Chemical Innovation and Regulation

University of Bologna

University of Barcelona

University of Algarve

Renewable resources

Bacterial Cellulose: a mini-review

Report for the purpose of evaluation of the module G01 Renewable resources - taught by Professor Dr. Chiara Samorì

Carla Thaís Pereira Coelho

Bologna

2022

Summary

ABSTRACT

Bacterial cellulose (BC) is an exceptionally versatile natural biomaterial. This review covers the production, properties, some the applications, and challenges to the insertion of this environment-friendly material in the market.

1. INTRODUCTION

Environmental concerns have acted as a driving force for the transition from classic processes to green technologies and the use of renewable raw materials (1; 2; 3). In this sense, cellulose is the most used natural polymer globally, which is typically isolated from plants; however, plant-derived cellulose are linked closely with hemicellulose, lignin, and many minerals (1; 4; 5). Also, the demand for cellulose increased deforestation and global environmental issues due to the use of wood consumption as raw material (6). On the other hand, microbial and enzymatically synthesized cellulose are highly pure, can be produced by agricultural and food waste, and have unique properties (1; 4; 3).

Bacterial cellulose (BC) or microbial cellulose (MC) is a highly crystalline linear biopolymer of glucose, which can be produced by different species of bacteria (1; 7). BC is chemically equivalent to plan-based cellulose and could be a substitute for it since the key in the cellulose structure is the presence of bountiful hydroxyl groups in the polymer chain (1; 8). It contains abundant OH groups on its surface, which allows its interaction with a variety of functional groups, thus leading to the formation of BC-based functional materials for different applications (4).

More than only a substituent of plant-based cellulose, BC has received substantial interest because of its unique properties (1). High purity, crystallinity, water absorption, retention capacity, tensile strength, high degree of polymerization, and low density are some of the many attributes (1; 9). Furthermore, bacterial cellulose is environment-friendly material as it is non-toxic, non-immunogenic, biocompatible, biodegradable, and renewable nature (4; 5). However, it lacks antibacterial, antioxidant, electrical conductivity, magnetic, and optical properties, so new processes have been investigated to improve its characteristics since these intrinsic structural features of BC are highly dependent on the culture conditions, the composition of the growth medium, the type of microbial strain used, and the incubation period (4; 7; 10).

2. PRODUCTION

The production of bacterial cellulose is a bottom-up process, which generally consists of fermentation by gram-negative bacteria (4; 9). Bacteria synthesize cellulose fibers in the cytoplasm by a series of reactions that involves uridine diphosphoglucose (UDP-Glc) as a precursor and different types of enzymes and regulatory elements (1; 4). Depending on the carbon sources, pH, chosen strains, and culture conditions, different structures, mechanics, morphologies, crystallinity, and porosity will be produced (3).

Different types of cellulose structures can be obtained depending on the culture method chosen, which has been reported in static, stirred, and agitated conditions (1). In static fermentation, BC is produced as a dense gelatinous pellicle at the air-liquid interface, creating a thin 3D network structure with great mechanical properties and purity (6; 8; 11). Under stirred fermentation, irregular pellets are synthetized, while under agitated cultivation, granules or sphere-like particles are produced (1; 4), which revealed worse material properties, such as purity and tensile strength, when compared to the film produced under static conditions (5). However, static fermentation is limited by air supply, and in this sense, agitated fermentation is more economically viable and can be easily amplified to industrial production (1; 11).

Regarding the cultivation medium, carbon and nitrogen are the main nutrients for successful fermentation and BC production (11). These nutrients can be found in many sources, such as a low-cost unconventional substrate or agro-industrial waste, coconut water/milk, beet molasses, waste beer yeast, and rotten fruit culture, for example, which can reduce the cost of the production and stimulate the industrial-scale production (4; 8).

