Potential Application of Agro-Industrial Byproduct for Bacterial Cellulose Production; Its Challenges and Emerging Trends for Food Packaging

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Abstract Most packaging used today is made of plastic, which is produced from fossil-based polymers. In terms of its ease of processing and cheapness, plastic is non-biodegradable. Apart from being a plastic substitute, cellulose-based packaging is bio-based and sustainable. Cellulose is commonly generated from vascular plants. However, numerous chemicals are required for cellulose isolation and purification. For plant cellulose replacement, bacterial cellulose is considered as the favorable resources. Bacterial cellulose, also well known as microbial cellulose, is the cellulose produced by the activity of non-pathogen gram-positive or gram-negative bacteria in the substrate containing carbon and nitrogen. Possessing a three-dimensional nano-structure, high reactive functional groups, high mechanical strength properties, and bacterial cellulose attracts much attention for research work or commercial purposes. However, Hestrin-Schramm, the synthetic or considered as standard medium for bacterial cellulose production, is expensive. Recently, there has been a lot of interest in searching for carbon and nitrogen sources as an alternative to synthetic bacterial growth media. Agro-industrial byproducts are derived from agriculture and food industry processing. Rich in carbohydrates and protein, these resources are suitable for bacterial cellulose production. This chapter aims to describe the agro-industrial residues for bacterial cellulose production and their recent possible application for food packaging.

Keywords Agro-industrial byproduct · Bacterial cellulose · Food packaging

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1 Introduction

Due to its excellent properties such as high strength, hardiness, ease of processing, and cost-effectiveness, plastic has become a popular and important material for food packaging (Andrady et al. 2009). The common commercial plastics for food packaging are generally derived from petrochemical-based polymers, specifically polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polyethylene terephthalate (PET) of which they account for almost 90% of total polymers manufacture (Napper and Thompson 2019). These plastics are non-biodegradable, and when their lifetime is over, the improper disposal of plastic waste would become a severe environmental problem. Due to poor management, plastic wastes are found in rivers. It was reported that 80% of plastic waste is distributed by more than 1,000 rivers globally (Meijer et al. 2022) which slowly goes to the ocean, becomes a **marine pollutant**, and gradually becomes a global oceanic serious problem (Long et al. 2022). Bulky plastics, often known as macro-plastics, have been found in the ocean, and their accumulation has significantly increased. As a result, marine animals were suffered and killed by plastic entanglement (Dasgupta et al. 2022). In the ocean, plastic gradually degrades into micro-plastic, whose accumulation is hazardous since it is easily swallowed by crustaceans whose digestive tract is usually consumed by humans (Rainieri and Barranco 2019). Besides causing the accumulation of plastic wastes, the manufacture of petroleum-based plastic triggers the reduction of its non-renewable resources. Nowadays, petrochemical industries are the source of more than 99% of the global plastics raw materials (British Plastics Federation 2019). Consequently, sustainable, renewable, and biodegradable-based biopolymers, specifically those originating from organic resources, are important as alternative resources for not only improving food quality but also producing environmentally-friendly food packaging.

The alternative source for petroleum-based polymer as a plastic replacement for various materials is addressed to cellulose, the most prevalent macromolecule on earth, a renewable and low-cost natural polymer. In general, cellulose is obtained from vascular plants, but it can also be found in tunicin, typically from *Microcosmus sulcatus*, *Halocynthia roretzi*, *Ciona intestinalis*, *Styela plicata*, and *Ascidia sp.* in the form of rod-like crystals (Zhao and Li 2014). Cellulose is also synthesized from green algae of *Cladophorales* (*Cladophora, Chaetomorpha,* and *Rhizoclonium*) and *Siphonocladales* (*Valonia*, *Dictyosphaeria*, *Siphonocladus,* and *Boergesenia*) (Mihranyan 2011). Additionally, cellulose is also found in the cell wall of *Saprolegnia monoica* (Fèvre et al. 1990).

Cellulose has been used in various fields for a long time for chemical-based materials, fabric supplies, and pulp paper production. For a wide range of applications, particularly when high purity and white color are considered necessary, cellulose should be isolated from lignin, hemicellulose, and pectin as the plant cell wall components through the pulping and bleaching process, which requires various synthetic chemicals. In addition, cellulose isolation and purification require a large amount of energy as well as the price of waste effluent and toxic material treatment.

Therefore, highly pure and environmentally friendly cellulose is an important topic of research subject. For this purpose, bacterial cellulose offers an alternative and interesting role as cellulose resources. In terms of cellulose isolation, bacterial cellulose is more beneficial than plant cellulose because it is free of lignin and hemicellulose, preventing the need for a pulping and bleaching process and making it more environmentally-friendly and energy efficient. Thus, bacterial cellulose is a source of pure cellulose as well as indicates higher water absorptivity, higher crystallinity, and a higher degree of polymerization (Salari et al. 2018).

Although BC possesses remarkable characteristics, it is costly to fabricate. The synthetic medium Hestrin–Schramm (HS) medium is one of the main factors causing to high production cost of BC. This synthetic medium is an indispensable material for bacteria to produce cellulose (Lahiri et al. 2021). Therefore, there is a need to explore the potential and low cost of natural resources for bacterial cellulose production. In this chapter, the production of bacterial cellulose by using abundant and low-cost agro-industrial byproducts and the possibility for food packaging application are presented.

