



Review article

Banana biomass waste: A prospective nanocellulose source and its potential application in food industry – A review

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ABSTRACT

Bananas are among the most produced and consumed fruit all over the world. However, a vast amount of banana biomass is generated because banana trees bear fruit only once in their lifetime. This massive amount of biomass waste is either disposed of in agricultural fields, combusted, or dumped at plantations, thus posing environmental concerns. Nanocellulose (NC) extraction from this source can be one approach to improve the value of banana biomass. Owing to its superb properties, such as high surface area and aspect ratio, good tensile strength, and high thermal stability, this has facilitated nanocellulose application in the food industry either as a functional ingredient, an additive or in food packaging. In this review, two different applications of banana biomass NC were identified: (i) food packaging and (ii) food stabilizers. Relevant publications were reviewed, focusing on the nanocellulose extraction from several banana biomass applications as food additives, as well as on the safety and regulatory aspects. Ultimately, further research is required to prompt a perspicuous conclusion about banana biomass NC safety, its potential hazards in food applications, as well as its validated standards for future commercialization.

1. Introduction

Over the past two decades, synthetic polymers have had a negative impact on the environment, including the accumulation of non-biodegradable materials, changes in the global climate, and the progressive depletion of fossil reserves. Worsening environmental concerns resulting from the overuse of synthetic polymers have led to extensive research on bio-based polymers. A variety of natural polymers exist, such as cellulose, starch, alginate, chitosan, and collagen [1,2]. Among the diverse biobased polymers, cellulose was found to be the most abundant in nature, producing up to 10^{11} t/annum [3]. Due to its biocompatibility, renewability, and biodegradability, cellulose is regularly investigated and is now a cutting-edge line of research. The advent of nanotechnology has led to an intense research interest on nanocellulose.

Nanocellulose (NC) represents nanoscale cellulose with a size of <100 nm [4]. Compared to cellulose, NC offers a large surface area and aspect ratio, exceptional mechanical properties with high tensile strength, modulus and stiffness, high surface reactivity, and unique optical properties [4], attributable to its nano-dimensional properties. Due to these properties, NC is in high demand in a

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variety of applications, such as paper making [5], biomedical applications [6], food [7], packaging materials [8], and cosmetics [9], among others. Moreover, their non-toxicity and versatility have led to their use in environmental remediation as flocculants, photocatalysts, adsorbents, and membranes [10]. The high reactivity and large surface area of nanomaterials are two notable properties that give them an advantage over other conventional alternatives in environmental remediation [11]. Nanocellulose is an ideal candidate for high-performance nanomaterials, owing to its appealing nanoscale architecture, well-defined molecular and supra-molecular structure, and its remarkable physical and biological properties.

Generally, the cellulose sources are derived from wood and cotton to obtain NC. Nevertheless, the overexploitation of these sources by competing industries leads to an increase in global deforestation, energy consumption, and construction. As a result, there has been growing interest in alternative sources of cellulose, such as agricultural biomass, herbaceous plants, and non-woody plants [12]. Various forms of agricultural biomass make an important contribution as an alternative cellulose source. Taking advantage of the high content of cellulose in banana waste makes it a promising nanocellulose source that remains to be underutilized.

FAO statistics show the banana is grown in over 130 countries and produces approximately 125 million tonnes of fruit in 2021. (The primary concern of banana production is the waste generated. The banana tree bears fruit only once in its lifetime, rendering them useless after harvest. This massive amount of biomass waste is either disposed of in agricultural fields, burned on-site, or dumped along roads and railroad tracks, thus posing environmental issues. Since this biomass contains a high percentage of cellulosic material, maximizing the recovery of this waste is critical. Several studies have been conducted on the extraction of nanocellulose from banana waste using various isolation methods to promote the recycling of agricultural waste and in turn reduce environmental pollution. However, currently, most of the utilization of banana biomass waste, after recovering or recycling steps, is largely limited to only a few value-added food products. For example, banana peel flour is commonly used to enhance the dietary fiber content in food products such as meat, bread, and cookies [13]. Considering the increasing interest of researchers in nanocellulose and its alternative sources, this review aims to highlight, critically analyze and fill the existing gap in the established literature while improving the understanding of the utilization of banana waste as an alternative source of nanocellulose. The potential application of nanocellulose derived from banana waste, particularly for food packaging and food stabilizers, is also discussed.

1.1. Resources

For the present review paper, a number of relevant articles were selected following the systematic literature review process. Scopus and Web of Science are used as the main databases to identify keywords and related terms. A total of 150 articles were retrieved from the databases.

1.2. Lignocellulosic composition in banana biomass

Banana waste generally includes banana rachis (BR), banana pseudostem (BPS), banana peels (BP), and banana leaves, as illustrated in Fig. 1. Each ton of banana fruit harvested yields three corresponding tons of BPS, 300 kg BP, and 150 kg BR [14]. Substantial banana waste is commonly generated during the production of banana flour, chips, puree, and frozen banana products. In large-scale banana plantations, harvesting loss bananas can be rejected and left behind in the field. Improper banana waste management may lead to environmental pollution such as water and soil contamination [15]. However, this circular economy can only be done if technologies are included to recover the banana waste losses, including banana waste generated in the household.

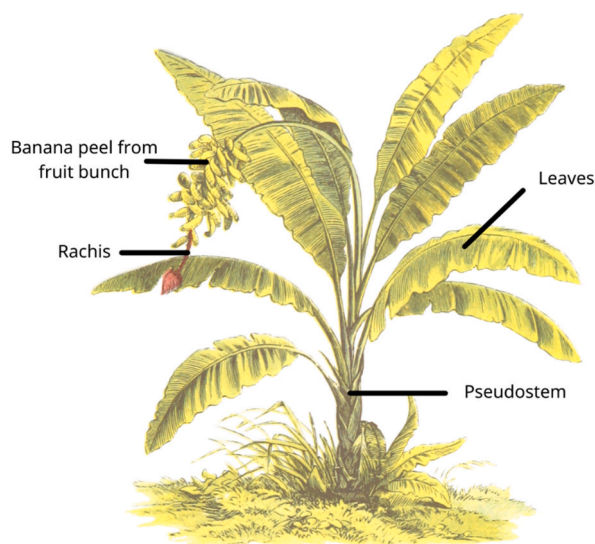


Fig. 1. Different parts of banana waste biomass.

