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Utilization of food waste in production of bacterial cellulose

Gıda atıklarının bakteriyel selüloz üretiminde kullanımı

Pelin ÖZKAYA [1]

Seval DAĞBAĞLI [1]

Müge UYARCAN [1*]

[1] Manisa Celal Bayar Üniversitesi, Mühendislik Fakültesi, Gıda Mühendisliği Bölümü, 45030, Yunusemre, Manisa, Türkiye

***** Sorumlu yazar (Corresponding author):

muge.akkara@cbu.edu.tr

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ABSTRACT

Cellulose is defined as a polymer that exists in the cell walls of plant tissues and is widely used in many industrial fields. However, the recent threat of deforestation has led researchers to find alternative wood sources for cellulose production. For this reason, literature studies have focused on certain types of bacteria known to be capable of producing cellulose, such as *Acetobacter, Gluconobacter, Alcaligenes*, etc. It is stated that cellulose of plant origin and bacterial origin have a similar structure. Bacterial cellulose possesses a big economic and commercial potential depending on the purpose and the production method and is generally used in food applications as a fat substitute, rheology modifier, immobilization material for probiotics and enzymes, stabilizer of pickering emulsions, component of food coatings and green packaging film. Recently, it has become more prominent to use food waste as production inputs, such as beet and sugar cane molasses, fruit waste, dairy industry waste, etc. So, the utilization of industrial by-products, agro-forestry, and food industry residues as carbon sources has been providing significant advantages, such as increasing yield and reducing cost. The objective of this study was to present a general look related to bacterial cellulose production in combination with the use of food waste and future trends.

Keywords: Bacterial cellulose, cellulose, food industry, food waste

ÖZ

Selüloz, bitki dokularının hücre duvarında bulunan ve endüstrinin birçok alanında yaygın olarak kullanılan bir polimer olarak tanımlanmaktadır. Ancak son zamanlarda ormanların yok olma tehlikesiyle karşı karşıya kalması araştırmacıları selüloz üretimi için odun yerine alternatif kaynaklar bulmaya yönlendirmiştir. Bu nedenle literatür çalışmaları selüloz üretebildikleri bilinen *Acetobacter, Gluconobacter, Alcaligenes*, vb. gibi belirli bakteri türlerine odaklanmıştır. Bitki kaynaklı ve bakteriyel kaynaklı selülozun benzer yapıya sahip olduğu ifade edilmektedir. Bakteriyel selüloz, üretim amacına ve yöntemine bağlı olarak büyük bir ekonomik ve ticari potansiyele sahiptir ve gıda uygulamalarında genellikle yağ ikame maddesi, reoloji düzenleyici, probiyotik ve enzimler için immobilizasyon materyali, pickering emülsiyonlarının stabilizatörü, gıda kaplamaları ve yeşil ambalaj üretiminde film bileşeni olarak kullanılmaktadır. Son zamanlarda pancar ve şeker kamışı melası, meyve atıkları, süt sanayi atıkları gibi gıda atıklarının üretim girdisi olarak kullanılması ön plana çıkmıştır. Bu nedenle, endüstriyel yan ürünlerin, tarım-orman ve gıda endüstrisi atıklarının karbon kaynağı olarak kullanılması, verimi artırmak ve maliyeti düşürmek gibi önemli avantajlar sağlamaktadır. Bu çalışmada bakteriyel selüloz üretiminde gıda atıklarının kullanımı ve gelecekteki eğilimler ile ilgili bilgiler derlenmiştir