2 Agro-Industrial Wastes for Bacterial Cellulose Production

Bacterial cellulose production depends on various basic factors such as oxygen supply (Wu and Li 2015), temperature (Lee et al. 2014), reactor design (Islam et al. 2017), and optimum pH (Reiniati et al. 2017). However, carbon and nitrogen play an important role in the synthesis of bacterial cellulose (Rajwade et al. 2015). Typically, the carbon and nitrogen sources were obtained from the Hestrin-Schramm culture medium. This expensive medium mostly contains synthetic glucose, peptone, yeast extracts, and various minerals. Therefore, exploring the low-cost carbon and nitrogen resources from agro-industrial byproducts for alternative resources is the right option.

Agro-industrial byproducts are defined as various wastes from the food and agriculture industries (Madeira et al. 2017). It is available in a huge amount every year. In terms of their abundance and sustainability, the agro-industrial byproducts can be deduced from the total volume produced from the plant waste from crops, approximately 250 million tons per year (FAO 2013). It was also informed that 1/3 of total human food production, or around 1.3 billion tons annually, is discarded worldwide (Duque-Acevedo et al. 2020). The use of agro-industrial residues for innovative products not only solves waste removal issues but also reduces pollution, reduces adverse effects on human and animal health (Zihare et al. 2018), and raises its value.

Agricultural commodities such as fruits, vegetables, legumes, and cereals and their processing generate unclear value byproducts (Almaraz-sánchez et al. 2022). Other agricultural primary activities such as harvesting, pruning, and collecting in the field crops generate residues in the form of logs, straws, leaves, husks, roots, and seeded pods from crops (Hiloidhari et al. 2020) as well as animal residues

(Forster-Carneiro et al. 2013). These underutilized products are important resources for new materials, chemicals (Madeira et al. 2017), and energy (Vandamme 2009). This is due to the important and valuable existing ingredients of the residues such as carbohydrates, protein, fibers, minerals, and vitamins (Lopes and Ligabue-Braun 2021). Carbohydrate and protein will be valuable resources and mediums for bacteria to propagate in the cellulose gel.

Depending on the material target, various pre-treatments of agro-industrial residue are commonly carried out. Chemical, biological, enzymatic, and physical pre-treatments such as milling, steam explosion/steam treatment, hydrothermal, irradiation, and chemical treatment such as alkaline hydrolysis are the most common pre-treatments (Singh nee' Nigam et al. 2009). These pre-treatments aim to reach the reactive molecule followed by procedures to obtain the desired raw material (De Corato et al. 2018). The fermentation, hydrolysis, precipitation, and filtration aim to eliminate the poisonous and low-value chemicals (Araújo et al. 2020), so that the existing organic substances could be changed into diverse products involving carbon and nitrogen as the intermediate compounds. The fine and highly de-crystalized structure was obtained by the milling process, whereas steam treatment/steam explosion increased the pore size of the fiber. Biological pre-treatment aims to degrade lignin; it generally involves the activity of white-rod fungi such as *Phanerochaete chrysosporium* (Singh nee' Nigam et al. 2009).

In agro-industrial industries, carbon and nitrogen could be found in the form of cellulose, hemicellulose, lignin, carbohydrate, or proteins (Urbina et al. 2021). The composition depends on the origin, type of raw material resources, and method of analysis. Based on these descriptions, they are particularly potential for BC production. The high carbohydrate and nitrogen contents of 56.9 and 28.5%, respectively, are found in oil palm frond (Rhaman and Naher 2021). Paddy straw also shows a high carbohydrate and nitrogen content of 50.2 and 84.9%, respectively.

The carbon and nitrogen generated from numerous agro-food industries is presented in Table 1.

2.1 Agro-Wastes

Available in a huge amount worldwide annually, agro-wastes are the most promising resource for the production of BC. Sugarcane straw is generated from sugarcane production, which plays a role in the daily required nutrient. Recently, sugarcane straw is utilized as bio-ethanol production, but its valorization is widely open to realization. It contains 35–45% of cellulose, which can be used for carbon resources. Sugarcane straw, which was previously boiled in water, was used as the medium for *Komagataeibacter xylinus ATCC 11142* and incubated statistically at 30 °C for 15 days. The dry pellicle of BC was weighed as 1.06 g/L (Dhar et al. 2019). A quite similar amount of BC yield was obtained from the root, stalk, and leaf parts of sweet sorghum, as of 2.28 g/L, stalk 1.82 g/L, and leaf 2.54 g/L, respectively. Commonly considered and used as an energy crop, sweet sorghum is an important resource

