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REVIEW ARTICLE

Fruit Wastes and Crop Residues as Nutrient Sources for Bacterial Nanocellulose Production: A Review

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Abstract Nanocellulose has been developed and used as a bio-based advanced material in modern biotechnology. Lately, bacterial nanocellulose (BNC) emerged as a prominent biopolymer because of its multi-functional application in various industries, such as food, biomedical, cosmetics, and environmental. The emerging concern for large-scale BNC production is the high fermentation costs, low productivity, and expensive culture medium. To minimise this issue, agro-industrial wastes can be used as feedstock. Recently, many studies have investigated the utilization of agro-industrial wastes as potential nutrient sources for BNC production. However, a comprehensive review of BNC production from fruit wastes and crop residues is lacking. To address this gap, the current review focuses on the utilization of fruit wastes and crop residues for BNC production, including its advantages and disadvantages. This study contributes to the scientific community by (a) providing an insight into fruit waste and crop residue utilization for BNC synthesis (b) an overview on its advantages and disadvantages (c) providing recommendations and future perspectives on BNC production from agro-industrial waste utilization. The sustainable concept of BNC production utilizing agro-industrial wastes opens a way for industries to produce BNC on a larger scale.

Keywords: Bacterial nanocellulose, fruit wastes, crop residues, agro-industrial wastes, waste management.

Introduction

Cellulose is the most abundantly available biopolymer found on earth, composed of repeating units of D-glucose. It can be found in a wide variety of living species, including plants and microbes. An estimated 10^{10} to 10^{11} tonnes of cellulose are extracted from plants each year (Figueiredo *et al*., 2014). Cellulose is composed of β-1,4-linked D-glucose, the fundamental structural component of plant cell wall (Sahari *et al*., 2023; Kumar *et al*., 2019). Figure 1 shows the structure of cellulose. The arrangement of glucose units will either result in a compact crystalline structure or a loosely packed amorphous structure. The crystalline region exhibits a high degree of order that contributes to the rigidity of the cellulose. In contrast, the amorphous region lacks a defined structure and provides stability and flexibility to the nanocellulose material. Plant cellulose is non-toxic and naturally stable (Bhaladhare & Das, 2022). It has been speculated that cellulose usually appears pure, particularly from cotton hairs. However, cellulose from wood usually contains lignin and other polysaccharides (Naomi *et al*., 2020). Removal of lignin and hemicellulose requires chemical treatments, which may alter the purity of the cellulose, thereby limiting its industrial applications (Fernández *et al*., 2019). The huge demand for nanocellulose increases deforestation resulting in environmental imbalance. This environmental concern could be avoided through more sustainable production of nanocellulose using bacteria under controlled conditions in the laboratory.

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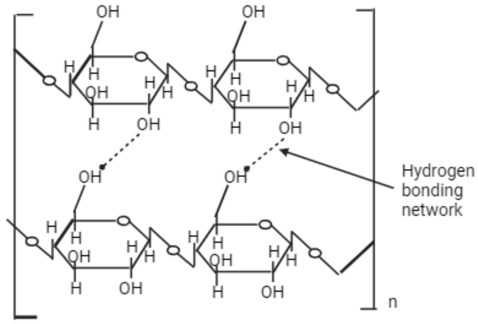

Figure 1. Structure of cellulose with hydrogen bonding networks

Nanocellulose secreted by bacteria are known as bacterial nanocellulose (BNC). Bacterial nanocellulose is a linear polysaccharide produced by bacteria composed of repeating D-glucose units connected by β-1,4-glycosidic bond. It exhibits greater mechanical properties and is higher in purity than plant-derived cellulose. Because of its superior mechanical properties, BNC is utilized in blood vessel and bone tissue engineering (Ao & Xun, 2024). Although the chemical compositions of BNC and plant cellulose are similar, BNC shows unique physicochemical characteristics, which endows it with superior properties (Walling *et al*., 2023; Fernández *et al*., 2019). Fibrils of BNC have an ultra-fine structure and are only one-hundredth of the breadth of plant cellulose. Therefore, BNC is referred to as "nanocellulose" (Meftahi *et al*., 2015). Professor Brown isolated this cellulose-producing acetic acid bacteria in 1886 and named it *Acetobacter xylinum*, which was later changed to *Acetobacter xylinus* (Jacek *et al*., 2019). Acetic acid bacteria, a rod-shaped, strict anaerobic Gram-negative bacterium, are classified as members of the Acetobacteraceae family and are distinguished by their ability to oxidize carbon sources and alcohols to produce acetic acid (Valera *et al*., 2015). Literature indicates a particular interest in *Komagateibacter xylinus* and *Komagateibacter hansenii* due to its high cellulose production. A single cell of K. *xylinus* is capable of polymerising 200000 glucose molecules and producing nanofibril polymer chains in 1 second (Chen *et al*., 2011). Other carbon sources, such as galactose, xylose, fructose, and other reducing sugars, as well as glucose-containing cellulose hydrolysate, can also be used to produce BNC. Table 1 summarises BNC producers isolated from various sources.

Table 1. BNC producer isolated from different sources

Sources	Bacterial isolates	References
The soil samples	*Bacillus* sp. strain SEE-3	(El-Naggar *et al*., 2023)
Fermented coconut water	*Bacillus velezensis* BV-HSTU-FPP	(Akhter *et al*., 2022)
	Bacillus subtilis BS-HSTU-FPP	
Kombucha	*Komagataeibacter hansenii* SI1	(Cielecka *et al*., 2021)
	Komagataeibacter hansenii JR-02	(Li *et al*., 2018)
	Komagataeibacter xylinus B-12068	(Volova *et al*., 2018)
Rotten fruits	*Gluconacetobacter xylinus* BCZM sp.	(Abba *et al*., 201)
Corn Steep Liquor	*Gluconacetobacter hansenii*	(Costa *et al*., 2017)
Stone fruit	*Agrobacterium tumefaciens*	(Moniri *et al*., 2017)
Kefir grain	*Rhizobium leguminosarum*	(Moniri *et al*., 2017)
Rotten fruit	*Gluconacetobacter xylinus*	(Jozala *et al*., 2015)