Anahtar sözcükler: Bakteriyel selüloz, selüloz, gıda endüstrisi, gıda atıkları

INTRODUCTION

Cellulose is a plant-originated polymer that exists in the cell wall. It is obtained from plant tissues such as tree trunks. However, benefiting from trees as the primary source of cellulose production has been threatening the wealth of forests. Thus, the environmentalist approach has promoted the researchers to explore new sources and techniques for cellulose production (Akoğlu et al., 2010). So, Bacterial Cellulose (BC) is also described as an eco-friendly material with excellent structural and functional properties (Navya et al., 2022). BC is a good alternative to satisfy this need which is based on a specific microbial bioprocess. BC was first identified in 1886, while Brown was observing vinegar fermentation and reported it to be a substance called the ‘‘vinegar plant” or ‘‘mother”, whose composition, structure, and reactivity were the same as plant cellulose (Cacicedo et al., 2016). Moreover, it is easily recognized that BC is superior to standard cellulose due to its advantageous aspects. It has been reported that BC has high purity, highly hydrophilic nature (high liquid loading capacity), high crystallinity, high surface area/mass unit, high degree of polymerization, good biocompatibility and biodegradability and excellent mechanical properties (Revin et al., 2018). In addition, it has high chemical purity, shape stability (when it is folded), long chained structure with a thin network, favorable for modifications during production, high mechanical strength, high water holding capacity, being ability to be synthesized with various substrates (Poyrazoğlu Çoban & Bıyık, 2008). BC is the purest form of cellulose available from microorganisms, it does not contain lignin or other contaminants, so purification step and extra energy request are eliminated (Bandyopadhyay et al., 2018). However, BC pellets are sometimes claimed to have impurities such as metabolic substances, cells, or nutrient residues, while elimination of these seems to be easy by application of the following three steps: alkaline treatment at 100°C / 15-20 minutes to remove the cells, isolation of the BC pellets from the alkaline solution and finally washing it with distilled water to obtain the neutral pH (Zhong et al., 2020). BC is also independent from regional and climatic conditions. In addition, microorganisms can be genetically modified to obtain desired properties, and their growth rate can be controlled for production in the requisite quantities and time span (Shi et al., 2014).

Thanks to all these advantageous properties, BC has promising applications in various food processes. For instance, BC is claimed to be a good reinforcement material, emulsifier-stabilizer, heat-stable suspending agent, non-caloric agent, texture enhancer (reducing stickiness of pasty foods), source of dietary fiber, and potential fat replacer to reduce the energy density of several foods (salad dressings, meatballs, etc.). Moreover, it has recently been used as a component of packaging film materials (Azeredo et al., 2017; Ferrer et al., 2017; Khan & Kamal, 2021; Thivya et al., 2022). These film materials are generally produced in disassembled form. Then, it is converted to micro/nanofibrils or nanocrystals via mechanical or chemical techniques (Mishra et al., 2018; Cazon & Vazquez 2021). So, types of nanocellulose can be aligned as cellulose nanocrystals, nano fibrillated cellulose, and bacterial nanocellulose (Bharmalla et al., 2017). The type of production is also effective on the morphology of obtaining BC. The BC membrane (pellicles) is obtained by static fermentation, while BC fibers (pellets) are produced by agitated fermentation (El-Gendi et al., 2023).

BC can be produced by many aerobic bacteria such as *Aerobacter, Agrobacterium, Azotobacter, Alcaligenes, Gluconacetobacter (Komagataeibacteria), Rhizopium, Rhodobacter, Pseudomonas and Sarcina, and Dickeya,* while particular *algaes (Vallonia)* and some moulds (*Saprolegnia, Dictystelinum discoideum*) are also capable of producing BC (Costa et al., 2017; Lin et al., 2020; Jang et al., 2023) and the cellulose ultrastructure together with its physical and mechanical properties are affected by cultivation techniques including static culture, agitated culture and bioreactor culture (Andriani et al., 2020). Addtionally , it is a multivariate biotechnological process in which the process inputs (production media), selected bacterial culture, process conditions, and the yield of the process are changeable. So, it has not been possible to claim that there is one type of production, and the biosynthesis process is generally complex. Nevertheless, the biosynthesis process of bacterial cellulose has recently attracted much attention due to its water retention capacity, high tensile strength, and ability to be modified with various elements, polymers, or bioactive materials (Jang et al., 2023). Moreover, production yield can also be enhanced via new developed media (Çakar et al., 2014; Mohammadkazami et al., 2015). However, the main drawback of such a production is its high cost (Azeredo et al., 2019). Thus, cost minimization requires finding alternative and valuable sources for the production which results in the valorization of waste as culture media (Esa et al., 2014; Zhong, 2020; Cazon & Vazquez 2021). As is known, the food industry produces waste continuously. Hence, waste management strategies and sustainable valorization of waste become as important as food production. In addition, handling these waste requires specific applications depending on the type of waste, because there have been a wide variety of waste materials from many kinds of production. The diversity of industrial waste generated from various food sources can be exemplified as solid waste (excreta, feathers, claws) or liquid waste (urine faeces, blood, and remnants of drugs and pesticides) from poultry processing; shells, roes, and trimmed parts from marine product processing; paneer whey skim milk, cheese whey, spilt milk, spoilt milk and curd chunks, buttermilk and ghee residue from dairy processing; husk, chaff, hull, bran and stalks from cereals and pulse processing; skin, pomace, peels, pith and stones from fruits and vegetable processing; hulks and stalks from spices and condiments, and so on (Kaur et al., 2023).