Similar to other types of plant biomass, banana waste is rich in lignocellulosic components such as hemicellulose, cellulose, and lignin. The composition can vary depending on banana variety, maturity stage, and growing conditions. Table 1 elucidates the composition of lignocellulose in dry matter from various parts of banana waste. Also, the chemical composition of banana biomass included in the same table.

2. Types of nanocellulose

Nanocellulose can be classified into three subgroups according to their morphological orientation, functional properties, and isolation methods. The three types of nanocellulose are: 1) cellulose nanocrystals (CNC), with other names, such as nanocrystalline cellulose, cellulose (nano) whiskers, and rod-shaped cellulose microcrystals; (2) cellulose nanofibrils (CNF), also known as nanofibrillated cellulose (NFC), microfibrillated cellulose (MFC), and cellulose nanofibers; and (3) bacterial nanocellulose (BNC), specified from microbial cellulose [22]. In nature, cellulose exists in a hierarchical structure of cellulose, hemicellulose, and lignin held together by hydrogen bonds and van der Waals forces [23]. Both CNC and CNF were isolated from lignocellulosic biomass using a top-down strategy, including enzymatic, mechanical, and chemical treatment. Bacterial nanocellulose, also known as microbial cellulose or bio-cellulose, is typically synthesized by bacterial fermentation of glucose or other carbohydrate feedstocks.

2.1. Cellulose nanocrystal (CNC)

Cellulose nanocrystals (CNCs) are rigid rod-shaped particles 5–15 nm wide and 100–300 nm in length [24]. By eliminating the amorphous region, CNCs are generally obtained by hydrolysis with strong inorganic acids, such as sulfuric acid [25], hydrochloric acid [26], nitric acid [27,28], phosphoric acid [29], and hydrobromic acid [30].

2.2. Cellulose nanofibrils (CNF)

Cellulose nanofibrils (CNFs) comprise long-chain cellulose molecules with both amorphous and crystalline domains. They are typically obtained by the mechanical destructuring of cellulose fibers using a grinder, homogenizer, or microfluidizer [31]. The aspect ratio of CNF is relatively large compared to CNC, with a diameter of about 5–60 nm and a width of 10 to several hundred nanometers [32]. Due to the amorphous or disordered region of CNF, it is more flexible compared to CNC.

2.3. Bacterial nanocellulose (BNC)

Bacterial cellulose (BC), bacterial nanocellulose (BNC), microbial cellulose, or bio-cellulose are all terms for cellulose formed and secreted by aerobic bacteria using low molecular weight sugars, such as glucose, fructose, arabinose, and sucrose. The bottom-up approach is used for synthesizing nanocellulose from monomeric sugars [33–35]. The most efficient producer of BNC is *Gluconacetobacter xylinus* or *Acetobacter xylinum*, a Gram-negative bacterium. Other bacteria that can produce cellulose include *Agrobacterium*, *Acetobacter*, *Alcaligenes*, *Rhizobium* or *Sarcina*, and *Pseudomonas* ([35,36]. BNCs are twisted ribbon-like fibers with an average diameter of 20–100 nm (consisting of nanofibers with a diameter of 2–4 nm) and a length of 1 μm [37,38]. Some fibers have a high degree of crystallinity (80–90%) and polymerization (3000–9000). BNC has a similar chemical composition to plant-derived cellulose, but has a higher purity. Similar to plant-derived cellulose, BNC does not contain other polymers such as lignin, hemicelluloses and pectin.

3. Source of nanocellulose

The primary source for obtaining nanocellulose is bleached softwood and hardwood pulps. Softwoods are generally preferred over hardwoods, owing to their longer fibers and lower energy requirements for optimal fibrillation [39,40]. In the past few years, the valorization of agricultural biomass as a source of nanocellulose has become an ongoing research topic because it is renewable, naturally abundant, cost-effective, has minimal energy use for conversion, and facilitates lignocellulosic biorefining on an industrial

Table 1
Chemical and lignocellulosic composition of different parts of banana waste biomass.

Biomass	Leaves	Peel	Rachis	Pseudostem	References
Lignocellulosic fractions, %					
Hemicellulose	34.34	2.5	9.8	4.5	[16,17]
Cellulose	43.34	12.2	26.2	29.5	
Lignin	15.0	18.4	8.6	7.4	
Chemical composition, %					
Crude protein	17	5.5–7.87	5.29	10	[18–21]
Lipid	12.7	2.24–11.6	0.99	5	
Ash	12.4	9–11	9.95	20.5	
Carbohydrate	–	59.51–76.58	35.89	46.58	
Dietary Fibre	–	47–53	56	61.14	

Table 2
Preparation of Nanocellulose from Various Agricultural waste biomass.