Although various studies on BNC synthesis have been conducted over the years, the cost of the culture medium used has been a significant issue. The main financial obstacle to the commercialization of BNC at a cheaper cost is the low conversion yield of BNC, which requires a high input of raw materials. Therefore, the current commercial goal is to look for sustainable and less expensive carbon and nutrient sources for BNC production. Numerous studies have been conducted on the utilization of agro-industrial wastes for low-cost and high-yield BNC production. The majority of the research is focused on using natural carbon sources from fruit wastes, i.e., citrus juices from oranges and grapefruits, aqueous extracts from citrus processing wastes (Andritsou *et al*., 2018; Kurosumi *et al*., 2009), rotten bananas (Hikal, 2022), and also crop residues such as potato peel wastes, coconut water and molasses that have been used instead of the glucose in Hestrin-Schramm (HS) medium. These fruit wastes and crop residues were considered as the most cost-effective carbon sources. It contains a great amount of fermentable sugars, nitrogen, and trace elements that will increase industrial-scale BNC production (Machado *et al*., 2018). Different carbon sources include sucrose, fructose, maltose, galactose, mannose, and arabinose (Chen *et al*., 2019; Molina-Ramírez *et al*., 2017). These can be used for culturing bacteria to produce BNC in an environmentally friendly way. From the standpoint of environmental friendliness, this technique looks promising. In line with the Sustainable Development Goals (SDG) No 12, principle of food loss and waste (FLW) management could be achieved by using agro-industrial wastes for BNC production. This review discusses the overview of BNC, its synthesis mechanism, and various fruit wastes and crop residues utilized for BNC production. This paper also highlights the advantages and disadvantages of agro-industrial waste utilization and its future perspectives on BNC production.

Molecular Mechanism of BNC Production

More than 20 years ago, the BNC synthesis mechanism of *Glucanocetobacter* sp. was studied due to its high BNC production. Generally, BNC production is classified as a dual-coupled process of polymerization and crystallization. BNC production involves four main steps which are the phosphorylation of glucose by glucokinase to glucose-6-phosphate (G6P); isomerization of glucose-6-phosphate to glucose-1-phosphate (G1P) by phosphoglucomutase (PGM); conversion of glucose-1-phosphate to uridine diphosphate glucose (UDP-glucose) by UDP-glucose pyrophosphorylase; and finally, the synthesis of cellulose from UDP glucose by cellulose synthase (Sahari *et al*. 2023; Chawla *et al*. 2009). Figure 2 shows the biochemical pathway of BNC production.

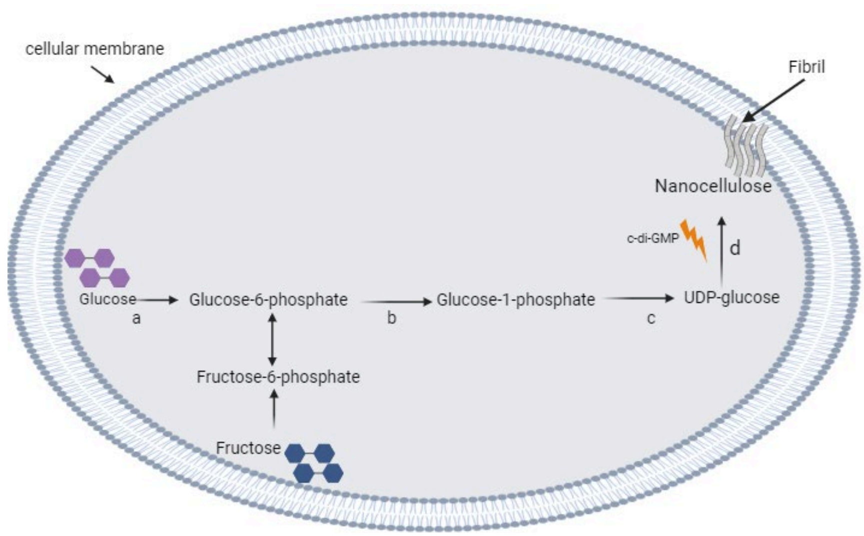

Figure 2. Biochemical pathway of bacterial nanocellulose production mediated by enzymes; a: glucokinase; b: phosphoglucomutase; c: UDP-glucose pyrophosphorylase; d: cellulose synthase

Cellulose synthase (EC 2.4.1.12) is the primary enzyme for cellulose production. It catalyses the polymerization of glucose molecules into long chains forming nanocellulose. Cellulose synthase complex in bacteria such as *Komagataibacter xylinus* typically comprises of several subunits. Bacterial cellulose synthase (Bcs) is responsible for the synthesis of BNC. Bacterial cellulose synthase comprises four different subunits, namely BcsA, BcsB, BcsC, and BcsD. According to previous studies, the BcsA and BcsB subunits are crucial for the synthesis of BNC, but the mechanism of action of BcsC and BcsD remains unclear (Ryngajłło *et al*., 2019). However, a study showed that mutation in BcsC and BcsD produced less BNC, suggesting their significant roles in BNC synthesis (Römling & Galperin, 2015). According to Barja (2021), BcsA is the catalytic component in the production of BNC. When the secondary messenger, c-di-GMP, binds to the PilZ domain of the BcsA subunit, it modifies its conformation, allowing UDP-glucose to bind to the catalytic site and activate the cellulose synthase activity (Sahari *et al*., 2023).

Commercial Medium for BNC Production

The genera *Gluconacetobacter*, *Sarcina*, *Rhizobium*, *Agrobacterium*, and numerous aerobic and non-pathogenic bacteria produce BNC in synthetic or non-synthetic medium. Hestrin-Schramm medium is the most widely used chemically defined medium for BNC production studies. Sufficient nutrients from the culture medium are important as they affect bacterial growth and functional metabolism. Several studies suggested that the yield of BNC may vary depending on the nutrient supplies, including the carbon and nitrogen sources. Various cellular responses, including cell growth and metabolite production, can be regulated by varying the nutrient content without changing any environmental or genetic factor (Kim and Kim., 2017). The HS medium consists of glucose as the primary carbon source. Most bacteria including *Komagataibacter*, are capable of fermenting and polymerising glucose into BNC. Moreover, HS contains yeast extract and peptone, the nitrogen sources, which are essential protein components for cellular metabolisms. Son *et al*. (2001) claimed that complex nitrogen sources such as peptone and yeast extract, including minerals, amino acids, carbohydrates, and short-chain peptides are crucial for the bacterial isolates to produce nanocellulose. Reports suggested that nanocellulose-producing bacteria require complex nitrogen sources for optimum cell growth (Hestrin and Schramm, 1954; Kim and Kim., 2017).