However, the valorization of food waste has not reached satisfactory levels yet. For instance, according to the data of the Republic of Türkiye Ministry of Agriculture and Forestry, 18 million tons of food is wasted annually (Tarım ve Orman Bakanlığı, 2022). FAO also reports that around 1.3 billion tons of food are wasted annually, accounting for a third of all edible foodstuffs produced worldwide (FAO, 2019). This unsatisfactory state reflects the gap between theory and practice, which is mostly due to the technological and economic unfeasibility of many of the valorization strategies (Mou et al., 2023). But new progressive studies seem to be promising by providing waste management and the production of alternative products as a contribution to the circular economy at the same time. Hence, this review aims to show how to utilize food waste in the production of BC, which enables both the valorization of food/industrial waste and the sustainable & green production of cellulose instead of plant-originated cellulose.

BIOSYNTHESIS MECHANISMS OF BACTERIAL CELLULOSE

The biosynthesis of BC takes place as a result of synchronic, accurate and regulated reaction chains with plenty of enzymes and protein complexes (Caciedo et al., 2016). BC yield and properties depend on how the biosynthesis has been performed. Several factors such as selection of the BC producing bacteria, composition of the culture medium, cultivation process, and process variables influence properties and yield of BC obtained. These aspects need to be carefully considered to get BC with yields high enough to increase its viability for food and food packaging applications (Azeredo et al., 2019)

Selection of BC producing bacteria

Among the BC producing bacteria (*Aerobacter, Agrobacterium, Azotobacter, Alcaligenes, Komagataeibacteria, Rhizopium, Rhodobacter, Pseudomonas, Sarcina, and Dickeya),* members of *Komagataeibacteria (*former *Gluconacetobacter)* are generally preferred for production because of their high capacity to utilize a wide variety of nutritional sources. The *Komagataeibacter* species is defined as gram-negative, strictly aerobic, living mainly in fruits and vegetables in the decomposition process, which are capable of converting common carbon sources at 25-30°C and pH 3-7 with changing yields and properties (Caciedo et al., 2016). However, this ability is not sufficient to fulfill the industrial demand (Lin et al., 2020). So, genetic engineering practices contribute to enhancing BC production yield for better results. For instance, genetically modified cells have been able to grow in spite of low nitrogen conditions and low oxygen environments (Azeredo et al., 2019).

Production medium

Production medium is especially claimed to be influential on the physical properties and morphology of BC. However, production cost is considered as important as the nature of obtaining BC (Navya et al., 2022). The high production cost and low yield of BC are significant issues, that limited its industrial production and wide range of applications (Lin et al., 2020). Thus, alternatives to the conventional culture medium (HS medium) are still being investigated. These alternatives may include a wide variety of fruit juices, coconut water or milk, molasses, starch hydrolysate, brewery waste, etc., resulting in different contents that are effective on BC yield (Navya et al., 2022).

