# CHAPTER 7

# CONCLUSION AND FUTURE SCOPE OF WORK

## 7.1. Conclusion

Nanocellulose was successfully isolated and characterized from banana rachis and pineapple peel using ultrasonication and high-pressure homogenization. Banana rachis nanocellulose (BRNC)-based Pickering nanoemulsions (PNE) exhibited remarkable stability for 35 days, with improved β-carotene retention and functionality in mayonnaise. The rheological, textural, and colour attributes were enhanced, while lipid digestion decreased with an increase in the concentration of cellulose nanoparticle, leading to increased β-carotene bioaccessibility. Incorporating BRNC into soy protein isolate (SPI) significantly improved the gelling properties and quality of ice cream, enhancing water holding capacity, gel strength, and texture. This also reduced fat content and melting rate, contributing to increased β-carotene bioaccessibility. Additionally, the integration of cellulose fibers (CF) and nanocellulose (NC) into polyvinyl alcohol (PVA) aerogels enhanced their structure, porosity, and water absorption capacity. Butterfly pea flower extract (BPFE) further modified the aerogels' thermal stability and crystallinity, forming a bioactive matrix for controlled release applications. Notably, BPFE-based aerogels demonstrated spoilage detection capabilities in minced chicken through visible colour changes, which correlated with pH and microbial load variations. Overall, the study highlights the potential of nanocellulose derived from agricultural waste as a versatile material for food systems. Its applications improve product stability, texture, and bioactive compound bioaccessibility, while also contributing to functional packaging solutions, offering a sustainable and innovative approach to enhancing food quality and safety.

The experimental works are detailed in Chapters 3-6. The key conclusions from this thesis are summarized chapter-wise, highlighting the main findings and insights from respective chapter.

### 7.2. Chapter 3

This chapter explored the physicochemical, thermal, and morphological characteristics of nanocellulose derived from banana rachis and pineapple peel following optimization of extraction conditions. It highlighted the differences in properties between the two sources, offering valuable insights for potential food applications. The major conclusions of this chapter are mentioned below:

1. The optimization results demonstrate that nanocellulose isolated using ultrasonication exhibits superior characteristics compared to high-pressure homogenization. Specifically, ultrasonication yields smaller particle sizes and more favourable zeta potential values, indicating better stability and dispersion, which are crucial for enhancing the performance and potential applications of nanocellulose in various food applications.
2. SEM images reveal distinct structural differences between the nanocellulose samples. The ultrasonication-extracted nanocellulose displays a smooth, fibrillar structure, suggesting well-organized cellulose fibers. In contrast, the nanocellulose from high-pressure homogenization has a rough, irregular surface, indicating a less uniform and potentially less stable morphology for certain applications.
3. The cellulose content in 100 g of banana rachis powder exceeds that in 100 g of pineapple peel powder. This suggests that banana rachis could be a potentially valuable source of cellulose for applications in nanocellulose production and its application in food.

### 7.3. Chapter 4

This chapter demonstrated that BRNC effectively stabilizes β-carotene-enriched Pickering nanoemulsions using a two-step homogenization method. The developed BRNC-stabilized β-carotene PNE mayonnaise was thoroughly characterized for colour, texture, rheology, oxidative stability, and comprehensive qualitative and quantitative analysis. The key conclusions drawn from the results are as follows:

1. Banana rachis nanocellulose (BRNC) is a natural, eco-friendly, and effective stabilizer for Pickering nanoemulsions (PNE) in food systems, demonstrating promising potential for enhancing stability and functionality in various food applications.
2. BRNC successfully stabilized hydrophobic bioactive compounds like β-carotene, with the resulting PNE exhibiting a particle size of 204 nm, a PDI of 1.722, and maintaining stability for 35 days. The encapsulated β-carotene demonstrated improved chemical stability, exhibiting a retention rate of 0.81.
3. BRNC-based PNE was incorporated into β-carotene-infused mayonnaise, resulting in improved oxidative stability, rheological properties ($R^2 = 0.99$), textural properties, and colour stability. HPLC analysis quantified the β-carotene content in mayonnaise as $61.26 \pm 0.08$ µg per 100 g.
4. The PNE-stabilized mayonnaise exhibited resistance to phase separation and effectively prevented hydroperoxide formation throughout the analysis period. BRNC incorporation reduced the fat content of mayonnaise while simultaneously improving its functional properties.
5. Lipid digestion was reduced with increasing concentrations of PNE as cellulose nanoparticles formed a dense interfacial film that blocked lipase enzymes, while β-carotene bioaccessibility was 48.1% in MS6 (higher concentration) compared to 24.5% in MS1 (lower concentration), indicating improved structural protection.
6. BRNC offers a sustainable and eco-friendly approach by converting agricultural waste into a versatile stabilizer, contributing to food innovation. This study highlights BRNC's potential to contribute to the development of functional, nutritious, and stable food formulations, paving the way for innovative and sustainable applications in the food industry.