Biomass/NC type	Structural composition, %			Extraction method	Yield, %	Properties	Reference
	Cellulose	Hemicellulose	Lignin				
Peach palm residue/CNC	44.59	27.05	3.22	Alkaline treatment: 5% NaOH and 10 drops CH ₃ COOH, 80 °C, 2 h. Delignification: 80% NaClO ₂ , 80 °C, 1 h.	28.9	Crystallinity: 49.8%–54.5%; Good thermal stability; width: approx. 100 nm	[43]
Tea stalk/CNC	35.0	20.5	28.0	Cellulose isolation: H ₂ O ₂ and CH ₃ COOH, 60 °C, 24 h. Acid hydrolysis: 60–65% (v/v) H ₂ SO ₄ , 40–50 °C, 90–150 min.	49.9	TEM and AFM showed a short rod-like structure; width 4–8 nm; crystallinity: 68.33; good thermal stability	[44]
Coconut coir/CNF	–	–	27.3	Dewaxing: benzene-ethanol Ultrasonic-assisted solvent immersion: 0.5 M NaOH and 0.5 M CH ₃ OH Alkaline treatment: 60 °C, 2.5 h. Bleaching: 5% NaClO ₂ , 80 °C, 2 h. TEMPO/NaClO/NaClO ₂	–	Average diameter: 5.6 nm; length: 150–350 nm; high zeta potential	[45]
Rice husk/CNF	35.0	30.0	18.0	Delignification: 4 mol/L NaOH, 80 °C, 12 h. Bleaching: 15% NaClO, 60 °C, 1 h.	95.0	Crystallinity: 65%; particle thickness: 25–27 nm	[46]
Corn cob/CNF	–	–	–	One step mechanochemical esterification - dispersion	–	Diameter: 1.5–2.8 nm; Tensile strength: 110–125 MPa; optical transparency up to 89% at 550 nm	[47]
Pineapple peel/CNC	–	–	–	Delignification: 7.5% (w/v) NaClO Alkaline treatment: 10% (w/v) NaOH, 25 °C; 10 h Acid hydrolysis: 64% H ₂ SO ₄ , 50 °C, 45 min	–	Diameter: 15 nm; length: 189 nm; higher thermal stability; needle-like structure; crystallinity: 61.19%	[48]
Lime residue/CNF	11.46	10.18	7.29	Blender chopped Autoclaved at 110–130 °C, 2 h.	35.84 (autoclaving at 110 °C)	Crystallinity index: 59–65%; diameter: 2–10 nm	[49]
Asian pear peel residue/CNC	38.5	23.6	28.1	One-pot process: 30 wt% H ₂ O ₂ , 90 °C, 5 h; Cr(NO ₃) ₃ metal salt catalyst, 8% H ₂ SO ₄ , 82 °C, 1 h	23.7	Crystallinity: 85.7%; spherical shaped with an aspect ratio of 24.6; low thermal stability	[50]
Jackfruit peel/CNC	–	–	–	Steam exploded: 4% soapnut solution, autoclaved at 20 lbs., 120 °C, 1 h Acid hydrolysis: 20% CH ₃ COOH and con. H ₂ SO ₄ , 80–90 °C, 30 min.	–	Thickness: 0.07 mm; Tensile strength: 102.06 MPa; degraded within 35 days	[51]
Passion fruit peel/CNC	28.58	23.01	36.18	Delignification: 2 M NaOH, 80 °C, 4 h Bleaching: 4% NaOH, and 50% H ₂ O ₂ , 50 °C, 1 h Acid hydrolysis: 52% H ₂ SO ₄ , 50 °C, 1 h.	58.1	Particle size: 103–173 nm; CNC has rod-like morphology; crystallinity: 77.96%; surface charge: 25 – 22 mV	[52]

5. Treatment processes for nanocellulose synthesis

5.1. CNC extraction

Generally, conventional acid hydrolysis followed by dialysis/neutralization against distilled water and ultrasonication is considered the key route for CNC preparation. As the amorphous region in the remaining cellulose diminishes in strength following pretreatment, it becomes more susceptible to destruction by acid, leaving only cellulose with significant crystalline segments [3]. reported that acid hydrolysis can be performed with both organic (e.g., phosphoric acid, hydrobromic acid, nitric acid, and tungstic phosphoric acid) and inorganic (e.g., hydrochloric acid and sulfuric acid) acids. Among them, sulfuric acid is the most commonly used acid because it forms the sulfate half-ester groups (OSO₃-) on the surface of CNCs [5,76]. The presence of these anionic groups on the surface of CNCs induces intermolecular repulsive forces that electrostatically stabilize colloidal suspensions and prevent the aggregation of CNCs [4]. Other commonly used acids are incapable of providing CNCs with a similar degree of colloidal stability as sulfuric acid. For instance, CNCs generated by hydrochloric acid hydrolysis tend to flocculate in aqueous dispersions due to the low density of

Table 3
Pre-treatment processes of lignocellulosic fibre before nanocellulose isolation.