According to the studies, the most important factors affecting BC production are the carbon and nitrogen sources used. In addition to being effective of BC yield, the carbon sources also affect the production cost of BC (Akoğlu et al., 2010). Çakmakçı et al. (2008) investigated the effect of using glucose, fructose, maltose, and galactose as carbon sources on BC production. According to the results, the use of fructose, maltose, sucrose, and glucose as carbon sources was claimed to support BC biosynthesis, while galactose was not found to be a good substrate. On the other hand, it was reported that D-xylose was not effectively metabolized by the BC forming bacteria unlike D-glucose (Ishihara et al., 2002). Moreover, glucose is reported to be more active than other carbon sources, except for the two sugar alcohols (arabitol and mannitol) (Navya et al., 2022). The price of complex nitrogen sources also affects the cost of BC production. Nitrogen sources, yeast extract, peptone, etc. are generally preferred, but these are expensive and complex production sources. Actually, synthetic fermentation medium is recommended instead of glucose containing complex growth medium (Akoğlu et al., 2010). Hestrin and Schramm's medium (HS medium) is widely used for BC production, having a specific formulation (2%, w/v, glucose; 0.5%, w/v, peptone; 0.5%, w/v, yeast extract; 0.27%, w/v, Na_2HPO_4) (Hestrin and Schramm, 1954). However, modification of the type and proportion of culture media is usually practiced to figure out the yield, cost, and properties of BC. At this point, it is suggested to optimize variables in defined media, then switch carbon & nitrogen sources to determine whether BC production has progressed (Singhania et al., 2022).

Recent studies have focused on finding alternative fermentation media to substitute for these expensive materials and HS medium. Castro et al. (2011) succeeded to perform an alternative and feasible production with the use of sugar cane juice and pineapple peel. According to the results, it was highlighted that the carbon and nitrogen sources of these waste were found to be sufficient for microbial growth. In a more recent study conducted by Hasanin et al. (2023), mango peel waste hydrolysate was found to be a significant inducible fermentation medium with no need for extra nutrients and increasing the BC yield about 2.5 fold in comparison to the HS medium. So, it can be re-emphasized that the composition of the fermentation medium is a critical determinant factor in both the production yield and cost.

Valorization of wastes can be an attractive practice. However, wastes can not be directly used in BC production. For this reason, pretreatment of waste before production is great important (Akintunde et al., 2022; El-Gendi et al., 2023). An effective pretreatment application is expected to satisfy three criteria. The first one is enhancing sugar yield or the ability to form sugars via enzymatic hydrolysis. The second one is elimination of carbohydrate degradation and the final one is being cost effective. Chemical and physical pretreatment processes are employed for agricultural waste. Chemical pretreatment includes acid and alkali pretreatment. Acid pretreatment is performed by organic (acetic) or inorganic (nitric) acids and is used for decomposing biomass waste, increasing cellulose availability, but alkali treatment is more common and is performed for improving the digestibility of the lignocellulose via swelling it, resulting in a higher surface area for the process, reduction of crystallinity and disruption of lignin structure. However, the type of waste is a determinant on the chemical pretreatment, and waste such as switchgrass and wheat straw require ionic liquid pretreatment in which imidazolium-based ionic liquids are used to improve enzymatic saccharification. On the other hand, pretreatment is also claimed to be effective on hydrolysis, which is one of the main steps of BC production. Hydrolysis is performed to make it easier for BC producing microorganisms to metabolize carbohydrates. Hydrolysis can be performed in two ways: acid hydrolysis and enzymatic hydrolysis. In acid hydrolysis, saccharification of waste is generally achieved by the use of diluted sulphuric acid. Although acid hydrolysis has some disadvantages and detrimental effects like corrosion of the equipment, high energy consumption, and the formation of some inhibitors during the reaction, this process eliminates the complexity of the carbon source, and formed simple sugars can easily be metabolized by the BC producer microorganisms. The problem about the formation of toxic (for microorganisms) chemicals can be eliminated by detoxification steps such as atmospheric cold plasma technique. These drawbacks are not seen in enzymatic hydrolysis and different enzymes can be used, including amylase, lactase, cellulase, etc., depending on the composition of the waste (El-Gendi et al., 2023). The practicability and applicability of the waste for several purposes can also be improved by some other biological (e.g.fungal pretreatment) and physicochemical (e.g. steam explosion pretreatment, extrusion pretreatment) methods, especially for lignocellulosic waste (Awogbemi and Kallon, 2022; Blasi et al., 2023).