De Souza *et al*. (2018) studied the utilization of a defined medium for BNC production rather than a complex medium. The defined medium has better reproducibility, process control, and monitoring (Tabaii & Emtiazi, 2016). De Souza *et al*. (2018) studied BNC production using a defined medium to evaluate bacterial growth and to assess a comparable amount of BNC production to the complex HS medium. The complex components, such as peptone and yeast extract in the HS medium were replaced with other nitrogen sources. The findings suggested that 25 mM of glucose and 10 mM of NH_4Cl were the appropriate concentrations of C and N ratio for the synthesis of BNC. When the carbon and nitrogen concentration was increased, a decrease in the yield of BNC was observed. This finding was supported by Molina-Ramírez *et al*. (2017) where 1% and 3% w/v of glucose, fructose, and sucrose, respectively, produced a lesser amount of BNC. The high concentration of carbon and nitrogen is not favourable and limits the growth of the bacteria. Moreover, some bacteria can utilize other carbon sources such as glycerol, lactose, and maltose. Rangaswamy *et al*. (2015) studied the utilization of glucose, fructose, sucrose, lactose, maltose, mannitol, and mannose as a carbon source for *Gluconacetobacter* sp. RV28. The results indicated that the optimum BNC production was achieved at pH 6, temperature of 30°C, 2% sucrose as a carbon source, and 0.5% peptone as a nitrogen source. This isolate was able to utilize sucrose, the disaccharide molecule, which will be hydrolysed first into monosaccharides, entering the BNC synthesis pathway.

The BNC formation either in static or agitated conditions, affects the structure and yield of the BNC. Generally, bacteria produce a thick gelatinous white pellicle at the air-liquid interface of the medium when incubated in static conditions which is more suitable for biomedical applications. This is because the nanosized fiber and higher water-holding capacity allow the drugs to be loaded and released much more quickly. BNC is produced in a higher yield in agitated conditions with loosely packed crystalline arrangements, which are more suitable for bioremediation applications (R *et al*., 2021). Several studies have also shown that BNC can be produced at the bottom of the flask, indicating its high amorphous regions as compared to the crystalline areas. The amorphous region creates gaps between the crystal units, which prevents the air from being trapped resulting in sinking the BNC to the bottom (Liu *et al*., 2023). However, the production of BNC also depends on the bacteria used, oxygen supply, medium pH, incubation time, and incubation temperature. Depending on these parameters, the BNC is produced in a few days (3-14 days) with a yield of up to 10 g/L (Revin *et al*., 2018; Gorgieva *et al*., 2023).

Agro-Industrial Wastes for BNC Production

Hestrin & Schramm medium is utilized for the synthesis of BNC studies. It is costly and requires high amounts of chemical reagents such as glucose, yeast extract, and peptone to obtain a high yield of BNC, which hinders the large-scale production of BNC. Most agro-industrial wastes from various processing industries are either dumped in landfills or thrown out in inappropriate sites, resulting in biomass accumulation. Agro-industrial wastes are discarded after processing juices, canned foods, harvest wastes, and crop residues. These wastes contain various valuable enzymes and biochemical components that can be reused and recycled to reduce environmental waste. Biotechnological approaches and advances in clean technology have provided scientists and researchers with a platform for utilizing agro-industrial wastes to produce BNC. Wastes and by-products from the agricultural sectors can be great alternative carbon sources, i.e., glucose in the HS medium. Generally, agro-industrial wastes are richer in proteins, carbohydrates, and trace elements, which confer a high yield of BNC production (Kongruang, 2008). Suitable agro-wastes include sugarcane bagasse, fruit peels, rice husks, and corn cobs. Alternative affordable carbon sources are preferred since the higher cost of glucose and other carbohydrates prevents their application in the large-scale production of BNC. Recently, reports have focused on using different low-cost carbon sources for the biosynthesis of BNC (Kiziltas *et al.*, 2015). Bacterial nanocellulose from agro-industrial wastes is an eco-friendly and sustainable approach that uses agricultural by-products to produce valuable and multifunctional biopolymers. Therefore, current research has mostly focused on using fruit wastes and crop residues as sustainable nutrient sources to produce BNC to lower production costs and environmental wastes. As shown in Table 2 and Table 3, in the past decade numerous studies have been done using agro-industrial wastes for BNC production.

Table 2. Production of BNC from various fruit wastes

Agro-industrial wastes	Other medium incorporation	Inoculum	Incubation time (days)	BNC dry weight (g/L)	BNC productivity (g/L/d)	References
Date fruit	NA	*Komagataeibacter saccharivorans* MD1	7	3.2	0.46	(Abol-fotouh *et al.*, 2020)
Date pomace	NA	Vinegar-mother	NA	0.92	NA	(Al-Hamaiedeh *et al.*, 2023)
Fig fruit wastes	NA	*Komagataeibacter saccharivorans* MD1	7	2.5	0.36	(Abol-fotouh *et al.*, 2020)
Orange juices	NA	*Komagataeibacter sucrofermentans* DSM 15973	13	6.1	0.47	(Andritsou *et al.*, 2018)
Grapefruit juices	NA	*Komagataeibacter sucrofermentans* DSM 15973	13	6.7	0.52	
Lemon peel extract	NA	*Komagataeibacter sucrofermentans* DSM 15973	13	5.2	0.40	
Grape peel extract	NA	*Komagataeibacter sucrofermentans* DSM 15973	13	5.0	0.39	
Orange peel extract	NA	*Komagataeibacter sucrofermentans* DSM 15973	13	2.9	0.22	
Orange peel juice	NA	*Acetobacter xylinum* NBRC 13693	14	5.9	0.42	(Kurosumi *et al.*, 2009)
Pineapple peel	NA	*Bacillus cereus* MMS1	12	2	0.17	(Lee *et al.*, 2022)
	NA	*Acetobacter xylinum*	12	NA	NA	
Pineapple waste	NA	*Acetobacter xylinum*	13	4.255	0.33	(Pham & Tran, 2023)
Pineapple waste	NA	*Acetobacter xylinum*	7	Approx 2 cm thickness	NA	(Le *et al.*, 2023)
Banana peel	5% sucrose content	*Gluconacetobacter xylinus*	6	15 cm thickness	NA	(Sijabat *et al.*, 2020)
Banana peel	NA	K.*xylinus* IITRDKH-20	16	5.34	0.33	(Khan *et al.*, 2023)
Mango peel waste	NA	*Achromobacter*	14	1.22	0.09	(Hasanin *et al.*, 2023)
Mango pulp waste	NA	*Komagataeibacter xylinus*	16	6.32	0.40	(García-Sánchez *et al.*, 2019)

Fruit wastes

Date Wastes

The production of BNC by *Komagataeibacter saccharivorans* MD1 was investigated by utilizing treated sugarcane molasses, date fruit waste extract, and fig fruit waste extract (Abol-fotouh *et al*., 2020). The highest yield (3.9 g/L) of BNC was obtained using the medium supplied with treated molasses, followed by date extract (3.2 g/L) after seven days of incubation. In comparison, the yield of BNC obtained using the standard HS medium was only 2.6 g/L (dry weight). Such findings might be due to the high carbohydrate contents in the molasses and date extract medium compared to the HS medium.