Pre-treatment method	Chemical/Enzyme/Solvents	Purpose	Advantageous	Drawback	References
Alkali	<ul style="list-style-type: none"> •Aqueous NaOH •KOH •Ca(OH)₂ •NH₄OH 	<ul style="list-style-type: none"> •Promote depolymerization and lignin solubilization. •Hydrolysis of the highly branched hemicellulose content to expose cellulose and improve accessibility for subsequent downstream processes •Effectively removes the acetyl groups and uronic acid substrate from hemicellulose. The procedure stimulates solvation and saponification reactions, which cause the fibre to swell. 	<ul style="list-style-type: none"> •Non-corrosive •Non-toxic •Easy to recover 	<ul style="list-style-type: none"> •Does not entirely remove the lignin and hemicellulose constituents. •The use of a large amount of sodium hydroxide, which is the most effective and the involvement of the heating process increases the capital expenditure, treatment cost and potential environmental threat. 	[60–64]
Enzymatic hydrolysis	<ul style="list-style-type: none"> •Celluclast •Cellic CTec3 •Cellic® CTec2 	<ul style="list-style-type: none"> •Endocellulases catalyse the cleavage of internal bonds in the disordered domains of the cellulose chains, resulting in the formation of new chain ends and swelling of the cell wall, which aids in the fibrillation of the feedstock. 	<ul style="list-style-type: none"> •More effective •Requires a lesser water usage •Generates no chemical residues 	<ul style="list-style-type: none"> •Slower reaction rates than chemical treatments •Cost-to-benefit ratio needs to be conducted for each specific cellulose feedstock 	[65–67]
Bleaching/delignification	<ul style="list-style-type: none"> •H₂O₂ •ClO₂ •NaClO •NaClO₂ •CH₃CO₃H •O₃ 	<ul style="list-style-type: none"> •Bleaching is required to remove any remaining lignin if the alkali treatment is insufficient. 	<ul style="list-style-type: none"> •Bleaching significantly improves the surface characteristics of purified cellulose fibres and is regarded as a critical pretreatment step. 	<ul style="list-style-type: none"> •Bleaching lignocellulosic fibre with chlorine and chlorine derivatives results in the formation of highly toxic and hazardous pollutants. •The degradation of cellulose during ozone bleaching 	[56, 68–70]
TEMPO-mediated oxidation	<ul style="list-style-type: none"> •2, 2, 6, 6-tetramethylpiperidine – 1-oxyl 	<ul style="list-style-type: none"> •Used in addition to alkali and enzymatic pre-treatment for surface modification of nanocellulose. •Under mild conditions, TEMPO converts the primary hydroxyl groups (OH₆) in cellulose's glucose units to carboxyl derivatives. 	<ul style="list-style-type: none"> •The weakening of the inter fibril hydrogen during the reaction aid in lowering the energy cost of mechanical defibrillation during CNF's production. •Commercially available and stable nitroxyl radicals. •Recovered cellulose at high purity and yield. 	<ul style="list-style-type: none"> •Reaction pH should be strictly controlled. •Low uniformity of the final product. 	[4,71,72]
Ionic liquids (IL) pretreatment	<ul style="list-style-type: none"> •1-ethyl-3-methylimidazolium acetate [emim] [CH₃COO]) •1-butyl-3-methylimidazolium chloride [bmim][Cl] •1-ethyl-3-methylimidazolium acetate [emim][CH₃CO₂] 	<ul style="list-style-type: none"> •Ionic liquids are relatively new solvents made up of a mixture of large organic cations and small inorganic/organic anions that disrupt non-covalent interactions. 	<ul style="list-style-type: none"> •Recovered cellulose at high purity and yield. 	<ul style="list-style-type: none"> •Poor biodegradability •High production costs. •Toxic behaviour 	[4,73,74]
Deep eutectic solvents (DES) pretreatment	<ul style="list-style-type: none"> •Choline chloride-lactic acid (ChCl-LA) •choline chloride-oxalic acid (ChCl-OA) 	<ul style="list-style-type: none"> •Deep eutectic solvents (DESS) were developed as a new generation of ionic fluids. They are composed of at least two eutectic compounds linked together via hydrogen bonds to form low-cost eutectic mixtures with physical and chemical properties comparable to those of an ionic liquid. 	<ul style="list-style-type: none"> •Save the energy consumption associated with the production of nanocellulose and increase the homogeneity of nanocellulose. •Renewable nature. 	<ul style="list-style-type: none"> •Limited research for broad application •DES has a higher density and viscosity than other common solvents. These aspects are disadvantages of using DES in continuous flow reactions. 	[74]
Organosolv	<ul style="list-style-type: none"> •The use of organic solvents or their aqueous mixture during delignification to obtain highly pure cellulose. 	<ul style="list-style-type: none"> •Ethanol •Acetone •Ethylene glycol •Formic acid •Acetic acid 	<ul style="list-style-type: none"> •Reusable solvents 	<ul style="list-style-type: none"> •Expensive organic solvents. •Solvents are highly flammable and volatile. 	[59,75]

Table 4
Preparation of Nanocellulose from Banana biomass waste.

Banana biomass waste	Structural composition, %			Extraction method	Yield, %	Properties	Reference
	Cellulose	Hemicellulose	Lignin				
Banana rachis/CNC	42.4	13.7	17.3	Dewaxing: hexane-methanol Alkaline pre-treatment: 100 g/L NaOH, 25 °C, 7 h. Mixed acid treatment: 80% CH ₃ COOH, 65% HNO ₃ , 110 °C, 20 min Acid hydrolysis: 64% v/v H ₂ SO ₄ , 45 °C, 60 min	23.6	Particle size: 63.6–210.5 nm; total surface area: 9.71 m ² /g	[81]
Pseudo-stem/CNC	–	–	–	Alkaline pre-treatment: 5% KOH, 16 H Bleaching: 1% NaClO ₂ , 1 H, 70 °C TEMPO-mediated oxidation		Long fibrillated fibre with width range 7–35 nm. High negative zeta potential (lower than –33.6). The high crystallinity index (57–69%).	[82]
Peel/CNC	7.45–11.89	15.26–21.56	7.31–9.29	One-pot hydrolysis: bleaching with H ₂ O ₂ , 90 °C, 5 H, acid hydrolysis with H ₂ SO ₄ , 80 °C, 1 H		Morphology studies show a porous network with a unique lamellar structure. Particle size: 176.1–362.2 nm.	[83]
Peel/CNF	7.5	–	7.9	Delignification: 1% NaClO ₂ , 70 °C, 1 H. Acid hydrolysis: H ₂ SO ₄ , 80 °C, 1 H	27.07–43.38	High crystallinity value (63.1–66.4%). High negative zeta potential value (–67.37 to –53.20).	[84]
Peel/CNF	–	–	–	Mechanical treatment: high-pressure homogenizer Soxhlet extraction using acetone and hexane solution for 10 H to remove polar and nonpolar extractive.	76.58	Average diameter: 73 nm; Average particle size: 1285 nm; crystallinity index: 61.1%	[85]
Bract/CNF	–	–	–	Microwave digestion: Mixed with deionized water and digested at 525 W, for 5 min H ₂ O ₂ added to assist bleaching. Ball milling and sonication method to produce sustainable nanocellulose	74.47	Average diameter: 89 nm; Linear fibrous morphology; Average particle size: 972 nm; crystallinity index: 75.8%	

the surface charges [77].

The properties of CNCs, such as morphology and yield, are influenced by various process parameters such as acid concentration, reaction temperature and duration. Higher acid concentrations, longer reaction periods, and higher temperatures generally result in a higher surface charge and a narrower diameter, but lower yield, crystallinity, and thermal stability of the CNC. The shorter time, on the other hand, leads to the incomplete removal of the amorphous domains, which directly affects the quality and yield of the CNCs. Therefore, the extraction of CNCs from different biomasses with various parameters for acid hydrolysis remains a popular research topic.

5.2. CNF extraction

In contrast to CNCs, CNFs are produced primarily by the mechanical treatment of cellulose fibers, such as high-pressure homogenization, microfluidization, grinding, and ultrasonic treatment. The cellulose feedstock and its pretreatment, as well as the pulping process itself, can affect the overall quality of CNFs.