Process variables

Process variables such as oxygen, pH, and temperature play a significant role in the biosynthesis of BC and have a direct impact on production yield due to their ability to promote microbial growth. The optimum pH range is explained to be 4-7, while the optimum process temperature is generally 28-30°C (except for some thermotolerant species that are isolated from some fruits and require high temperatures of 37-40°C) (Akoğlu et al., 2010). Monitoring and controlling the pH is suggested to achieve maximum BC yield since the pH of culture medium could change as time passes because of the deposition of secondary metabolites, such as acetic, lactic, or gluconic acids produced during the consumption of nitrogen and sugar sources (Azeredo et al., 2019). Oxygen is the other necessity for this process and approximately 10% of oxygen is reported to be needed (Akoğlu et al., 2010).

Another crucial process variable that must be controlled during cultivation is ventilation. Since the BC producing bacteria are highly aerobic, a sufficient supply of oxygen is essential in the process. When dissolved oxygen levels in the production environment are low, bacteria cannot grow and produce BC, but high oxygenation helps the production of gluconic acid (Azeredo et al., 2019). Especially in old-type fermentors, insufficient ventilation due to cellulose formation and an increase in viscosity are claimed to cause less performance (Akoğlu et al., 2010). So, these issues cause to design new alternative reactors such as airlift bioreactors (Navya et al., 2022).

Cultivation process

The process is considered as a determinant factor to obtain maximum BC production yield and recent studies have mostly focused on enhancing the yield, while controlling the costs at the same time. In this frame, type of reactor and the fermentation process are influential as well as the species and genetic modifications of bacteria, feedstock type & composition (Lin et al., 2020).

The selection of cultivation process involves static or agitated cultivation and these two types of production differ from each other at some points. For instance, agitated cultivation is found to be superior in terms of BC yield. However, this method may cause the mutation of BC producing microorganisms because of high shear stress and turbulance and this problem needs to be overcome by the addition of ethanol to the culture medium or by the use of different reactors. Moreover, obtaining fibrous BC is generally highly viscous and requires high agitation power and energy consumption for the same reason, but alternative reactor designs such as airlift bioreactors, which continuously supply oxygen from the bottom into the culture medium, seem to be promising to overcome this problem (high shear stress) with extra advantages (higher water holding capacity in comparison to BC obtained by the static cultivation method). However, in these reactors, BC is obtained in irregular form. On the other hand, static cultivation is a simple method and widely used but is also time consuming and inapplicable for meeting industrial demand. Static cultivation system is based on static fermentation, resulting in the formation of 3D-interconnected reticular BC pellicles (Navya et al., 2022), floating on the surface due to entrapping CO_2 bubbles generated by the bacteria (Lin et al., 2013). Alternative bioreactor designs, such as horizontal-lift reactor and aerosol bioreactor provide better BC yield in this type of production, too (Azeredo et al., 2019). As a result, the reactors, in which the cultivation process takes place can have different designs. Examples of reactors operating at static conditions can be aligned as horizontal lift reactors, aerosol bioreactors and rotary disc reactor, while the reactors operating at agitated conditions can also have several kinds according to agitator configurations (turbine, maxblend, helical ribbon, screw with draft tube, gate with turbine) (Shi et al., 2014) or airlift bioreactors can be used (Singhania et al., 2022). However it should be mentioned that the operation should be well organized depending on the intended production capacity so that the application of cultivation processes may require large-scale, semi-continuous/continuous productions for commercialization (Azeredo et al., 2019).

In summary, it can be concluded that BC production is based on these fundamentals and especially nutritional conditions can dramatically affect production. This fact points out the importance of a fermentation medium, which contains a big potential for valorization of waste with plenty of alternatives, while production details may also bring some individual requirements (Caciedo et al., 2016).