Table 1 Carbon and nitrogen content from agro-industrial byproducts

Resources	Carbon content (from)	Nitrogen content (from)	References
Cassava wastewater	Carbohydrates 58.11%	Total nitrogen 1.94%	Ribeiro et al. (2019)
Cheese whey	Lactose, 77%	Protein, 13%	Lopes et al. (2013)
Coconut oil cake	48.16%	1.69%	Sathish and Shetty (2013)
Coffee husk	18%	13%	Mussatto et al. (2011)
Corn cob	53.61%	1.9%	Sathish and Shetty (2013)
Grape pulp	Carbohydrate, 6.53%	1.96%	Ekanah et al. (2017)
Oat straw	Cellulose 40%, hemicellulose 27%, lignin 18%	NA	Singh nee' Nigam et al. (2009)
Oil palm empty fruit bunch	43.8–54.7%	0.25–1.21%	Chang (2014)
Oil palm frond	56.9%	28.5%	Rhaman and Naher (2021)
Orange peel	Cellulose (71.2 g/kg), hemicellulose (128 g/kg)	Crude protein (57.2 g/kg)	Ahmad et al. (2012)
Orange peel	Carbohydrate 52.90%	Crude protein 12.3%	Gotmare and Gade (2018)
Paddy straw	50.2%	84.9%	Rhaman and Naher (2021)
Pineapple waste	45.68%	0.61%	Sathish and Shetty (2013)
Rice bran extract	Glucose 38.3% cellulose 7.8%	13.2%	Choi (2020)
Rice husk	Cellulose 22%, hemicellulose 23%, lignin 15%	NA	Megawati et al. (2011)
Rice straw	Cellulose 32%, hemicellulose 24%, lignin 18%	NA	Limayem and Ricke (2012)
Rice washed	Carbohydrate, 90%	Protein, 8%	Srikandace et al. (2022)
Sawdust	55.2%	34.3%	Rhaman and Naher (2021)
Sugarcane bagasse	48.32%	0.2%	Sathish and Shetty (2013)
Sugarcane straw	Cellulose 36%, hemicellulose 21%, lignin 16%	NA	Saad et al. (2008)

(continued)

Table 1 (continued)

Resources	Carbon content (from)	Nitrogen content (from)	References
Tofu liquid waste	Carbohydrate, 25%	Protein, 65%	Srikandace et al. (2022)
Tomato juice	Carbohydrate, 2.52%	Protein, 1%	Ismail Abdullahi et al. (2016)
Wheat straw	Cellulose 27%, hemicellulose 21%, lignin 23%	NA	Adapa et al. (2011)

NA: Not available

for BC production, which will be possible for building block material application (Wang et al. 2021). A higher BC production of 2.86 g/L was reported from corn stalk, containing 3.87 g/L of glucose and glucan (35%), which were previously treated with acetic acid for *Acetobacter xylinum* ATCC 23767 (Cheng et al. 2017). Another corn residue can be obtained from the corn stover. Mainly contains glucose and xylose as well as available abundantly as agricultural residues, corn stover can be used as a low-cost feedstock in the manufacturing of BC. *Enterobacter sp.* FY-07 (CGMCC No. 6103) was used during the fermentation and incubated under static conditions at 30 °C for 24 h. The productivity was 14.35 g/L/ day but with the addition of xanthan gum, the productivity increased significantly up to 17.13 g/L/day. Interestingly, the pilot scale for BC has been reported by using oat hulls. Previously chemically treated with HNO_3, followed by enzymatic saccharification and the addition of sodium hydroxide, oat hulls were performed in a 100 L fermentor. After purification, 80.5 tons of 98%-wet BC gel per 100 tons of oat hulls were obtained with a 93% crystallinity index and composed of 100% cellulose I_α-allomorph (Skiba et al. 2020). Another approach to scale-up BC production has been explored. In a 30 L working volume, *Acetobacter xylinum* KJ1 was used, and the BC yield was achieved at 5.6 g/L using saccharified food wastes (Song et al. 2009). DHU-ATCC-1 strain, a mutant of *Komagataeibacter xylinus* ATCC 23770, was employed in a 75 L stirred-tank reactor to scale up BC production with the final yield of 17.3 gr/L using overripe bananas (Molina-Ramírez et al. 2020). Other possible agro-wastes for BC production are presented in Table 2.

2.2 Fruit-Food Wastes

Various studies have been reported regarding the use of agro-waste as a source of carbon and nitrogen for BC production. Green waste generated from fruits, vegetables, and food wastes is the potential resources due to its high glucose and fructose content. Citrus peel and pomace enzymolysis from beverage industrial waste were successfully used for BC by using *Komagataeibacter xylinus* CICC 10529 with a yield of 5.7 ± 0.7 g/L higher than from HS medium with 50 nm for its average diameter. The entire results confirmed the role of citrus peel and pomace enzymolysis