Among mechanical disintegration techniques, high-pressure homogenization is the most frequently approached to produce high-quality CNF [78]. Due to the rapid change of pressure, high-pressure homogenization can generate a variety of forces such as high pressure, high shear, high velocity, and turbulence, which are able to break the cellulose fibers and eventually release aggregated nanofibrils [79]. It is crucial to note that the stiffness of CNFs, which is determined by the ratio of crystalline to non-crystalline domains, is affected by the number of homogenization cycles and the applied pressure. The isolation of cellulose nanofibers without destroying the cellulose crystals is challenging, even more so when various cellulose sources and extraction methods are applied. CNFs recovered in aqueous suspension typically form shear-thinning and thixotropic gels. The high shear stresses exerted during mechanical comminution can damage the crystalline ordered segments, and TEMPO-mediated oxidation may convert the crystalline domains into disordered structures. Therefore, the CNFs may have a lower crystallinity than the raw material [80].

6. Nanocellulose from banana biomass

Presently, most nanocellulose available commercially is extracted from wood pulp and cotton. In 2020, Research Insight released the “Global Nanocellulose Fiber Market Report”, expecting the global market value of nanocellulose to reach a maximum of \$2.712 billion by 2025, and predicting an 18.80% annual growth rate from 2018 to 2025. Therefore, the production of nanocellulose cannot rely on limited sources, considering that the overutilization of such sources, competing industries (energy and construction), and deforestation is unsustainable in the long run. However, it is worth mentioning that numerous recent reports have been presented on the utilization of agricultural biomass as a source of cellulose and its derivatives. Employing banana waste as an alternative precursor for the production of nanocellulose may be of significant value to banana growers. Table 4 presents the recently reported nanocellulose extraction from several types of banana biomass waste and their properties.

Based on Table 4, chemical methods are the most used to obtain NC from banana biomass [81]. obtained NC from banana rachis by alkaline treatment and acid hydrolysis with mixed acid (acetic acid and nitric acid). The NC presents a high total surface value of 9.71 m²/g, which is significantly lower than the values reported in the literature (Table 3). Despite the fact that chemical treatment is the most used method to extract NC from any source, this method has the disadvantages of low yield and high energy, water, and harsh chemical use [86] Alternately [83], managed to extract NC from banana peels using the one-pot oxidation method, which employs mild acid and hydrogen peroxide as a timid oxidizing agent compared to sodium hydroxide.

Another inventive strategy is the combination of chemicals and physical or enzymatic methods, which have been extensively studied [82]. used a chemical method during pretreatment to remove the lignin and hemicellulose from banana pseudostem, followed by the TEMPO-mediated oxidation. The extracted NC not only has a high crystallinity index (57–69%) but also exhibits a low surface charge which indicates good colloidal stability. Similarly [82,84], combined chemical and physical methods to extract NC from banana biomass. Their study indicates high crystallinity index and comparatively high NC yield compared to using a single method alone. This grants further research on the optimization of the extraction condition to maximize the nanocellulose recovery.

7. Potential value in food industry application

NC is attributed to unique properties such as biodegradability, non-toxicity, biocompatibility, good mechanical properties, and high-water absorption and holding ability, which make it an excellent potential application for versatile industries (automotive, food, biomedical, electronic, and biosensor) and water treatment [51,57]. In the food industry, NC has greater development potential for food packaging materials, food additives, active substance carriers, and functional ingredients [57].

7.1. Food packaging

Packaged food consumption continues to rise, with an annual growth rate of 5% and a market value of \$1.9 trillion in 2020, and is expected to increase to \$3.4 trillion by 2030 [87] Food packaging is invented to minimize food contamination throughout the production process, especially from environmental factors such as dust, microorganisms, gasses, and water vapor [88]. Food packaging currently not only shields food from environmental factors, but also serves to extend its overall shelf life [89], reduce waste [90], and promote purposes [91]. Despite these advantages, the conventional materials used for food packaging are still derived from fossil fuels, rendering them non-renewable and almost non-biodegradable, which poses a great threat to the environment, especially if not

properly managed.

Therefore, there has been a surge in demand for biodegradable, non-petroleum-based packaging materials that have a minimal environmental impact and are preferably composed of sustainable and renewable resources [92]. Biodegradable and bio-based polymers used for food packaging include poly (lactic acid) (PLA) [93], polyhydroxyalkanoates (PHAs) [86,94], chitosan [95], and proteins derived from animals (gelatine and caseinates) and vegetables (soy and gluten) [96]. However, compared to synthetic polymers, these biopolymers exhibit poor barrier, thermal, and mechanical properties [97]. For this reason, their use in commercial applications such as food packaging is limited. The properties of these materials can be improved by introducing reinforcing structures such as NC, which can synergistically interact with other materials to improve the barrier, thermomechanical, and rheological properties of the nanocomposite. The hydrogen bonds between molecules and within molecules make cellulose insoluble in virtually all solvents, primarily due to its high bond strength [98].

Prior studies have demonstrated that the addition of 2–6% CNC in alginate improves mechanical properties. The elastic modulus and tensile strength of alginate films were enhanced by 35% and 25%, respectively [99]. However, the water vapor permeability remained constant as the pure alginate when 4 wt% CNC was added [100]. demonstrated that tensile strength and Young modulus values improved as CNC was supplemented into chitosan increase (CNC in the range of 5–30%). Chitosan films with 20% CNC exhibited the highest value for a young modulus value of 52.35 MPa. However, due to the lower crystallinity of the film, there was no significant improvement in water vapor permeability. Interestingly, a gradual antimicrobial activity of chitosan-CNC composite films was found in this study. In agreement with the study by Ref. [101] the nanocellulose-chitosan composite film efficiently suppressed the production of lactic acid bacteria, Gram-positive bacteria (*Staphylococcus aureus*), and Gram-negative bacteria (*E.coli*), on the surface of the meat.