Recently, Al-Hamaiedeh *et al*. (2023) utilized date pomace (DP), a by-product of the date sugar industry, as a substrate for BNC production. Date pomace is a solid residue obtained from date fruit processing and contains 35% sugar on a dry basis (Haris *et al*., 2023). The study reported BNC production of 0.62 g/L (dry weight) when 10% of the DP juice ratio was used as a substrate at pH 6. At the end of the experiment, a decrease in the initial glucose and fructose content was observed, suggesting the utilization of sugar as a carbon source for BNC production. However, increasing the DP sugar ratio to 20%, resulted in a slightly reduced BNC production. This could be due to the high sugar content in 20% DP juice which has been utilized by the bacteria for cell metabolism, resulting in the release of by-products and acetic acid, hence reducing the pH of the culture medium. Notably, pH is one of the most important factors that affect the growth of the bacteria, which correlates with BNC production. The higher sugar content results in lower BNC production when incubated for a longer period.

Citrus Fruits

Due to their bitter flavour, citrus peels are typically discarded. The peel wastes contain about 30–60 g per 100 g of citrus fruit weights. Various components, such as pectin in the peel wastes, are being used as a renewable resource. Although citrus peel wastes such as orange peels and grapefruit peels are commercially used as food stabilizers, these by-products can also be another valuable resource for BNC production (Suri *et al*., 2022). Andritsou *et al*. (2018) have studied the use of citrus fruits as nutrient sources for BNC production. Orange juices, grapefruit juices, and aqueous extracts from citrus peel wastes of orange, grapefruit, and lemon were used for BNC synthesis by *Komagataeibacter sucrofermentans* DSM 15973. This study employed citrus fruit juices and peel juices as the sole carbon source, and the production was compared to the standard HS medium. The results showed that grapefruit juice medium showed the highest BNC production, which was 6.7 g/L, followed by orange juice medium (6.1 g/L), lemon peel extracts medium (5.2 g/L), and grapefruit peel extracts medium (5.0 g/L). The lowest BNC yield was obtained from orange peel extracts medium (2.9 g/L). As shown in Table 2, BNC productivity using grapefruit juice medium showed the highest (0.515 g/L/d) among the other fruit wastes used. The high production may be due to the nutrient content in the medium, which is rich in carbohydrate content, as well as other trace elements that might support the growth of the bacterial strain. Grapefruit has a high sucrose content with total carbohydrates ranging from 75.81 to 85.43 g/L (Kelebek, 2010). The higher sucrose content in the grapefruit juice increases the reducing sugar content in the culture medium by hydrolysing it into monosaccharides. These monosaccharides namely glucose and fructose will further enter the BNC production pathway, increasing BNC production.

However, Kurosumi *et al*. (2009) reported that orange juice medium produced 5.9 g/L of BNC using *Acetobacter xylinum* NBRC 13693 after 14 days of incubation. The BNC production showed a higher yield might be due to the different types of strain used and the experimental parameters that can influence its production. These studies suggested that BNC production utilizing various citrus-based fruits can be great alternative nutrient sources. A recent study by Güzel & Akpınar (2019) showed that phenolic content in the peels affects the BNC production. This study concluded that acid-hydrolyzed peel extracts with low phenolic and high citric acid content showed an increase in BNC production. This is because high phenolic content suppresses bacterial growth, thus reducing its metabolism to secrete BNC. In general, phenolic compound is known to have antimicrobial activity against some microorganisms by inhibiting bacterial virulence factors such as proteins and enzymes (Miklasińska-Majdanik *et al*., 2018).

Pineapple Wastes

The tropical pineapple is widely grown in Malaysia and Southeast Asian countries. A substantial quantity of agro-industrial waste is produced during the canning process, of which pineapple waste accounts about 44% of the peel and 15% of the core of the total raw materials used (Sukruansuwan & Napathorn, 2018). Pineapple waste is rich in a variety of nutrients, including carbohydrates like sucrose, glucose, fructose, and galactose, which can be used as a carbon source during fermentation by bacteria. Recently, BNC production using pineapple wastes as an alternative carbon source was studied by Lee *et al*. (2022). *Bacillus cereus* MMS1 and a control strain, *Acetobacter xylinum* were inoculated into the pineapple peel medium separately and incubated for 12 days at 30°C, 150 rpm. The BNC yield produced by *Bacillus cereus* MMS1 was 2 g/L; however, no BNC production was recorded for *Acetobacter xylinum*. This may be due to the lack of lignocellulose-degrading enzymes in the bacterial cell. Most BNC-producing bacteria do not contain ligninolytic or cellulolytic enzymes that can degrade cellulose, hemicellulose, and lignin (Lee ***et al***., 2022). Despite that, Pham & Tran (2023) studied BNC production from pineapple wastes using *Acetobacter xylinum.* The pineapple waste used in the study was collected from the local market, which was then pressed to produce the pineapple waste juices. After 13 days of incubation in the pineapple waste medium, the optimum crystallinity of BNC produced was 82%. These studies showed the potential use of pineapple waste as a carbon source for BNC production. Even though *Acetobacter xylinum* was used as the inoculum in both Lee ***et al***. (2022) and Pham & Tran (2023) studies, the type of pineapple used, and its nutrient contents affects the composition of the pineapple waste medium, which explains the productivity of BNC.

Recently, the use of BNC produced from pineapple waste as an aerogel for the adsorption of dyes was studied (Le ***et al***., 2023). The abundance of hydroxyl group in BNC is one of its distinctive features. The presence of this functional group improves its ability to retain water and makes modification techniques possible. In this study, the extract of pineapple peel waste (Ananas comosus Spanish) was used as a culture medium to produce BNC under static conditions for seven days. The bacteria *Acetobacter xylinum* was able to produce approximately 2cm thickness of BNC which was further used for dye removal application. A significant methylene blue dye uptake of 29.7 mg/g was achieved at 30°C, pH 6.5 for 30 min of incubation (Le ***et al***., 2023). This is because of the abundance of OH groups present in the BNC which is involved in the dye uptake process. Methylene blue dye, a positively charged group, will bind to the negatively charged OH- groups via electrostatic interaction resulting in removing methylene blue from the aqueous solution. Moreover, various modification techniques, such as chemical precipitation and coagulation, can be introduced into BNC, enhancing its bioremediation processes.

