# ABSTRACT

The objectives of the research work are to explore the unique properties of nanocellulose from fruit waste like banana rachis and pineapple peel, such as high specific surface area, mechanical strength, biodegradability, and sustainability, while analyzing its diverse applications in food, including emulsion stabilizers, hydrogels and aerogels. The study seeks to characterize and optimize cellulose morphologies by examining the influence of cellulose sources and processing conditions on functional properties, crystallinity, and particle morphology. It further focuses on developing nanocellulose-stabilized Pickering emulsions as sustainable, non-toxic particle emulsifiers, minimizing traditional surfactants use, and optimizing their design for controlled release of a bioactive molecule in the gastrointestinal tract. The research also advances natural polymer-based hydrogels by creating nanocellulose/protein-based hydrogels with stable network structures for functional food applications to enhance the stability and bioavailability of encapsulated ingredients. Additionally, it promotes the development of polysaccharide-based aerogels, including nanocellulose, as sustainable alternatives for food packaging and biomedical applications. Finally, the work contributes to environmental sustainability by utilizing biopolymers in packaging, while enhancing human health through improved drug delivery systems and stabilization of bioactive compounds using nanocellulose-derived materials.

The study systematically addressed research gaps by structuring the work into four objectives, focusing on innovative product development, detailed characterization, and advancing sustainable applications of nanocellulose in diverse fields. **Chapter 3** focuses on the materials and methodologies employed for the isolation of nanocellulose from banana rachis and pineapple peel samples. Two distinct methods, ultrasonication and high-pressure homogenization, were used for nanocellulose isolation. For ultrasonication, independent variables included temperature (40-60°C), time (20-60 min), and concentration (25-45%), with particle size and zeta potential as dependent variables. In high-pressure homogenization, the independent variables were pressure (250-500 bar), passes (1-3), and concentration (30-50%), with particle size and zeta potential as dependent variables. Both methods underwent optimization to determine the most effective parameters for nanocellulose extraction. Results indicated that ultrasonication produced nanocellulose with superior characteristics compared to high-pressure