### 7.4. Chapter 5

This chapter demonstrated that integrating (BRNC with soy protein isolate (SPI) enhanced the hydrogel's functional properties, such as water-holding capacity, gel strength, and stability. Applied to ice cream, it improved texture, stability, and nutrient bioaccessibility. The following points can be concluded from the study:

1. The incorporation of BRNC into SPI-based hydrogels and ice cream formulations significantly improved functional, structural, and nutritional properties, highlighting its potential as a versatile and beneficial ingredient in food applications.
2. Increasing BRNC concentration from 0.5% to 2% (w/v) improved water-holding capacity, gel strength, thermal stability, and viscoelasticity, resulting in a more robust hydrogel that is suitable for diverse applications.
3. Higher hydrogel content reduced lightness (L*) while increasing greenness (a*) and yellowness (b*). These changes led to increased overrun and gas-hold up in ice cream, as well as a slower melting rate, contributing to a stable, airy structure and improved sensory experience.
4. Texture profile analysis revealed significant increases in hardness, gumminess, and chewiness with higher hydrogel concentrations, resulting in improved structural integrity of the ice cream.
5. Rheological studies showed that ice cream mixes exhibited non-Newtonian, shear-thinning behaviour, where viscosity decreased with increasing shear rate. This behaviour enhanced the creamy texture of the ice cream, with IC-40 (hydrogel - 18.4%) achieving the optimal balance between creaminess and texture.
6. The inclusion of BRNC hydrogel reduced fat content by up to 20.4% in IC-40 without compromising texture or stability. Additionally, it inhibited fat digestibility by coalescing fat droplets, contributing to a healthier lipid profile.
7. The hydrogel improved the bioaccessibility of β-carotene from 12.3% in IC-10 to 19.8% in IC-40 within the small intestine, demonstrating its role in enhancing the nutritional value of ice cream.
8. BRNC hydrogel is a multifunctional ingredient that enhances the structural, sensory, and nutritional properties of ice cream. It represents a promising solution for developing healthier, lower-fat, and higher-quality frozen desserts while contributing to the innovative application of nanocellulose/protein-based hydrogels in food technology.

## 7.5. Chapter 6

This chapter demonstrated that hybrid aerogels reinforced with PVA, nanocellulose, and banana rachis cellulose and incorporated with butterfly pea flower extracts, effectively monitored minced chicken freshness at 4 °C. This represents the first use of banana rachis in aerogel development for meat spoilage detection. The key conclusions are as follows:

1. Pure PVA aerogels exhibit a denser, less porous structure, while incorporation of cellulose fibers (CF) and nanocellulose (NC) creates a more organized, three-dimensional network. Adding BPFE has minimal impact on the aerogel's internal morphology.
2. FT-IR analysis confirmed the incorporation of BPFE into the aerogel matrix, evidenced by characteristic bands associated with hydroxyl groups, alkanes, carboxylic acids, and other functional groups from BPFE and the bioactive aerogels.
3. Reduced relative crystallinity was observed in PVA+CF+NC+BPFE aerogels compared to PVA+CF+NC, likely due to BPFE's low crystallinity disrupting PVA's crystallization. Additionally, BPFE's phenolic compounds are thermally unstable, contributing to a lower thermal breakdown temperature, although the aerogel matrix offers protection below 200°C.
4. Water absorption values were 1116.99% for CF aerogels, 1821.66% for CF/NC aerogels, and 460.66% for pure PVA aerogels. Adding CF and NC reduced the aerogel density to below 0.1 g/cm³ and increased porosity to over 90%.
5. Antioxidant activity declined due to the dilution effect caused by CF and NC; however, high antioxidant capacity and progressive compound release were observed in both hydrophobic and hydrophilic food simulant mediums with BPFE incorporation. For hydrophobic foods, CF-based aerogels were more effective, while CF+NC-based aerogels showed greater promise for hydrophilic foods.
6. This study provides valuable data supporting the use of cellulosic materials derived from organic sources for active packaging and food preservation applications.
7. BPFE-based aerogels exhibit colour changes in response to acidic and alkaline vapours at an anthocyanin concentration of 0.44 mg/100 ml. These colour changes can indicate spoilage in minced chicken by detecting increased microbial load, pH, and total volatile basic nitrogen (TVB-N) levels.

## 7.6. Future scope of work

The research findings and insights from this study highlight potential areas for further exploration, offering new avenues for advancing applications and innovations in related fields. They are as follows –

1. Conduct in vivo studies to assess the safety, bioavailability, and health impacts of β-carotene and bioactive compounds in BRNC-stabilized Pickering nanoemulsions, focusing on food products like mayonnaise and ice cream.
2. Develop BRNC-based hydrogels for encapsulating and releasing bioactive compounds, enhancing the nutritional profile of foods like yogurt, beverages, and baked goods, and serving as edible coatings with antimicrobial or antioxidant properties.
3. Utilize BRNC-based aerogels as carriers for bioactive compounds in active packaging with antimicrobial or antioxidant properties, while exploring their potential for moisture regulation, thermal insulation, and structural integrity in food packaging systems.
4. Explore BRNC's use in emulsified food products like dressings and sauces, low-fat formulations, biodegradable food packaging, and as a natural stabilizer in beverages such as juices and plant-based milks.
5. Develop BRNC-based solutions to address food-related challenges, including enhancing shelf life, nutrient retention, sensory qualities, reducing food waste through smart packaging, and fortifying underutilized or low-quality food products with added functionality.