Banana Wastes

Banana peel wastes are rich in fermentable sugar whereas ripe banana peels contain about 30% of free sugars (Hikal, 2022). According to research, banana peel extract may be able to partially replace commercial carbon and nitrogen sources for BNC production (Adnan ***et al***., 2015). Banana peel culture medium was prepared and used as a fermentative medium utilizing *Gluconacetobacter xylinus* (Sijabat ***et al***., 2019). The average BNC dry weight produced was 15 cm thick when 5% of sucrose was employed as the carbon source. The BNC produced from banana peel in this study was nanofibril of 30-50 nm which supports the nano-structured nature of the polysaccharide produced. The density and shape of the BNC nanofibrils network depend on the organism and methods used for the BNC production. The cross-linked three-dimensional networks and nanofibrillated structure of BNC were analysed by physicochemical studies.

Banana peel extract medium as a carbon source was recently studied utilizing K. *xylinus* IITRDKH-20 strain (Khan ***et al***., 2023). BNC production in two different media, banana peel extract (E-BPW) and banana peel extract incorporated with HS medium components (EBPW-HS) were evaluated. The results showed that after 16 days of static incubation, a two-fold BNC was produced in the EBPW-HS medium (5.34 ± 1.03 g L^{-1}) compared to the E-BPW medium. The study was further expanded by studying the BNC production using static intermittent fed-batch with a supply of fresh bacterial culture on every fourth day of incubation. The results suggested that supplying sufficient nutrients and new culture growth are important to produce a high yield of BNC. After 16 days of the intermittently fed batch, the BNC yield was 9.24 ± 0.31 g L^{-1}. The supplementation of new bacterial culture to the medium ensures continuous bacterial growth and proliferation, which results in more secretion of BNC. However, one of the limitations of this study is as the BNC thickens over time, it limits the oxygen permeability to the bacterial culture resulting in lower BNC production even though a new bacterial culture has been added.

Mango Wastes

The production of BNC by *Achromobacter* S3 was investigated by utilizing peels of apple, orange, banana, pomegranate, pineapple, and mango (Hasanin ***et al***., 2023). Among the different types of wastes utilized, mango peel waste medium produced BNC with the highest yield of 0.52 g/L, compared to HS medium which produced 0.48 ± 0.02 g/L BNC. The highest synthesis of BNC might be due to the suitable type and concentration of carbohydrate present. Other factors, such as inhibitors in the waste sample, play a crucial role in bacterial growth. While the extract from mango peel waste can be directly incorporated into the culture medium, it is important to pretreat the peel wastes to ensure the cellulose in the peel is hydrolyzed yielding higher carbohydrate content. In this study, hydrolysis of the peels with nitric acid resulted in various yield of BNC. This is due to the breakdown of hydrogen bonds between the polysaccharides of the wastes resulting in easy access to cellulose. Statistical optimization of the BNC production in mango peel waste medium showed a 2.5-fold increase with 1.22 g/L of BNC dry weight. When produced using agro-industrial wastes as substrates, BNC can have unique physicochemical properties due to the variable composition of these waste materials. The variability influences its unique physicochemical properties, such as high purity, crystallinity, tensile strength, and water retention capacity, making it versatile for various applications, from biomedical to industrial. The crystallinity of BNC produced from mango peel waste was 79% as compared to BNC produced from HS medium with 72%. It is notable that, the FTIR results showed a shift in the wavenumber for BNC produced from mango peel waste. According to Abol-fotouh *et al*., (2020), these results might possibly be due to certain chemical compounds present in the mango peel that might improve the BNC production.

Another study conducted by García-Sánchez *et al*., (2019) reported the use of mango pulp waste for BNC production using *Komagataeibacter xylinus*. The BNC produced using only mango pulp waste as a medium showed lesser yield due to low nitrogen content. Incorporation of various nitrogen sources into the medium showed a better BNC production. Organic nitrogen sources are the most favorable for cellulose biosynthesis. It plays a crucial role in BNC production since it is the primary component and essential for cell growth and metabolism (El-Naggar *et al*., 2023). Results showed that, after 16 days of static incubation conditions, mango pulp wastes with yeast extract as a nitrogen source produced 6.32 g/L of BNC. However, the crystallinity index of BNC produced from mango pulp waste is lesser than the BNC produced in HS (control) medium. The composition of wastes can affect the physicochemical properties of the BNC. BNC with lower crystallinity produced may have some potential application in the bioremediation field. As an example, BNC with more amorphous regions has higher surface area which allows more adsorption of the pollutants. In contrast, stronger intra- and intermolecular bonds between the higher crystalline structure of BNC requires chemical treatment for the breakdown (Mathivanan *et al*., 2024). Bacterial nanocellulose with more amorphous region offers a greater potential for modification to be applied in bioremediation without further chemical treatments.

Crop Residues

Tobacco Wastes

The consumption of tobacco, a global commercial crop has been steadily increasing (Wang *et al*., 2017). With over two million tonnes of tobacco trees being cut annually for cigarette production, China has become the largest producer and user of tobacco products globally (Liu *et al*., 2015). About one million tonnes of tobacco trash, consisting of scraps, undesirable tobacco leaves, and stems, were discarded during the production process (Zhong *et al*., 2010; Wang *et al*., 2013). The use of tobacco waste extract as a carbon source was evaluated by Ye *et al*. (2019). The study involved the preparation of tobacco waste extracts at different solid-to-liquid ratios. The sugar composition analysis revealed that the solid-to-liquid ratios of 1:6 provided the highest sugar content, hence it was chosen for medium preparation. However, the study found that BNC production by *Acetobacter xylinum* in tobacco waste medium prepared at 1:6 of solid-to-waste ratios was lower than at 1:10 and 1:8 ratios. This may be because the tobacco waste with a 1:6 ratio is concentrated with nicotine, which acts as an inhibitor and affects the growth of the bacteria. Several pre-treatment methods can be introduced to remove the nicotine level. In this study, after the steam distillation method, it was observed that an increase in BNC production yielded up to 2.27 g/L dry BNC after seven days of static incubation.

Potato Peels

Crop peels are a great source of vitamins, proteins, reducing sugars, and different acids. The crop peels can be used as a substrate or feedstock for microbial growth to produce various enzymes, biochemicals, biofuels, and metabolites, all while taking into account their nutritional value. An enormous amount of potato peel waste is produced annually from industrial potato processing, especially from frozen food processing. Since potato peel waste (PPW) is too fibrous to be digested, it is not recommended for non-ruminants without prior treatments (Liitiä *et al*., 2003). The use of PPW as an initiative to reduce the cost of culture medium for BNC production was investigated by Abdelraof *et al*. (2019). This study found that treating the PPW with acid hydrolysis resulted in a high reducing sugar concentration. Acid hydrolysis treatment helps break down and solubilize structural carbohydrates, such as cellulose or starch, increasing the amount of glucose and reducing sugar in the sample. The results showed that incubation of *Gluconacetobacter xylinum* ATCC 10 245 for four days in the HS medium yielded 1.21 g/L of BNC. The BNC yield from this study was in the same range as those reported in the literature using the same HS medium (El-Saied, *et al*., 2008; Kuo *et al*., 2016). On the other hand, during the first two days of fermentation, BNC was visibly produced on the air-liquid interface of the PPW acid hydrolysate medium. This shows the efficiency of the strain used to produce BNC in a short time. The cultivation conditions are also crucial factors to note for better and faster BNC production. The PPW-nitric acid hydrolysate (2.61 g/L) yielded the highest BNC, followed by PPW-sulfuric acid hydrolysate (2.18 g/L), exceeding that of the other PPW acid hydrolysate.