PRODUCTION OF BACTERIAL CELLULOSE FROM FOOD WASTE

Obtaining the data from the information as reported by Seberini (2020), Caldeira et al. (2019) and FAO (2019) observations, it has been estimated that approximately 46% of the fruits, vegetables, tubers, and roots are wasted. On the other hand, 30% of cereals and 35% of fish and shellfish are wasted. The FAO has declared that this ratio accounted for the food produced on nearly 1.4 billion hectares, representing 28% of the world's agricultural area. If this issue is evaluated in detail, it would easily be seen that waste formation is proportional to the population of the countries. It was reported that according to the status of total food wastage around the world, Australia, Spain, Russia, the United Kingdom, France, Germany, Japan, the United States, India and China are aligned in increasing order. In the same research, worldwide wastage of several foods was reported as cereals, vegetables, fruits, fish waste, orange peels, oil crops, milk, tomatoes and bananas, onions, pineapples, and meat in descending order (Lahiri et al., 2023).

Wastage problem leads to new ideas and innovative applications such as bioconversion of the waste (e.g. dairy waste) into value-added products which contributes to the circular economy approach and promotes sustainable production with waste reduction (Usmani et al., 2022). Valorization of the waste is also advantageous instead of using overpriced pure substrates (Tsang et al., 2019). Normally, Hestrin-Schramm (HS) is a standard and the most appropriate medium for cultivation of BC, but it is expensive (Ghozali et al., 2021). So, this fact is considered as a starting point for many research studies, and obtaining cellulose is found to be substitutable with satisfactory or even superior characteristics as shown by recent studies (Table 1).

Table 1 summarizes the recent studies related to BC production from food or food industry waste and/or by-products. Ghozali et al. (2021) investigated the utilization of liquid tapioca waste for BC production. In their study, *Acetobacter xylinum* was used as fermentation culture, and different concentrations of sugar and urea were used as nitrogen sources for biosynthesis. According to the results, it was reported that Fourier transform infrared spectroscopy (FTIR) and Scanning electron microscopy (SEM) analysis approved the bacterial cellulose structure and the usage of liquid tapioca waste is suitable for BC production, which has already been widely used (tapioca starch) as a non-staple food resource in many industrial fields due to its low cost and high availability.

