conclusion

- The Nanocellulose particles exhibited a size range of 220–458 nm with a PDI of 0.42 and a zeta potential of -35.2 mV.
- The Carbon Dots (CDs) displayed a smaller size distribution ranging from 28–396 nm, a PDI of 0.367, and a more negative zeta potential of -46.6 mV.
- UV-vis absorption spectra showed distinct peaks at 240 nm (representing C=C bonds) and 332 nm (representing C=O surface functional groups).
- The CDs demonstrated excitation-dependent emission with a maximum fluorescence intensity at 432 nm, emitting a blue light under UV (365 nm).
- The synthesized CDs showed significant antibacterial performance against both Gram-positive and Gram-negative bacteria.

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