Table 2 Agro-industrial waste for BC production

Resource	Bacteria strain	Yield (gr/L)	References
Cacao mucilage exudate	*G. xylinus*	13.13	Saavedra-Sanabria et al. (2021)
Cashew tree	*K. rhaeticus*	2.3–6.0	Pacheco et al. (2017)
Cashew tree exudate	*K. rhaeticus*	2.8	Silva et al. (2010)
Coffee cherry husk	*G. hansenii UAC09*	6.24	Usha et al. (2011)
Corn stalk	*K. xylinum, ATCC 23767*	2.86	Cheng et al. (2017)
Corn stover	*Enterobacter sp. FY-07*	2.08	Gao et al. (2021)
Oat hulls	*Medusomyces gisevii Sa-12*	2.2	Skiba et al. (2020)
Pecan nutshell	*G. entanii*	2.8	Dórame-Miranda et al. (2019)
Prickly pear peels	*Lactiplantibacillus plantarum strain AS.6*	2.94	El-Gendi et al. (2023)
Sugarcane straw	*K. xylinus ATCC 11142*	1.06	Dhar et al. (2019)
Sweet sorghum	*Acetobacter xylinum ATCC 23767*	Root 2.28, stalk 1.82, leaf 2.54	Wang et al. (2021)
Wheat thin stillage	*G. sucrofermentans B-11267*	6.19	Revin et al. (2018)
Wheat straw	*K. xylinus* ATCC 23770	8.3	Chen et al. (2013)

as potential sources for BC production with similar characteristics to HS medium, being more environmentally-friendly and less expensive to produce (Fan et al. 2016). Other mango peel waste was also developed as an alternative culture medium for *Komagataeibacter xylinus DSMZ 2004*. The yield of BC was 6.32 g/L after 16 days of fermentation by the static culture technique. Structural analysis showed the diameter of BC from mango waste peel was 98.8 nm and showed a similar chemical structure to BC synthesized from pure sugar. This resulted BC was proposed for biomedical and pharmaceutical applications (García-Sánchez et al. 2020). Additionally, pineapple peels as an alternative medium were used for *Komagataeibacter xylinus* IITR DKH20 which was incubated for 384 h resulting in 11.44 g/L dried. The resulted BC revealed similar physicochemical properties to the BC produced using HS medium and was proposed for biomedical application (Khan et al. 2021). When wasted rotten tomato media was used as a substitute medium for *Gluconacetobacter hansenii* and cultivated for 7 days, the yield BC was 3.71 g/L. BC was produced after 7 days and aimed for medical and pharmaceutical fields (Fatima et al. 2021). However, a higher dry BC of 7.8 gr/L was obtained from the tomato juice when used as an optimization process for the 10 L production fermentation medium for *Acetobacter pasteurianus* RSV-4 after 7 days of incubation. Furthermore, *Komagataeibacter xylinus* DSM 6513 was successfully grown in a medium generated from red and white grape bagasse from the wine industry. It was reported that the white grape bagasse was a better

Table 3 Fruit wastes

Resource	Bacteria strain	Yield (gr/L)	References
Citrus peel pomace	*K. xylinus* CICC 10529	5.7	Fan et al. (2016)
Grape bagasse	*G. xylinus NRRL-B42*	8.0	Vazquez et al. (2013)
Kitchen waste	*K. rhaeticus K15*	4.76	Li et al. (2021)
Litchi extract	*K. xylinus CH001*	2.5	Yang et al. (2016)
Mango peels	*K. xylinus DSMZ200*	6.32	Sanchez et al. (2020)
Musk melon	*K. persimmonis GH-2*	8.08	Hungund et al. (2013)
Orange pulp	*A. pasteurianus RSV-4*	2.8	Kumar et al. (2019)
Pineapple peels	*K. xylinus IITR DKH20*	2.57	Khan et al. (2021)
Pineapple residue	*G. medellinensis*	3.24	Algar et al. (2015)
Rotten fruits	*G. xylinus*	0.06	Jozala et al. (2015)
Rotten tomato	*G. hansenii PJK KCTC 10505BP*	3.83	Fatima et al. (2021)
Tomato juice	*A. pasteurianus RSV-4*	7.8	Kumar et al. (2019)
Various fruit juice	*A. xylinum NBRC 13693*	0.2–2.1	Kurosumi et al. (2009)

substitution as a low-cost medium resource than the red grape. White grape bagasse also produced a five times higher yield, five times higher water holding capacity as well as greater flexibility than the HS medium. Red grape bagasse-based BC is suitable for the food industry, whereas white grape BC is appropriate for the textile and biomedical industries (Ogrizek et al. 2021). Another study reported that dried BC of 8.08 g/L was obtained from musk melon as a natural, cheaper carbon source medium for *Gluconeacetobacter persimmonis,* which was incubated at 30 °C for 14 days (Hungund et al. 2013). Kitchen wastes could also be the promising carbon and nitrogen resources for BC production, since it is composed of carbohydrates and protein. A new cellulose-producing bacteria, namely, *Komagataeibacter rhaeticus* K15, has been isolated from kombucha tea and shown the capability to use kitchen wastes as a carbon source for cellulose production of as much as 4.76 g/L (Li et al. 2021). The detailed lists of fruit wastes are shown in Table 3.