Table 1. BC production with various food or food industry waste/by-products

***Çizelge 1.** Çeşitli gıda veya gıda endüstrisi atıkları/yan ürünleri ile bakteriyel selüloz üretimi*

Waste	Culture	Production Method	Results	Reference
Beer yeast waste	*Gluconacetobacter hansenii* CGMCC 3917	0,1 M NaOH treatment Ultrasonication High speed homogenizer Microwave treatment	Ultrasonication combined with mild acid hydrolysis was an effective pre-treatment and the resulting BC had good physicochemical attributes	Lin et al., 2014
Sugar cane juice and pineapple waste	*Gluconacetobacter medellinensis*	Static and dynamic culture conditions	The physicochemical attributes of BC produced from pineapple waste were comparable to those produced from standard culture media Different morphologies were biosynthesized under static and dynamic culture conditions	Algar et al., 2015
Waste water from candied jujube-processing industry	*Gluconacetobacter xylinum* CGMCC No.2955	Ammonium citrate treatment Acid hydrolysis	Acid hydrolysis increased the yield of BC but decreased the crystallinity index Ammonium citrate was enhancing the crystallinity index and yield of BC	Li et al., 2015
Acidic food industry by-products (alcohol and dairy industries)	*Gluconacetobacter sucrofermentans* B-11267	Cultivation of the bacterium on thin stillage and whey	The greatest yield of BC was obtained on thin stillage Cost-effective production was achieved with usage of thin wheat stillage and whey	Revin et al., 2018
Tobacco waste extract	*Acetobacter xylinum* ATCC 23767	Nicotine removal from the waste in different fermentation stage	Nicotine was found to be an inhibitory factor for synthesis Obtaining BC from the tobacco waste extract was similar to that of obtained by HS standard medium	Ye et al., 2019
Orange peel waste generated from catering services	*Komagataeibacter sucrofermentans*	Airlift bioreactor	68 kg BC obtained from 1 ton of orange peel (extra value-added products were phenolic-rich and pectin rich extracts, essential oils)	Tsouko et al., 2020
Citrus processing waste biorefinery	*Komagataeibacter sucrofermentans*	Ultrasound-assisted dilute acid hydrolysis process	5.82 g BC per 100 g waste was produced by fermentation process	Karanicola et al., 2021
Crude confectionery waste hydrolysates	*Komagataeibacter sucrofermentans*	Production of BC and BC nanostructure in static culture conditions	*K. sucrofermentans* cultivation in static cultures at carbon / free amino nitrogen ratio of 24.5 g/g and pH 5 produced 5.7 g/L BC. The obtained nanoBC analysis results showed that they could be used as reinforcing agents in innovative food formulations and biopolymers in various forms (hydrogels, aerogels, emulsions, nanocomposites) and bio-based films for food packaging application	Efthymou et al., 2022
Winery waste streams	*Actinobacillus succinogenes*	Holistic biorefinery scheme	The biorefinery produced 42,65 g BC and other value co-products from 1 kg of each waste stream	Filippi et al., 2022
Grape pomace hydrolysate	*Komagataeibacter melomenusus* AV436 ^{T} and *Komagataeibacter xylinus* LMG 1518	Different culture conditions	*Komagataeibacter melomenusus* AV436^{T} was found to be the most efficient microorganism in this process in comparision to *Komagataeibacter xylinus* LMG 1518	Gorgieva et al., 2023
Okara (a Japanese food product and a by-product of agro-industrial soybean waste)	*Gluconacetobacter xylinus*	Nanocellulose production by biosynthesis using acetic-acid modified okara protein, homogenized okara and okara protein	The higher cellulose yield was achieved by acetic-acid modified okara protein as compared to homogenized raw okara and okara protein	Taokaew et al., 2023

Table 1. Continued

Çizelge 1. *Devamı*

Waste	Culture	Production Method	Results	Reference
Coffee by-products	*Kombucha* cultures	Production of BC by kombucha fermentation including coffee by-products	Obtaining BC was sustainable reinforcing and active filler for biopolymers	Agüera et al., 2023
Oil palm frond juice	*Acetobacter xylinum* 0416	Corn steep liquor addition as nitrogen sources Homogenization Ultrasonication	6-fold higher yield in BC (in comparison with HS standard medium) Combining ultrasonication and homogenization was an effective safe and simple method for converting BC obtained from oil palm frond juice to nanofibrillated BC	Azmi et al., 2023
Kitchen waste	*Komagataeibacter rhaeticus (K15)*	Production of BC by K15 culture isolated from kombucha tea	Obtaining BC has good crystallinity, and the K15 strain presents a highly viable alternative strategy to reduce the production costs using agro- industrial residues as nutrient sources	Li et al., 2021
Liquid tapioca waste	*Acetobacter xylinum*	Different glucose and nitrogen source composition	Obtaining good crystal structure with an economical process	Ghozali et al., 2021
Pomegranate peel extract	*Gluconacetobacter hansenii*	Pristine BC produced by HS standard medium Production of BC by pomegranate peel Ex situ preparation of BC/pomegranate peel extract (PGPE) composite	BC/PGPE composite was produced as a promising antibacterial wound dressing material	Ul-Islam et al., 2023
Sugar beet molasses	*Gluconacetobacter xylinus* NRRL B-759	Conventional static culture (CSC) with HS medium Conventional static culture with sugar beet molasses Series static culture (SSC) with sugar beet molasses	The use of developed SSC resulted in a 22.02% increase in BC production. High crystallinity index of BC obtained from CSC and SSC (in comparison with HS medium). Obtaining nano-sized cellulose fibrils with high mechanical strength and water holding capacity	Öz & Kalender, 2023
Industrial residue of cashew apple juice processing	*Komagataeibacter xylinus* ATCC 53582 and *Komagataeibacter xylinus* ARS B42	Different culture conditions	Despite its lower titer, the BC from *K. xylinus* ARSB42 presented a high thermal resistance and a remarkable absorption capacity (a potential superabsorbent biomaterial).	Guimaraes et al., 2023