Table 3. Production of BNC from various crop residues

Agro-industrial wastes	Other medium incorporation	Inoculum	Incubation time (days)	BNC dry weight (g/L)	BNC productivity (g/L/d)	References
Tobacco	NA	*Acetobacter xylinum* ATCC 23767	7	2.27	0.324	(Ye *et al.*, 2019)
Potato peels (Nitric acid hydrolysis)	NA	*Gluconacetobacter xylinum* ATCC 10 245	4	2.61	0.653	(Abdelraof *et al.*, 2019)
Potato peels (sulfuric acid hydrolysis)	NA	*Gluconacetobacter xylinum* ATCC 10 245	4	2.18	0.545	
Treated sugarcane molasses	NA	*Komagataeibacter saccharivorans* MD1	7	3.9	0.557	(Abol-fotouh *et al.*, 2020)
Molasses	Corn steep liquor	*Acetobacter* sp. V6	7	4.98	0.711	(Jung *et al.*, 2010)
Coconut water	NA	*Acetobacter xylinum*	12	3.612 g BNC/g glucose	NA	(Lestari *et al.*, 2014)
Coconut water	NA	A. *xylinum*	7	2.44	0.349	(Fathiyah *et al.*, 2021)

Molasses

Molasses is a widely studied agro-industrial waste for BNC production as it is rich in various sources of carbohydrates, making it an ideal fermentative medium. Recent studies using sugarcane molasses medium have shown excellent BNC production with greater physicochemical characteristics (Perna Manrique *et al*., 2018; Abol-Fotouh *et al*., 2020). BNC production by *Komagataeibacter saccharivorans* MD1 was studied with an initial 10% v/v molasses concentration (Abol-Fotouh *et al*., 2020). Although the study reported a higher sugar content in date fruit waste medium than in molasses and fig fruit waste media, the highest BNC yield was achieved using molasses medium (3.9 g/L). The higher BNC yield in molasses medium than other mediums (date fruit waste, fig fruit waste, and HS medium) could be due to the lower glucose content. This is because higher glucose content in date fruit resulted in the formation of gluconic acid and by-products. The accumulation of gluconic acid reduces the pH of the culture medium, resulting in a more acidic environment inhibiting the growth of the bacteria. According to Perna Manrique *et al*. (2018), an initial molasses concentration of 13.3% was used because molasses concentrations lower and above this value inhibit the growth of the bacteria and decrease BNC synthesis. Additionally, similar FTIR profiles were obtained for BNC produced from molasses and complex media, indicating the capability of the bacteria to metabolize various carbon sources for BNC production (Jung *et al*., 2010).

In another study, molasses and corn-steep liquor (CSL) were used as a culture medium under agitated conditions (Jung *et al*., 2010). In the medium containing molasses and CSL, the maximum BNC yield was 3.12 ± 0.03 g/L after eight days of incubation. These results demonstrated the potential use of molasses and CSL as cost-effective substrates for BNC production using *Acetobacter* sp. V6, replacing the expensive nitrogen complexes, such as yeast extract and peptone. According to Table 3, the utilization of molasses with CSL produced the highest BNC productivity rate (0.711 g/L/d) compared with other crop residues. This can be due to the high carbohydrate content found in molasses. Sugarcane molasses contains around 62.3% sugar, organic acids and trace elements. Molasses is predominantly composed of sucrose (48.8%), followed by fructose (8.07%), and glucose (5.29%) (Palmonari *et al*., 2020). As molasses is rich in carbohydrates and glucose as the starting molecule, it increases its utilization by bacteria for BNC production. Moreover, the CSL added to the medium acts as a nitrogen source, facilitating the bacteria's growth for protein synthesis and cellular metabolism. Similar forms of cellulose (type I) were observed in the FTIR spectra of the BNC synthesised from the molasses and HS media, suggesting the capability of the bacteria to metabolise various carbon sources to produce BNC with similar physicochemical properties.

Coconut Water

In many Southeast Asian countries, coconut water is dumped from agro-industries. However, research has demonstrated the potential use of coconut water for the production of highly pure BNC as the coconut water is rich in carbon and nitrogen sources (Kongruang, 2008; Kurosumi *et al*., 2009). BNC production using two different agro-industrial wastes, pineapple waste, and coconut water, was investigated by Lestari *et al*. (2014). Based on this study, a higher yield of BNC was obtained in the coconut water medium (19.34 g/L) than in the pineapple waste medium (10.04 g/L). However, the reducing sugar utilization was higher in the pineapple juice medium than in the coconut water medium. This finding suggests that the bacteria A. *xylinum* utilized the sugar in the pineapple waste medium for its bacterial growth and synthesis of proteins rather than for BNC production.

A similar study was conducted using coconut water as an alternative fermentative medium for BNC production using A. *xylinum* (Fathiyah *et al*., 2021). At a volume ratio of coconut water to distilled water of 20:80, a maximum yield of BNC was obtained (2.44 g/L). Further increase in the ratio of coconut water resulted in reduced BNC production. This reduction could be due to the high sugar content in the coconut water that results in gluconic acid accumulation. However, incorporating oil palm frond juice with coconut water has resulted in a higher BNC yield (4.50 g/L) with a ratio of 40:60 of oil palm juice and coconut water, respectively. The sugar contents such as sucrose, glucose, and fructose in mature coconut water were 18.8 g/L, 116.2 g/L, and 15.6 g/L respectively (Burns *et al*., 2020). The high sugar content in coconut water is a promising alternative substrate for BNC production. Disaccharide molecules such as sucrose are hydrolyzed first into glucose and fructose before entering the BNC metabolism pathway. In contrast, monosaccharides such as glucose and fructose can be directly fed into the BNC synthesis pathway. It is also important to consider the influence of the type of bacteria used for BNC production as different bacteria may favor different metabolic pathways for cellular growth and BNC synthesis, resulting in different types of chemical and physical compositions of BNC.