2.3 Food and Beverage Industrial Wastes

Based on daily activity, food-beverage industries generate large amounts of waste. Proper waste management can create economic benefits as well as provide free-contamination caused by their accumulation. On the other side, the wastes are rich in carbohydrates and protein thus promising to be a low-cost resource of media used for BC production. Beer manufacturing is a significant economic activity. Modern brewing is commonly a big industry that generates large quantities of byproducts nowadays. Waste beer yeasts are the second most common byproduct of the brewing

industry that is discarded or fed to livestock. The waste beer yeast hydrolysates with 3% sugar concentration when it was treated by ultra-sonication, resulted BC yield of 7.02 g/L, nearly 6 times compared with the untreated waste beer yeast at 1.21 g/L (Lin et al. 2014). Cheese whey is today recognized as a source of functional and bioactive compounds, especially proteins and peptides but a significant amount of the whey produced globally is still not valorized whereas it contains rich nutrient components (Pires et al. 2021). The dry BC of 6.77 g/L was synthesized from the *K. xylinus* when enriched with β-galactosidase and proposed as a food packaging application. Corn steep liquor is a byproduct of the corn wet-milling production which generally consists mainly of water and other ingredients such as sugar and protein. Therefore, it is potential as nutrient medium for bacteria. A strain of *G. hansenii* UCP1619 was incubated in corn steep liquor at 30 °C for 10 days. A dry of 7.02 gr/L BC was resulted from this fermentation process and showed the future applications in the textile field (Costa et al. 2017). Another promising carbon source is thin stillage from rice wine distilleries. The strain of *G. xylinus* was incubated in the rice wine distillery by static cultivation for 7 days. A dry BC of 6.26 g/l was obtained which was reported almost 50% higher than produced in an HS-only medium with slightly denser reticulated structures and higher crystallinity (Wu and Liu 2013). Utilization of crude confectionery waste hydrolysates for *K. sucrofermentans* was reported for BC production. The waste contained 28.3% g/g free sugars, 28.4% g/g starch, 7.1% g/g protein, and 24.9% g/g fats was used in order to explore the lower cost alternative medium. BC was produced with a yield of 5.7 g/L and the potential as a bio-based packaging reinforcing agent (Efthymiou et al. 2022a, b). Other possible resources obtained from food and beverage industrial waste are presented in Table 4.

Table 4 Food and beverage industrial wastes

Resource	Bacteria strain	Yield (gr/L)	References
Cheese whey	*K. xylinus* DSM 2325	6.77	Rollini et al. (2020)
Confectionery wastes	*K. sucrofermentans*	5.7	Efthymiou et al. (2022a, b)
Corn steep liquor	*G. hansenii UCP1619*	7.02	Costa et al. (2017)
Jujube-processing industry	*K. xylinum CGMCC 2955*	2.2	Li et al. (2015)
Maple syrup	*A. xylinum BPR 2001*	1.51	Zeng et al. (2011)
Rice wine distillery	*G. xylinus*	6.26	Wu and Liu (2013)
Sugar cane molasses	*K. rhaeticus*	2.23–2.58	Machado et al. (2018)
Tofu liquid waste	*K. xylinum*	3.8	Srikandace et al. (2022)
Waste beer yeast	*K. hansenii CGMCC 3917*	7	Lin et al. (2014)
Whey	*G. sucrofermentans B-11267*	5.45	Revin et al. (2018)

2.4 Others

Other industrial wastes (Table 5) such as biodiesel wastes, Chinese medicinal herbs, cotton-based waste textiles, distillery effluent, dry olive mill residues, and tobacco extract wastes also show the potential resources for bacterial cellulose production.

3 Bacterial Cellulose and Its Properties

Bacterial cellulose, also known as bio-cellulose or microbial cellulose, is cellulose produced by the activity of non-pathogen, either positive or negative bacteria in a medium containing nitrogen and carbon as nutrient resources. The acetic bacterial that plays a role in the cellulose formation is commonly known as *Acetobacter xylinum* (Yamada et al. 1997), which is re-classified as *Gluconeacetobacter xylinum* and recently known as *Komagataeibacter xylinum.* This non-phatogen-aerobic bacteria can convert 108 glucose molecules per hour into cellulose and is considered as the most effective strain for bacterial cellulose production commercially due to its high productivity (Wang et al. 2019). Other producing bacteria are *Pseudomonas* (Ude et al. 2006), *Rhizobium* (Robledo et al. 2012), *Sarcina* (Yang et al. 2013a, b), *Agrobacterium* (Barnhart et al. 2013), and *Lactobacillus* (Khan et al. 2020). It was reported that Rhizobium and Agrobacterium produced cellulose in Rhizobium and Agrobacterium reportedly produced cellulose in exceedingly low yields. On the other hand, from the family of *Acetobacteriaceae* such as *Komagataeibacter*, *Acetobacter*, *Gluconacetobacter*, *Gluconobacter*, and *Asaia* together with the *Bacillus*, Leifsonia, *Salmonella*, *Erwinia*, *Enterobacter*, *Pseudomonas*, and *Shewanella* in non *Acetobacteriaceae* produce high cellulose (Li et al. 2022a, b). Generally bacterial cellulose is produced purposely, but it was hypothesized that cellulose is formed to protect bacteria from unfavorable factors such as UV radiation, harsh chemicals, and accessibility to oxygen (Retegi et al. 2010).