Bacterial cellulose production methods had previously been classified as agitated/shaking culture, and bioreactor culture methods. However, in a recent study conducted by Öz & Kalender (2023), a new static cultivation system, which is being called as “series static culture (SSC)” was developed to solve the problem of air limitation in conventional static culture. This system includes plastic autoclavable containers for the culture medium, silicon tubes for medium transfer, valves, and peristaltic pump. It is based on transferring the fermentation broth at the bottom of the BC pellicle to the next empty sterile culture medium at the end of fermentation (10 days) until BC production has stopped. As a result, the culture medium under BC was transferred from one stage to the next using related valve and peristaltic pump. Purified BC was obtained, dried, weighed and characterization tests were carried out. The process is started with sugar beet molasses at 30°C / pH=5 and *Gluconacetobacter xylinus* NRRL B-759, while total BC production increased with increasing sugar level in the system (BC yield 22.02 % at initial sugar concentration of 100 g/L). It was determined that BC produced under these conditions had high water holding capacity mechanical strength, and crystallinity index. According to obtained results, it was concluded that the use of alternative carbon sources which are also cheap, waste, and renewable provides a feasible process instead of synthetic media. So, sugar beet molasses is re-confirmed to be a good substrate for such a process that, it has already been used in many fermentation processes, since its content is suitable for such a purpose (containing fructose, sucrose, glucose, vitamins, and N, Fe, Ca, K, Mg).

In the last ten years, the studies indicated that any kind of food waste and/or industrial waste could be utilized as a good production substrate for the production of BC in addition to reducing the process cost. Among these studies, especially utilization of fruit and vegetable peels, tomato juice, pecan nutshell, or vegetable oil etc. in the BC production become prominent (Güzel & Akpınar, 2018; Bozdağ et al., 2021; Saleh et al., 2022; Varjani et al., 2023). Moreover, food industry by-products such as beet molasses, vinasse, and waste beer fermentation broth can also be valorized with some differences in structural properties when compared with BC obtained by HS-medium usage (Heydorn et al., 2023). Diversity of potential feedstocks can be re-emphasized with another recent study which was dealing with acidic dairy industry by-products as growth medium. The process was found to be feasible and a promising application and it was reported that the maximum BC yield was 2.42-fold higher than cellulose produced by HS medium under optimum conditions (after 15 days under static conditions at room temperature) (El-Bestawy et al., 2023). On the other hand, food waste can sometimes be utilized in different ways, too. For instance, *Novacetimonas hansenii* strain, which was capable of producing cellulose was isolated from rotten pomegranate for BC production in a recent research performed by Neelima et al. (2023). This is an example to a different type of utilization from waste where function of the waste has changed and become the source of culture instead of being production media. The research of Hasanin et al. (2023) is also a similar example that strawberry was reported as a source for isolation of newly BC producing bacteria. In general, the usage of waste seems to be widespread with an increasing trend and multifunctional utilization opportunities might draw more attention in the following years.

CONCLUSIONS and FUTURE TRENDS

Various cellulosic waste from agro-forestry residues or industrial by-products were utilized as carbon sources in BC production and those are claimed to improve the yield, while also reducing the economic cost. Thus, the main limitation of BC production is the requirement for highly priced substrates such as Hestrin-Schramm (HS) medium. On the other hand, the composition of different kinds of waste varies as well as the production type (at laboratory scale or in static/agitated reactors), resulting in different product (BC) properties. Hence, process conditions are specifically examined and optimized in the basis of the operation itself. That kind of process would promote the circular economy and sustainable & green technology approach in addition to obtaining high quality BC to be used in many fields of industry. In conclusion, the valorization of waste for BC production seems to be open to progress because there have been plenty of different substrates and cultures that verify production potentials. Additionally the process design can also be improved as in SSC (series static culture), while utilization of the waste might be in a different way, too. Obtaining BC producing cultures from food waste is a good example of this concept. As a result, all of the efforts are expected to reach a satisfactory level by supporting green production and waste management at the same time in the future.

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