A number of dated studies investigate the use of banana waste biomass nanocellulose as a reinforcement in bio-polymeric matrices and showed similar enhancement properties [102]. developed a nanocomposite film of chitosan-banana pseudostem CNC that showed high tensile strength and good swelling properties. They also reported pronounced effectiveness of tetracycline-incorporated nanocomposite against *E. coli* and *S. aureus* with a zone of inhibition diameter of 36.3 mm and 39.3 mm, respectively. This is unlikely to occur in the pure chitosan film. The reason postulated by the researchers was the use of the sulfuric acid hydrolysis method to obtain a negatively charged NC and the tetracycline being easily loaded to the negatively charged surface of NC. The release of tetracycline and its adsorption against the bacterial cells through electrostatic attraction explained its antibacterial mechanism [102].

[103] reported that 3% CNC from banana pseudostem in polyvinyl alcohol (PVOH) film showed a significant improvement in tensile strength, maximum stress modulus of elasticity, and barrier properties. The tensile strength was reduced by 23% as 5% CNC was loaded into the film. Uniformly, NC dispersion is crucial to ensure the effective hydrogen bond formation between NC and the biopolymer, resulting in a maximum enhancement effect of nanocomposite [31]. Poor dispersion causes the aggregation of NC in polymer matrices, which raises incompatibility issues [31]. point out that surface modification technologies such as carboxylation, sulfonation, quaternary ammonium salination, phosphorylation, and an increase in the surface charge density may aid in the repulsion between fibers. Furthermore, the authors suggest that a steric hindrance can be formed on the surface by the introduction of suitable macromolecules, which may lead to an increase in interface compatibility.

[104] developed a free-standing film from banana pseudostem NC with a relatively strong and high initial degradation temperature compared to other bioplastics. However, calcium oxalate crystals were detected in the film, which affected the transparency and most likely influenced the contact angle and tensile strength. They suggest considering a treatment to remove calcium oxalate crystals from the film in future studies [84]. demonstrated that the combination of both chemical and mechanical treatments (two-stage high-pressure homogenizing) produces banana peel CNF with high crystallinity values (63.1–66.44%), which indicates that it is a good reinforcing agent of polymeric matrices.

7.2. Food stabilizer

The embedded biologically-active substances are commonly incorporated into a range of colloidal delivery systems to improve oral bioavailability. These delivery systems developed include emulsions, liposomes, microgels, microemulsions, molecular complexes, and biopolymer particles [105]. Amongst these systems, the emulsion has been widely practiced in the food industry to carry bioactive components [99]. However, emulsion applications can sometimes be challenging, because they are prone to gravitational separation, coalescence, creaming, flocculation, sedimentation, phase inversion, and Ostwald ripening due to their thermodynamic natural instability [56]. Hence, emulsifiers have become vital components for forming and stabilizing emulsion-based food [106]. For this purpose, conventional molecular-based emulsifiers have been applied to decrease the interfacial tension and form protective coatings [67]. Howbeit, [107] reported that molecular-based emulsifiers do not work well in preventing emulsion destabilization under some environmental variables such as certain ionic strength, pH, mechanical treatment, and temperature. This can limit their utilization in commercial food products, subjected to various environmental conditions. Besides, some emulsifiers (especially synthetic surfactants) may cause environmental pollution or have hazardous effects on human health in long-term consumption [108]. For instance, one study indicated that polysorbate-80, a common low molecular weight surfactant, may contribute to the development of metabolic disorders, such as inflammatory bowel disease and a variety of obesity-related diseases [109]. Henceforth, several researchers are currently investigating natural alternatives (such as proteins, polysaccharides, or phospholipids) to substitute the typical synthetic surfactants [110,111].

Pickering Emulsion (PE), stabilized by solid particles instead of conventional surfactants, has gained growing interest, owing to material science advancements [112]. PE is a surfactant-free system, and its usage of solid particles is also often inexpensive, abundantly available, has a low risk of toxicity, is environmentally friendly, and is amenable to physical or chemical modification [113].

Therefore, many studies on innovative particles have shown promising properties that have been tailored to stabilize PEs. Currently, there are two primary groups of biocompatible polymeric particles that have been reported to be efficient Pickering stabilizers: carbohydrate-based and protein-based [114]. To date, some of the salient carbohydrate-based Pickering stabilizers are cellulose nanocrystals [115], cellulose microfibrils [116], regenerated chitin fibrils [117], starch granules [118] and *Flammulina velutipes* polysaccharide nanoparticles [114].

In this context, this has widened the potential use of nanocellulose as a suitable candidate for a polysaccharide-based Pickering stabilizer. Not only is nanocellulose abundantly available, cheap, and associated with a low risk of toxicity, but it also can be chemically or physically modified [119]. Contrary to synthetic surfactants, NC does not lower the interfacial stress between the oil-water phase to enable emulsion. Instead, NC migrates to adsorb permanently (high energy desorption) and is arranged at fluid-fluid interfaces to form a firm structure that prevents bubble coalescence [120].

The four major factors that affect the ability of NC to stabilize Pickering emulsion are: 1) mechanical properties; 2) particle morphology, concentration, and surface charge; 3) surface and interfacial tension; and 4) adsorption and wettability ([121]. Meanwhile, three properties of NC that can be concluded to be capable of being PEs stabilizers are: 1) size; the particle can be one order of scale smaller than the anticipated Pickering emulsions droplet; 2) wettability; solid particles can be wetted partially by both of the oil and water phases; and 3) absorbability; the solid particles can be adsorbed onto a water-oil interface [111]. According to Ref. [122], the aspect ratio affects the properties of PEs, by which higher aspect ratios can form more stable PEs due to the increased ability to wet both the dispersion and continuous phases. The surface charge of NC particles is another vital factor that influences the interfacial diffusion rate and position [123]. [124] pointed out that the NC surface charge could attribute to the electrostatic screening effects that determine the resistance ability of flavor oil Pickering emulsion against pH and ionic strength changes.