BC is illustrated by an ultrafine network structure, with emerging chains combining to generate sub-fibrils with a width of 1.5 nm (Ross et al. 1991). The spatial configuration of the pre-microfibril accumulation results in crystallinity of

Table 5 Other industrial wastes

Biodiesel waste	*G. xylinus NRRL-B42*	10	Vazquez et al. (2013)
Chinese medicinal herb	*Taonella mepensis*	0.54	Wu et al. (2021)
Cotton-based waste textiles	*G. xylinus ATCC 23770*	10.8	Hong et al. (2012)
Distillery effluent	*G. oboediens*	8.1	Jahan et al. (2018)
Dry olive mill residue	*K. sacchari sp.*	0.85	Gomes et al. (2013)
Elephant grass	*G. xylinus CH001*	6.4	Yang et al. (2013a, b)
Tobacco extract waste	*K. xylinum ATCC 23767*	5.2	Ye et al. (2019)

up to 84–89% (Czaja et al. 2004). The crystallinity highly relates to mechanical strength (Nishiyama et al. 2002) such as Young's modulus of BC, approximately in the range of 15–35 GPa, and the tensile strength typically in the range 200–300 MPa, respectively (Brown et al. 1976). The sub-fibrils are subsequently self-assembled to generate microfibrils, resulting in a fibrillar ribbon then tightly aggregating each other with a width of 50–80 nm. The resulted fibrillary ribbon is 200 times finer than cotton fiber with an extremely large surface area (Vitta and Thiruvengadam 2002). With a high surface area to mass ratio, bacterial cellulose shows high-water retention capability. The high-water content of bacterial celluloses is also due to the hydrophilicity property caused by the pore structure. The relative hydrophilicity was approximately around 40–50% (Bishop 2007). Additionally, BC shows the degree of polymerization around 14.000—16.000 at pH 4 but its polymerization lowered when pH increased to 5 (Tahara et al. 1997). A low degree of polymerization was also found when bacterial cellulose was synthesized spherical-type bubble column bioreactor (Choi et al. 2009).

BC is usually produced in a simple static method in which the container is filled with the acidic medium containing carbon–nitrogen where the bacteria strain is inoculated at room temperature for a certain time, usually from 1 to 2 weeks. The static method results in a thick pellicle at the top of the medium. The thickness increases with the increase of fermentation time (Fig. 1). High crystallinity, strong tensile strength, dense network structure, high-temperature resistance, and good flame retardancy were generated from bacterial cellulose in static culture. Additionally, under static culture conditions, bacterial cellulose was uniform in film shape as well as showed good biocompatibility and biodegradability (Gao et al. 2020).

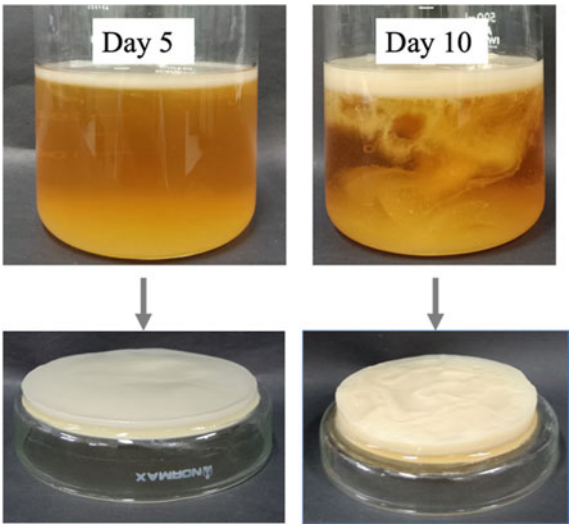

Fig. 1 Hestrin-Schramm-based bacterial cellulose

On the other hand, agitated cultivation is simply carried out by growing the bacteria in a container containing growth nutrients and agitated for several days. The agitation technique aims to increase the oxygen supply for the bacteria which finally resulted in pellet-like aggregates. In the agitation culture, the crystallinity and cellulose Iα are lower than from the static culture. However, the degree of polymerization is higher than the static culture (Watanabe et al. 1998). Furthermore, through the agitation culture, the smaller particle size of bacterial cellulose resulted in the high-water holding capacity, compared to the static culture. Additionally, the lower Young's modulus and higher suspension viscosity were shown from the agitation technique (Ougiya et al. 1997). Additionally, more porous bacterial cellulose was produced by the agitation culture (Gao et al. 2020). So far it is considered that agitation is the most proper method for cost-effective BC production (Hu et al. 2013). The selection of these two methods is based on the BC application target with its various property considerations. The pellicle-type BC was developed for a plasmonic paper sensor (Purwidyantri et al. 2020) while the hollow-type spherical BC was proposed as a seamless capsule for drug delivery applications (Hoshi et al. 2018). In addition to the culture method, additional elements such as nutrients, type of bacterial strains, oxygen availability, and the alignment of its three-dimensional network the environment of fermentation also have an impact on the bacterial cellulose properties (Kim et al. 2019).