homogenization. Particle size and zeta potential analysis showed that ultrasonication yielded a more uniform and stable product, suggesting it is a more efficient technique for isolating nanocellulose. Further characterization focused on nanocellulose extraction using ultrasonication only, as it proved to be more effective. It was found that banana rachis powder contained a higher cellulose content than pineapple peel powder. This higher cellulose content, along with the better results from ultrasonication, led to the selection of banana rachis cellulose for the subsequent studies, ensuring optimal outcomes for the remaining objectives. **Chapter 4** discusses the results of the studies performed to fulfil objective 2. With a polydispersity index (PDI) of 0.463 and a particle size of 196 nm, the nanocellulose-stabilized Pickering nanoemulsion (PNE) created in this work demonstrated exceptional stability for 35 days and a uniform size distribution. Encapsulating β-carotene within the PNE significantly enhanced its chemical stability, achieving a retention rate of 0.81, demonstrating the effectiveness of this method in preserving the bioactive compound. The banana rachis nanocellulose (BRNC)-based PNE showed resistance to phase separation that is crucial for maintaining emulsion consistency. In mayonnaise samples, the control exhibited a significant increase in hydroperoxide levels by day 14, signalling oxidative degradation. However, mayonnaise with encapsulated β-carotene showed no significant increase in hydroperoxide levels, indicating protection from oxidative deterioration. The incorporation of BRNC-based PNE improved the mayonnaise's functional properties. A strong correlation ($R^2 = 0.99$) between emulsion concentration and viscosity indicated positive effects on the mayonnaise’s rheology. Texture and color improvements were observed, enhancing consumer appeal. HPLC analysis showed a β-carotene concentration of 61.26 ± 0.08 µg per 100 g of mayonnaise. As the PNE concentration increased from 15% (w/w) in MS1 to 20% (w/w) in MS6, lipid digestion efficiency decreased, likely due to the formation of a dense interfacial film. However, β-carotene bioaccessibility was significantly higher in MS6 (48.1%) compared to MS1 (24.5%), suggesting improved bioavailability. This approach offers a promising strategy for developing functional food products with enhanced stability and nutrient retention. The impact of BRNC on the gelling properties of soy protein isolate (SPI) is examined in **Chapter 5**. The gel strength, thermal stability, water-holding capacity, and viscoelasticity of SPI hydrogels were all markedly improved by raising the BRNC concentration from 0.5% to 2% (w/v). These improvements suggest that BRNC reinforces the gel matrix, making SPI hydrogels more robust for various applications. The study also investigated the impact of BRNC hydrogel on ice cream mixes, focusing on texture, consistency, colour, melting rate, overrun, and rheological properties. Lightness (L*) decreased while redness (a*) and yellowness (b*) increased, according to colour measurements, indicating that BRNC hydrogel influences the visual appeal of ice cream. Increased hydrogel concentration resulted in higher overrun, improved gas retention, and a lighter texture, which contributed to a creamier mouthfeel and a slower melting rate. Texture profile analysis revealed increased hardness, gumminess, and chewiness as BRNC concentration rose, improving the ice cream's structural integrity. The ice cream mixtures showed shear-thinning, non-Newtonian behaviour, with increasing shear rates causing the viscosity to decrease, a property beneficial for processing and achieving a creamy texture. The optimal formulation, SPI-2.0 (containing 2% BRNC), balanced creaminess and texture, making it ideal for ice cream production. Additionally, the incorporation of BRNC hydrogel facilitated lipolysis and increased the bioaccessibility of bioactive compounds during digestion, suggesting that BRNC not only improves texture but also enhances nutritional benefits. Overall, BRNC proves to be a versatile ingredient, improving both the sensory and functional properties of ice cream. **Chapter 6** fulfills Objective 4. The study found that polyvinyl alcohol (PVA) aerogels were denser and less porous, but the inclusion of cellulose fibers (CF) and nanocellulose (NC) created a more organized, three-dimensional network structure. Butterfly pea flower extract (BPFE) had minimal impact on the internal morphology of these aerogels. FT-IR analysis confirmed BPFE integration into the aerogel matrix, as indicated by characteristic bands for functional groups such as hydroxyl groups, alkane compounds, and carboxylic acids. The reduced relaxation time in the PVA+CF+NC+BPFE aerogels, compared to those without BPFE, was attributed to BPFE's low crystallinity and disruption of PVA crystallization by the fillers. BPFE's inherent thermal instability, especially from its phenolic compounds, lowered the thermal breakdown temperature, though the aerogel matrix provided some protection below 200°C. Water absorption capacity significantly increased with the addition of CF and NC, reaching 1116.99% and 1821.66%, respectively, while pure PVA aerogels had a lower capacity of 460.66%. The inclusion of CF and NC also reduced aerogel density to less than 0.1 g/cm$^3$ and increased porosity to over 90%. However, because of the filler's diluting impact, antioxidant activity dropped. Studies on in vitro release demonstrated that the aerogels preserved their structure while enabling a gradual release of bioactive compounds. The color-change response of BPFE-based aerogels was investigated, showing potential for packaging chicken cut pieces. Optimal color transformation

occurred at an anthocyanin concentration of 0.44 mg/100 mL when exposed to acidic and alkaline vapours, indicating potential for spoilage detection. The study highlights the potential of BRNC-based bioactive aerogels for controlled release and functional packaging applications.

This study systematically explored the development and characterization of nanocellulose-based materials derived from banana rachis for diverse applications. Ultrasonication was optimized as the superior method for nanocellulose isolation, yielding stable and uniform particles, with banana rachis proving to be a more effective source than pineapple peel. The nanocellulose-stabilized Pickering nanoemulsion (PNE) enhanced β-carotene stability, rheological properties, and bioavailability in functional mayonnaise. Banana rachis nanocellulose also improved soy protein isolate hydrogels, enhancing gel strength, water-holding capacity, and viscoelasticity, and contributed to better texture, creaminess, and bioaccessibility in ice cream. Additionally, BRNC reinforced polyvinyl alcohol aerogels, increasing porosity and water absorption capacity while enabling the gradual release of bioactive compounds. The inclusion of butterfly pea flower extract (BPFE) further imparted spoilage detection capabilities through pH-responsive color changes, demonstrating potential for active packaging applications. These findings highlight the versatility of BRNC in advancing sustainable, functional, and innovative products across food and packaging sectors.

**Keywords:** Nanocellulose, Pickering emulsion, Hydrogel, Aerogel, Functional foods