According to Ref. [125], crystalline cellulose stabilized the emulsion system by adsorption on the droplet surfaces. Meanwhile, cellulose nano-fibrillated undergoes a depletion mechanism (Fig. 3a) to alter the droplet-droplet interactions. The CNF concentration is depleted (exclusion zone) in a region surrounding each droplet in the emulsion system. Hence, there is an osmotic pressure between the exclusion zone, which causes two lipid droplets to approach each other, leading to flocculation [126]. Two major factors that affect the depletion flocculation occurrence are the molecular weight and the molecule hydrodynamic radius. Fig. 3b illustrates the adsorption mechanism of NC at the oil-water and water-oil interfaces. During homogenization, the non-polar groups of NC protrude into the oil phase, while the aqueous phase is protruded by the polar group. The reduction of oil-water interfacial tension and Laplace pressure enables further droplet disruption. γ_{po} is the interfacial tension between the oil phase and NC, whereas γ_{pw} is the interfacial tension between the water phase and NC. γ_{ow} indicates the oil and water phases' interfacial tension within the colloidal system. θ is the three-phase contact angle of the NC particle with the water and oil phases, while r is the NC radius. The particle with a contact angle below 90° is hydrophilic and enables to stabilization of oil in water emulsion. In contrast, the particle with a contact angle above 90° is hydrophobic and aids in the stabilization of water in oil emulsion [127]. The obtained PE is most stable when the contact angle is approximately 90° , due to the equal energy detached from both phases. Nevertheless, a PE with a 90° contact angle has not yet been reported in the literature [128].

[129] investigated the application of banana peels CNF as a Pickering stabilizer and reported varied outcomes depending on the emulsification processes. The creaming phenomenon of the oil droplets was observed when the emulsion was produced using both an ultrasound and a high-pressure homogenizer, while the use of only a high-pressure homogenizer causes the coalescence phenomenon on emulsions. The researchers also pointed out that banana peel CNF with a smaller diameter, length, and aspect ratio is optimal as an emulsion stabilizer due to the better oil droplet accommodation, which boosts the emulsion stability.

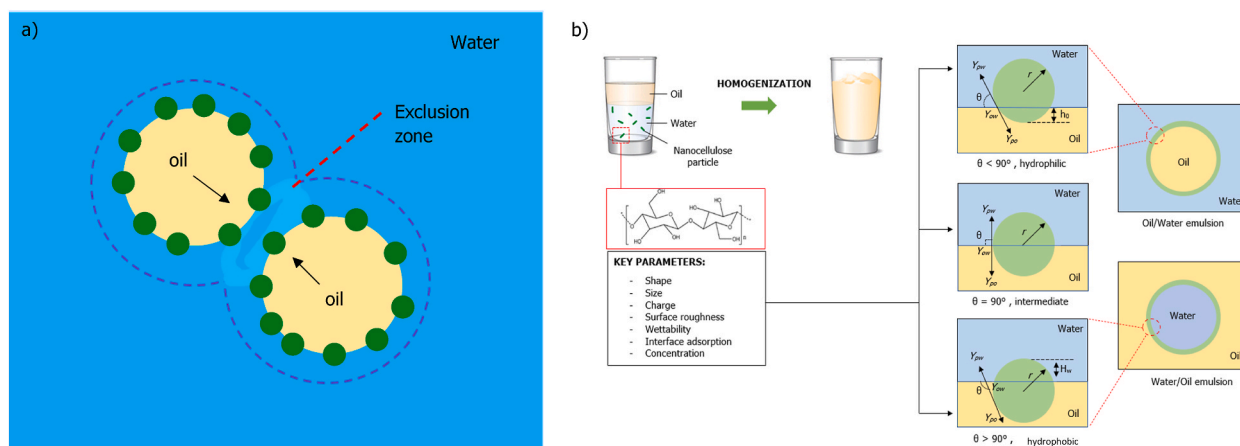


Fig. 3. a) Depletion Flocculation of Oil Droplet When CNF added in the system b) Adsorption Mechanism of Nanocellulose at Oil-water and Water-oil Interface.

7.3. Food additives

Aside from being used as a food stabilizer, nanocellulose emerged as a promising candidate for food additives to improve food homogeneity, either as a texture enhancer, fat replacer, foam stabilizer, or thickener [130]. [131] attempted to fabricate CNF derived from brown waste algae as a milk thickener. The obtained CNF revealed the ability to absorb casein micelles via hydrogen bonds to form a weak gel-like structure, thus demonstrating remarkable thickening behavior. A study by Ref. [132], however, suggested that NC as a thickener does not provide adequate capacity to reduce the bitterness of quinine hydrochloride. Meanwhile, astringency was the most reported description for the NC-containing samples. Although there is no clear reason for the astringency, they theorize that the small particle size or the possible residue of NC source may be the cause of astringency.

[81] immobilized Andean berry polyphenols using NC derived from the banana rachis. The resulting polyphenol NC complex was able to retain the primary color (magenta) of berries, and show high thermal stability, thus prolonging the polyphenols shelf life during storage at different temperatures. Moreover, the polyphenol NC complex exhibits high antioxidant capacity, thus delaying the oxidative modifications of a peptide tryptophan residue and Sacha inchi oil that presents in the emulsion.

7.4. Encapsulating agent

In the food industry, the inactivation of the active substance can occur when subjected to unstable conditions such as low pH, high temperature, and mechanical destruction. Therefore, controlled delivery technology is crucial to allow stability improvement, the bioavailability of active substances, a reduction in overdosing side effects, and regulation of the targeted release [133]. A variety of delivery systems have been developed to embed bioactive compounds against environmental factors such as light, temperature, oxygen, pH, and enzymatic degradation. According to Ref. [134], nano-encapsulation has been successfully used in encapsulating bioactive and nutraceuticals to develop functional nutrients and enriched food. The bioavailability of bioactive compounds increases when the size of the particle used for the carrier decreases, due to faster digestion and the ability to penetrate the mucus layer and cells [135]. Recently [136], developed nanocellulose-fortified alginate beads to regulate the digestibility and behavior of lipid droplets under a stimulated gastrointestinal tract, in order to design emulsified food with reduced fat digestibility. The study reported that the beads with nanocellulose (especially CNC) showed a slow-release rate, indicating the ability of the NC to hinder the diffusion of the lipase molecules. In another study by Ref. [137], alginate–CNC–lecithin microbeads were designed to encapsulate the *Lactobacillus rhamnosus* (AT9595). The viability of *L. rhamnosus* was reported to be improved during gastric passage and storage. The results demonstrated that the developed microbeads provide protection to the probiotic against temperatures at 25 °C and 4 °C, with a decrease in viability by 1.23 and 1.08 log, respectively.