Generally, bacterial cellulose has far better properties than plant cellulose such as purity higher than 99% (Klemm et al. 2005), total surface area of more than 150 m^2/g (Ul-Islam et al. 2012), water holding capacity of more than 95% (Rebelo et al. 2018), and tensile strength 20–300 MPa (Feng et al. 2015). Crystallinity is also an important properties for evaluation since it relates to mechanical strength. A high crystallinity of up to 98.4% was observed in bacterial cellulose produced from confectionery using *Komagataeibacter sucrofermentans* after a 24 h HCl treatment (Efthymiou et al. 2022a, b). Additionally, a crystallinity of 75.37% was obtained from bacterial cellulose in sweet sorghum by *Acetobacter xylinum* ATCC 23767 (Wang et al. 2021). By using a laboratory-scale bioreactor with a 41 cm^2 cross-sectional area, overripe banana-based bacterial cellulose cultivated by *Komagataeibacter medellinensis* showed a crystallinity of 82.93% (Molina-ramírez et al. 2020). The high crystallinity highly corresponds with mechanical performance The tensile strength and Young's modulus of BC are 200–300 MPa and 15–35 GPa which are higher than synthetic polymer (Cacicedo et al. 2016). These values usually vary depending on the bacterial strain, cultivation method, culture nutrient as well as drying method. A tensile strength of around 27.3–37.2 MPa was achieved when bacterial cellulose was oven-dried (Illa et al. 2019). The tensile strength of bacterial cellulose-based stalk and leaf of sweet sorghum when prepared in the medium of *Acetobacter xylinum* ATCC 23767 was 8.24 MPa and 4.83 MPa, respectively. When bacterial cellulose was produced in rotten guava mixed with cheese whey by using *Komagataeibacter intermedius MO*, the tensile of 30 MPa was achieved (Lotfy et al. 2021). Furthermore, rotten banana-based bacterial cellulose showed tensile strength and Young's modulus of 280.6 MPa and 9.4 MPa, respectively, much higher than those synthesized by Hestrin-Schramm medium (Molina-Ramírez et al. 2018). Young's modulus of 8.7

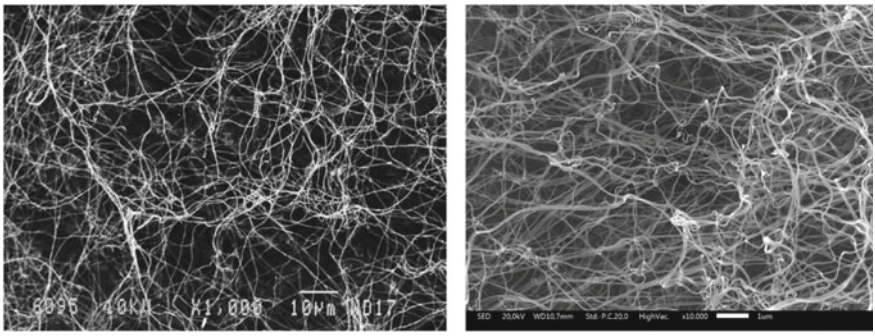

Fig. 2 Purification by 2% NaOH (left) (Skiba et al. 2020), purification by boiling water (right) (Srikandace et al. 2022)

GPa was achieved from bacterial cellulose synthesized using tofu liquid water, higher than from bacterial cellulose cultivated in the Hestrin-Schramm medium. This bacterial cellulose also revealed the same irregular three-dimensional network made of disordered dense fibrils arrangement with that produced from the synthetic medium (Srikandace et al. 2022).

The resulted bacterial cellulose requires purification by removing the remaining bacterial cell or nutrients in the medium. Different from plant cellulose which is chemically linked with hemicellulose and lignin and thus makes it difficult to remove impurities, purification of bacterial cellulose is much easier to carry out. Purification is easily carried out by boiling dilute sodium hydroxide followed by rinsing it with water (Revin et al. 2018). However, it has been proved that by boiling in water for 10 min with 2–3 replication after the water is decanted, pure bacterial cellulose was obtained (Srikandace et al. 2022). Figure 2 shows the morphology of bacterial cellulose purified by sodium hydroxide and boiling water, respectively.

3.1 Drying of Bacterial Cellulose

The drying method plays a role in the performance and properties of bacterial cellulose. As bacterial cellulose is too thick and slippery, the dry state is preferable for its wider application and it is more easily handled with stable properties. Various drying method has been reported for bacterial cellulose treatment, such as oven drying (Illa et al. 2019), microwave heating and air convection heating (Gao et al. 2020), and evaporation (Zeng et al. 2014). These drying techniques provide various performance alterations. When compared with the freeze-drying technique at −84 °C for 24 h, oven drying of bacterial cellulose resulted in higher crystallinity, decreased fiber diameter, narrowed size distribution, and increased mechanical properties (Illa et al. 2019). However, the swelling ability of the bacterial cellulose gel was reduced through freeze drying (Clasen et al. 2006). Additionally, whitish BC with higher porosity

was shown by the freeze-dried method whereas transparent and film volume reduction was deduced from bacterial cellulose by oven drying (Vasconcellos and Farinas 2018). Furthermore, a long drying time of 120 h at 100 °C provided tensile strength of 250.7 MPa and a tensile modulus of 18.6 GPa (Abral et al. 2021). The supercritical drying technique provided mechanically robust and extremely light films of bacterial cellulose (Zeng et al. 2014) whereas freeze drying at −30 °C resulted in transparent film with higher porosity (Urbina et al. 2019a, b). It was reported that the lyophilizer technique employed at −50 to 20 °C for 36 h yielded a loose reticulated porous structure with a high-water absorption capacity (Feng et al. 2015). Microwave heating was carried out in a short time but it provided bacterial cellulose with slightly lower crystallinity and a higher swelling degree with the wrinkled surface (Indriyati and Puspitasari 2019).