Oil Palm Wastes

The oil palm frond (OPF) is the primary biomass source in the oil palm industry. Malaysia accounted for 25.8% of global palm oil production and 34.3% of global palm oil exports in 2020 (Malaysia Palm Oil Council, 2023). According to reports, the OPF constitutes 47% of oil palm waste, accounting for the largest biomass (Roslan *et al*., 2014). Similar to sugarcane juice, oil palm frond juice (OPFJ) can be obtained by pressing the fresh OPF. Oil palm frond juice is a suitable fermentation medium since it contains carbohydrates as well as nutrients like nitrogen, magnesium, calcium, zinc, phosphorus, and sulphur (Abdullah *et al*., 2015). Several studies have reported the use of OPFJ as a carbon source for BNC production.

The use of OPFJ as a sole carbon source or with the incorporation of other carbon and nitrogen sources has also been studied. The potential use of OPFJ as a medium for *Acetobacter xylinum* 0416 has successfully produced BNC, yielding 0.051 g BC/g of glucose (Said Azmi *et al*., 2023). This study also revealed that the incorporation of CSL as a nitrogen source increased the BNC yield six-fold. The BNC pellicles produced in the study showed a significant swelling ratio, great crystallinity, and better thermal stability. One of the most prominent components needed for the cell's building block is the nitrogen source. It was reported that A. *xylinus* subsp. could produce nanocellulose when CSL was combined with other nitrogen sources (El-Saied *et al*., 2008). While some studies reported that varying carbon and nitrogen sources for some bacteria did not affect the structure of the BNC, a few studies reported a diversity in the structure of BNC with varied carbon and nitrogen sources (Nguyen *et al*., 2010; Keshk, 2014). Moreover, the addition of extra nitrogen sources does not generally favour BNC production rather, it favours biomass formation. The type of nitrogen source utilized in a culture medium is a crucial factor as it affects the cell growth and cell metabolism of the bacteria, resulting in higher or lower BNC production.

In another study, Fathiyah *et al*. (2021) evaluated the incorporation of OPFJ with coconut water at different ratios. The results showed that the incorporation of OPFJ with coconut water at the ratio of 40:60 of OPFJ to coconut water resulted in a higher BNC yield (4.50 g/L). A lower volume is required since the highest sugar content in OPFJ (40g/L total sugars) may produce gluconic acid. The incorporation of lignosulphonate showed promising results in reducing the pH of the culture medium to prevent the accumulation of gluconic acid. This is because lignosulphonate contains polyphenolic and antioxidant chemicals that can alter the kinetics and minimise gluconic acid formation (Chawla *et al*., 2009).

Advantages and Disadvantages of Agro-Industrial Waste Utilization

The enormous use of agro-industrial wastes for BNC synthesis has attracted more interest due to its positive economic and environmental advantages. Wastes from agro-industrial processes, such as leftovers from food processing or crop wastes are abundant and renewable resources that can be turned into useful goods. Bacterial nanocellulose has unique properties compared to plant-derived cellulose making it a versatile polymer that can be used for various industrial applications such as biomedical, food, and packaging. Though there are some promising benefits of using agro-industrial wastes, there are a few drawbacks as well that need to be addressed and taken into consideration. We discussed the advantages and disadvantages of using agro-industrial wastes as nutrient sources for BNC production, highlighting both the opportunities and potential drawbacks of this approach.

Advantages

Cost Effective

Using agro-industrial wastes as a substrate for BNC production is a cost-effective method. The agro-industrial wastes are often found in abundant and inexpensive, making them a viable option for BNC production. Generally, the commercial medium used for BNC is HS medium. This medium is composed of costly chemicals such as glucose and yeast extract which hinders the viability of BNC to be applied for large-scale production (Chawla *et al*., 2009; Kadier *et al*., 2021). The starting molecule, glucose is often found abundant in wastes, which can be potentially used for BNC studies. Most agro-industrial wastes such as coconut and pineapple juices are discarded, but they are high in carbohydrates and trace elements (Abol-Fotouh *et al*., 2020). Additionally, agro-industrial wastes with higher cellulose content can potentially yield higher BNC production. Fruit and vegetable peels, for instance, are known to contain significant amounts of cellulose, making them promising substrates for BNC production. Studies show that in general, yeast extract is rich in vitamins, especially B complex, amino acids, and trace elements that stimulate bacteria's growth. A few agro-industrial wastes such as CSL are richer in nitrogen sources which may replace the high cost of yeast extract utilization in HS medium. Utilizing these wastes not only leads to cost-effectiveness by reducing waste disposal expenses but also supports the growth of bacteria for a higher yield of BNC.

Environmental Sustainability

The production of BNC from agro-industrial wastes contributes significantly to the environmental sustainability. By reusing agro-industrial wastes, it decreases the load on the landfills which prevents the accumulation of wastes. It also significantly reduces the greenhouse gas released into the environment. Annual food waste has a global carbon footprint (CF) of about 3.3 Gt carbon dioxide equivalent (CO_2e) (Fan *et al*., 2020). The utilization of agro-industrial wastes prevents the reliance on raw materials such as plant cellulose. Primarily, the cellulose was extracted from wood, cotton, and other plant sources. This harvesting method was not only time-consuming but also required a few chemical treatments to remove the polysaccharides. These processes release toxic effluents and chemicals which in turn cause environmental pollution (Jozala *et al*., 2015). Furthermore, the reliance on plant-derived cellulose increases deforestation which is not environmentally friendly.

In contrast, agro-industrial wastes offer a sustainable alternative as they are readily available by-products of agricultural and industrial processes. These wastes are often generated in large quantities that can be recycled for value-added applications such as BNC production. Moreover, utilizing agro-industrial wastes for BNC production aligns with the principles of sustainability, where waste materials are regarded as valuable resources to be recycled and reused. This approach promotes resource efficiency and waste reduction while fostering sustainable production practices.

Renewable Feedstock

The utilization of agro-industrial wastes for BNC production promotes the principles of circular economy by turning wastes into valuable resources. Agro-industrial wastes are renewable resources that are replenished through cyclic agricultural activities. Agro-industrial wastes are generated continually as a result of ongoing agricultural processes such as planting, harvesting, and processing of crops, in contrast to fossil-based resources, which are limited and non-renewable. It is continuously available as feedstock for BNC production since agricultural activities are periodic, which prevents resource depletion and long-term impact on the environment. Utilizing agro-industrial wastes for BNC production aligns with principles of sustainable agriculture and circular economy. An estimated 5 tonnes of solid grape trash are produced annually per hectare during cultivation and harvesting (Zacharof, 2016). Thus, it becomes evident that valuable compounds from the wastes need to be recovered, recycled, and reused. The continuity presents of agro-industrial wastes opens a way to use this renewable feedstock for BNC production.