7.5. Functional food ingredient

Food can only be considered “functional” if it is able to deliver enhanced or additional health benefits above its basic nutritional value. By this definition, an early study by Ref. [138] demonstrated that NC can be used to replace oil to develop a low-calorie salad dressing (US 4378381). The combination of NC with vinegar and dried Italian salad is comparable to that of authentic Italian dressing, especially in terms of color and texture [139]. [139] attempted to substitute the conventional ingredients in sausages; phosphate, maize starch, and sodium caseinate with cellulose nanofibrillated were obtained from hardwood kraft pulp. The results indicated that 0.5% CNF successfully substitute phosphate and maize starch without negatively affecting the fat and water retention ability of the sausages. However, when sodium caseinate was removed from the ingredients list, CNF substitution was unable to attain the acceptable quality of the sausages.

Another characteristic of nanocellulose that make it a superb candidate as a functional ingredient is dietary fiber (DF). It is generally known that DF intake provides a number of health benefits, such as lowering the risk of hypertension, obesity and diabetes, and maintaining a healthy function of the gastrointestinal. The most fascinating aspect of DF is its capability to lower glucose levels of plasma, and in turn the peril of type 2 diabetes [140]. [141] demonstrated that CNF at a 0.5% concentration significantly increased digesta viscosity. The increased digesta viscosity mechanism was reported to be associated with delayed glucose diffusion in the intestinal lumen [142]. Additionally, an *in vitro* study shows that CNF binds with glucose molecules, thus hindering the movement and transport of glucose in the intestines [141]. However, the ability of NC to adjust the digesta viscosity depends on the aspect ratio of the particle and the charge density [142]. [142] reported that smaller NCs are better at delaying glucose diffusion. Further *in vivo* studies should be performed to fully understand the influence of NC on starch digestion, as well as the hypoglycaemic effects.

8. Safety and regulatory aspects

The banana biomass NC application in the food industry is promising and merits further extensive research. However, studies on the overall safety and hazard potential of this material remain scarce in the literature. Validated standards to allow NC commercialization in the food field are still indispensable, and the policy of usage remains unclear. Although the micron-sized cellulose and its derivatives have been “generally regarded as safe (GRAS)” for ingestion [143], the use of nanoscale cellulose has not yet been approved by the Food and Drug Administration (FDA). This is primarily due to concerns about the chemical modification and nano-size particles of NC [144]. In agreement with [106], the toxicity occurrence from ingested nanomaterials depends on several factors, such as composition, structure, and properties [145,146]. [145,146] found that unrestrained nanoparticle exposure can cause dermal toxicity. Taking an account, the self-aggregation and non-degradation properties of the nanoparticle, it can possibly induce pulmonary inflammation if

inhaled [147]. Considering the variations of NC sources and methods of isolation, mixed findings on the toxicity aspect are expected.

Following the current European legislation, the nanocellulose-based composites intended for food packaging should comply with framework Regulation (EC) No 1935/2004. In accordance with this regulation, the materials manufactured shall comply with the Good Manufacturing Practice (GMP) to warrant that none of its constituents migrate to food in concentrations that could; 1) endanger human health; 2) cause an unacceptable change in food composition; or 3) deteriorate the organoleptic properties [148].

Currently, only one toxicity study was conducted on NC obtained from banana biomass [84]. pointed out that banana peel NC toxicity is highly dependent on the level of intake. Cytotoxicity assessment of banana peel CNF showed that at a low dosage (50–500 µg/mL), there was no cell death found in the Caco-2 cell (human small intestine epithelial layer), indicating its safeness to being consumed. At a dosage above 1000 µg/mL, however, the cell activity profoundly decreased [149]. demonstrated that the immune system's response to nanocellulose shows that the pro-inflammatory response of NC can be lowered, and even become anti-inflammatory, through surface modification. However, considering the differences in cellulose source, method of extraction, and testing conditions, these results are still far from acting as a benchmark for any judgment regarding NC safety in food applications.

According to Ref. [141], nanoscale material can enter the human gastrointestinal tract (GIT) either as a food ingredient or a contaminant. The lack of related studies on the possible toxicity of banana biomass NC remains to be a barrier to effectively assessing its consumption safety. The toxicity of NC is negligible and has rarely been reported, but reliable tools to measure NC physicochemical and morphological are necessary to better understand NC safety in the human system, thus precluding the commercialization of NC in various food applications in the future. The author also recommends further research to be carried out to prompt a perspicuous conclusion on the safety of banana biomass NC in food applications. The Life Cycle Assessment (LCA) can be a reliable environmental management tool to evaluate and quantify the potential risk of nanocellulose production and consumption to the environment and human health [150]. As ongoing research is being carried out on nanocellulose research and an attempt for industrial application, extensive LCA can provide a crucial step towards commercialization in the near future.

9. Conclusion and future outlook

The nanocellulose potential for food applications was first recognized in 1983 by Turbak and co-workers. Since then, studies and patented work have been reported on the use of nanocellulose as a food additive. The nanocellulose obtained from banana biomass shows diverse properties, depending on its extraction method. Given the abundance of banana biomass produced, this provides an added value to the by-product. Owing to its large surface area, high thermal stability, good strength, and outstanding mechanical properties, nanocellulose serves as an excellent biocomposite in novel food packaging. Since most bioplastic performance levels are insufficient to meet practical applications, nanocellulose addition has been proven to improve the overall quality properties. Furthermore, Pickering emulsion stabilized by nanocellulose has been extensively investigated as an alternative to conventional surfactants in the food industry. The possible surface modification in nanocellulose with polyphenols, protein, and other polysaccharides is another superior advantage that can be exploited to increase emulsion stability, particularly in emulsion-based food products.

However, further research is required to determine the possible health risk factors of NC obtained from banana biomass. This step is crucial before nanocellulose can achieve complete industrialization and commercialization. Validated standards and policies for nanocellulose application in the food industry must be taken seriously to prevent uncertainties about its hazard to human safety.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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