3.2 Bacterial Cellulose-Based Food Packaging

There have been various studies were carried out to use bacterial cellulose for food packaging thus the evaluation of its properties for that purpose is indispensable. Bacterial cellulose is hydrophilic due to its rich hydroxyl group content, therefore bacterial cellulose has low barrier properties. Water vapor permeability (WVP) of bacterial cellulose is frequently studied for food packaging applications. It appraises the amount of water vapor that can pass through the package layer from the inner or outer environment, which possibly leads to unfavorable alterations in the product's characteristics. For this purpose, bacterial cellulose produced by *Gluconeacetobacter hansenii* CGMCC3917 was used as a reinforcing agent and it was incorporated with agar for edible packaging. The concentration of 3–5% of bacterial cellulose showed favorable WVP properties. The application of BC up to 10% decreased WVP up to 25.7% (Wang et al. 2018). The WVP ranged from 1.87×10^{-11} to 2.04×10^{-10} g/m s Pa was obtained from a composite film containing bacterial cellulose, glycerol, and polyvinyl alcohol. The film is the potential for food packaging to keep the quality of food as well as increase the shelf-life (Cazón et al. 2020).

Another important characteristic consideration for food packaging is mechanical strength which plays a role during production, storage, application, transportation, and distribution. Mechanical properties such as ultimate tensile strength, elongation at break, tensile Young's modulus, tensile toughness to break, ultimate puncture strength, puncture deformation, puncture Young's modulus, and puncture toughness to break were evaluated for bacterial nanocomposite film incorporated with polyvinyl alcohol, glycerol and boric acid. Due to its suitable mechanical properties, the resulted nanocomposites are suitable for disposable packaging (Rouhi et al. 2017). Improvement of mechanical properties as well as possess good antibacterial activity and antioxidant capacity was shown from alternative edible and environment-friendly sheets for food packaging made of bacterial cellulose, curdlan, and cinnamon essential oil (Zhou et al. 2022). Other enhancements of mechanical properties together with

barrier and antibacterial properties were reported from a sheet prepared from bacterial cellulose with the addition of konjac glucomannan and cucurmin. The resulted film was claimed to support beef freshness (Li et al. 2022a, b). In addition, the wrapping nanopaper generated from bacterial cellulose and *Lactobacillus plantarum* was efficient against *Lactobacillus monocytogenes* in freshly ground beef (Shafipour Yordshahi et al. 2020).

When bacterial cellulose was combined with cyanidin-3-glucoside, it resulted in a smart pH-sensitive sheet that possessed an antioxidant characteristic and was applicable for tilapia filet freshness non-destructive packaging indicator (Shi et al. 2022). Another smart film based on bacterial cellulose was developed by 2,2,6,6-tetramethylpiperidine-1-oxyl radical (TEMPO)-oxidation containing thymol and anthocyanin-rich purple potato extract. It was reported that the film showed improved thermal stability, UV protection, and water vapor barrier characteristics but somewhat decreased tensile strength. With real-time assessment of freshness, these particular characteristics of composite film illustrate the prospective tool for commercial shrimp packaging (Wen et al. 2021). Interestingly, isolates of sunflower protein and bacterial cellulose with improved mechanical properties, water vapor permeability, and solubility were developed for food packaging materials, specifically for fresh fruit preservation (Efthymiou et al. 2022a, b).

Transparency as another important characteristic should be taken into account not only for the product performance but also for consumer satisfaction. Transparency and hydrophobicity improvement as well as antioxidant capacity was obtained when bacterial cellulose-apple pomace-based nanopapers were combined with hydrophobic medium-chain-length polyhydroxyalkanoate as a coating agent. The film was developed for active packaging application (Urbina et al. 2019a, b). Additionally, bacterial cellulose from sago liquid waste was developed for meat sausage packaging. Its transparency was improved by the addition of carboxymethyl cellulose into the bacterial cellulose. This treatment improved mechanical characteristics as well as kept sausage quality for 6 days at room temperature (Yanti et al. 2021). Cheese whey permeates as a by-product of whey ultrafiltration, as a cheap substrate for bacterial cellulose production by *Komagataeibacter xylinus*, and conjugated with Sakacin-A, produced by *Lactobacillus sakei* was reported as the potential antimicrobial packaging material (Rollini et al. 2020).

4 Conclusion

As petroleum-based plastic supplies continue to decline the price rises whereas its demand increases in line with the population growth as well as the awareness of environmental rules have prompted an exploration for low-cost bacterial cellulose production for environmentally-friendly food packaging. Even though the resources are varied based on the type of activity, it has been reported that agricultural wastes show potential as an alternative source of carbohydrates and nitrogen for bacterial

cellulose production. The studies contributed to investigating the applicable technique for food packaging application. If this biomass is used to produce bacterial cellulose massively or on a large scale, this not only increases the value added of the residues but also supports the waste management from the related agro-industrial operation as well as the possibility of creating economic growth.

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