Disadvantages

Variability in Composition

Agro-industrial wastes can vary significantly in composition based on factors such as crop variety, harvesting methods, and processing techniques. The source of agro-industrial wastes can significantly influence BNC production. As the different regions worldwide harvest different fruit or crop types, the nutritional composition of the fruits or crops may differ. As a result, the wastes may have different compositions. Variability includes parameters such as moisture content, cellulose, hemicellulose, and lignin content. As explained in section 4.1.3, even though pineapple waste is used as the substrate for BNC production, the composition of the wastes may differ which showed the result in the BNC productivity. This is because agro-industrial wastes such as fruit wastes and crop residues may contain carbohydrate compounds in different ratios including monosaccharides and disaccharides content. Due to the different ratios, some strains may need to hydrolyze the disaccharide molecule first to be able to be utilized it as a substrate. Certain agro-industrial wastes have high content of monosaccharides, which makes it possible to achieve a noticeably higher BNC yield in a shorter timeframe. This is explained by the possibility that bacterial metabolism needs more time to effectively hydrolyze the disaccharide molecules. Moreover, the effect of trace elements also influences the bacterial metabolism for BNC production. This variability may lead to inconsistent bacterial growth and nanocellulose production, affecting its quality and yield.

Inhibitors

Agro-industrial wastes may contain contaminants such as pesticides, heavy metals, or microorganisms. Inhibitors such as antimicrobial agents can interfere with bacterial metabolism which inhibits the bacterial growth for BNC synthesis. Research indicates that fruit wastes, including extracts from the peels of pomegranates (*Punica granatum*) and sweet oranges (*Citrus sinensis),* have antimicrobial properties against a variety of microorganisms, including B. *cereus*, E. *coli*, S. *aureus*, B. *subtilis*, and P. *aeruginosa* (El-Beltagi *et al*., 2022). This antimicrobial agent may suppress the growth and proliferation of the bacteria affecting the BNC production. Other than that, research has also reported that phenolic compounds inhibit cellulose-hydrolyzing enzymes and cellulose-producing bacteria (Ximenes *et al*., 2011). Phenols are chemical compounds that are present in a wide range of plants with an aromatic ring bearing one or more hydroxyl constituents (Onuoha *et al*., 2011). A study conducted by Li *et al*., (2014) showed that the major polyphenolic compounds that exist in pineapple peels were catechin, epicatechin, gallic acid, and ferulic acid. This was supported by analysis done by Zhang *et al*. (2014) showed that several model phenolic compounds present in the wastes such as coniferyl aldehyde, ferulic acid, vanillin, and 4-hydroxybenzoic acid showed an inhibitory effect on BNC production by G. *xylinus*. These compounds can potentially inhibit bacterial growth and affect the BNC synthesis.

Complex Pretreatment

Agricultural wastes are usually lignocellulosic biomass which contains complex molecular structures including cellulose, hemicellulose, and lignin. Generally, agricultural wastes consist more of cellulose than hemicellulose and lignin (Awogbemi & Kallon, 2022). Owing to their complex physicochemical structure and composition, certain lignocellulosic biomass, such as agricultural wastes, are difficult to break down. The biomass is put through a few processes in order to break down lignin and hemicellulose, making cellulose more accessible for bacterial fermentation. The procedure used on the biomass to get over the initial barrier is known as the pretreatment process. Some agro-industrial wastes may require pre-treatment to enhance cellulose accessibility and remove impurities or inhibitors. Pre-treatment methods such as physical, chemical, or enzymatic treatments can improve the efficiency of BNC production. However, the feasibility and cost-effectiveness of pre-treatment methods should be evaluated to ensure optimal utilization of resources. Pretreatment methods may incur additional costs and energy consumption, offsetting the economic benefits of using agro-industrial waste as a nutrient source.

Future Perspectives

This paper reviews the recent advancements and sustainable approaches for BNC production. Different types of agro-industrial wastes, including fruit wastes and crop residues used for BNC production, are highlighted in this paper. BNC holds great promise in many industries due to its unique properties. Using agro-industrial wastes for BNC production aligns with sustainability goals which aim to reduce waste and the reliance on raw resources. This approach can contribute to more environmentally friendly processes. For future outlooks of BNC in agro-industrial utilization, some recommendations that can be made are to study solid-state fermentation production methods using naturally adapted in-situ mixed culture. Microorganisms such as lactic acid bacteria, acetic acid bacteria, and yeast in SCOBY are known to work mutually to produce BNC. These microorganisms are known to ferment sucrose, which can further be studied for their BNC production utilizing agro-industrial wastes as carbon sources. The major components of crop wastes such as molasses, contain higher amounts of sucrose than glucose and fructose. A study by Palmonari *et al*. (2019) reported the total sugar content in cane molasses is 62.3%, including sucrose (48.8%), fructose (8.07%), and glucose (5.29%). The study of mixed culture for BNC synthesis in agro-industrial waste medium will be a promising approach due to its higher carbohydrate content.

Agro-industrial wastes are often available in abundance and inexpensive compared to commercial medium for BNC production. Substituting the commercial medium with agro-industrial wastes can result in cost-effective processes, making BNC more economically viable for a range of applications. Another future outlook for enhancing BNC production is to optimise fermentation conditions. This can be done by the fed-batch method of BNC production using an agro-industrial waste medium. With abundant waste being produced yearly, the wastes can be recycled and reused as the culture medium continuously. This is because as the fermentative incubation time increases, the limited nutrients in the culture medium will result in the re-utilization of BNC as a nutrient source, which decreases the yield. As the fed-batch fermentation medium promotes a continuous supply of substrate to the fermentation process, the bacteria will be able to utilize the nutrient resources to produce a higher yield of BNC. In conclusion, the unique features of BNC present it as a versatile material with a wide range of potential applications in several sectors. Ongoing research is exploring new and innovative approaches for BNC production and its future outlooks are promising.

Conclusion

Bacterial nanocellulose is a versatile biomaterial with a wide range of potential industrial applications. The synthetic HS medium used for BNC production is costly as it requires a high input of raw material. Since, agro-industrial wastes are rich in carbohydrates, their utilization as nutrient sources offer suitable approach for BNC production. This review highlights the growing importance and value of waste utilization for the production of BNC. A green and sustainable environment is made possible by using fruit wastes and crop residues as substrates for BNC synthesis, which addresses the environmental concerns that have emerged in recent years. An abundance of inexpensive resources can be found in fruit wastes and crop residues. The search for BNC production from various agro-industrial wastes is an ongoing process for the commercialization of BNC to be viable. Future research focusing on optimization and synthesis of BNC from these fruit wastes and crop residues may eventually result in more affordable and less expensive BNC production methods. Continuous research and technology improvements will result in better BNC production techniques contributing to a more sustainable and resource-efficient future.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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