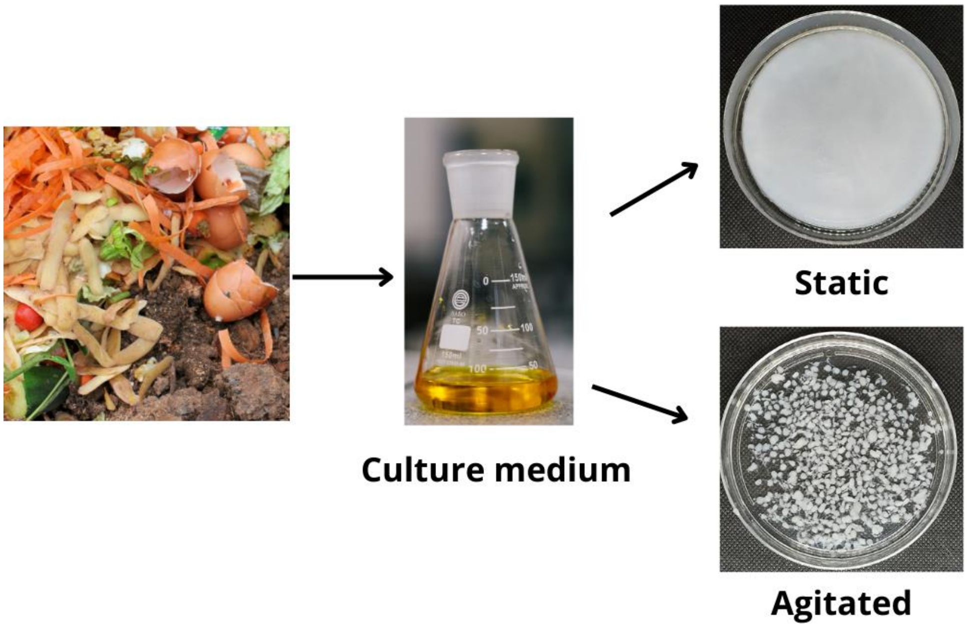

Figure 1: Scheme of BC production from waste as source of nutrient. Images from: (8) and Canvas.

3. STRUCTURE AND PROPERTIES

Bacterial cellulose is identical in molecular formula and polymeric structure to plant/algae cellulose, but it has unique properties such as high purity, stronger and longer fibers, higher stability, higher water swelling, and can be shaped into any form (3; 8). Also, for the production, several substrates can be used as a nutrient source and the membrane properties and yields vary depending on these sources, but also on the bacterial strain used (3).

Some unique properties of BC are because of its crystallinity due to the high degree of polymerization (3) (8). BC has a high number of inter and intra hydrogen bonds between chains of glucan, making the crystalline region more ordered, so the glycosyl units are positioned in a different way than the plant-based cellulose, creating a distinct diffraction pattern, swelling, and reactivity of cellulose (3). Like cellulose, it has also a non-crystalline region, but the high crystalline regions are the major compound of the structure, giving the high mechanical strength and flexibility to the biopolymer (8).

BC structure is also characterized by the nanofibers 3D reticulated network (8). This network corroborates to the mechanical properties, the high water holding capability, high suspension stability, and excellent gas permeability (8).

In addition, due the presence of innumerable OH functional groups, the chemical structure of BC can be modified to include specific functional groups to acquire particular responses (2; 3; 12). This functionalization can be conducted in situ, altering culture conditions with additives or by changing the carbon source, and ex-situ, such as physical absorption of active agents by the purified pellicles (2; 12).

4. APPLICATIONS

Due to the interesting properties of bacterial cellulose, such as high purity, high porosity, and non-toxicity, it has been attracting attention to be used in a broad spectrum of applications (7; 10). It is used as a bulk material for food, paper, packaging, and textiles, also by the cosmetic and electronic industries, pollutant remediation and there is a huge interest in the use of BC for biomedical applications (2; 10).

The food industry uses microbial cellulose as an edible biopolymer which can be used to gelling, thicken, and stabilize some products such as yogurt and pastries (2; 12). What makes BC such a good ingredient for food production is its high water-holding capacity, biocompatibility, purity, and low-calorie fibers along with the health benefits, such as reduction of diabetes and obesity (2; 7). As a biopolymer, it can be also used in the packaging industry for the production of a biodegradable, non-toxic, green film to substitute petrochemical-derived plastics (2; 11). The paper industry has a huge environmental impact due to deforestation to foment the number of resources necessary for its production (2). In this sense, BC is a suitable source of cellulose itself, but also, due to its excellent mechanical properties, it can improve the physical properties of recycled paper when mixed in the process (2; 11). Still, regarding the great mechanical properties, BC fibers are also suitable to be used in textiles, improving flexibility and replacing the synthetic fibers commonly used (2).

Given the facility for functionalizing the BC surface is possible to produce superabsorbent polymers (SAPs) (12). A film of BC can work as an adsorbent for specific pollutants depending on its functionalization and be used in the bioremediation of industrial waste (2).

In addition to the aforementioned properties, BC also has great resistance to insulating/ionic liquids (ILs), which is a key advantage for electronic applications (2). For this application different strategies can be followed, one example is the carbonization of BC, resulting in an electrode material with excellent mechanical and stability under bending and stretching strains that can be used in flexible storage devices (2). Another strategy is combining other compounds with BC, such as reduced graphene oxide (RGO) to improve electrical conductivity and mechanical performance, which can be used for the development of flexible electronic devices (2) (3).

In cosmetics, the biocompatibility, high water-holding capacity, absorption and release of substances, and skin adhesion, make BC a potentially sustainable option to replace many components (2). The excellent biocompatibility of BC makes it also suitable to be used in biomedical applications (7). Along with its structural variability, mechanical strength, 3D fibrous structure, porosity, water retention capacity, and transparency, BC can be exploited in wound healing, drug delivery, tissue engineering, and also in artificial blood vessel fields (2).

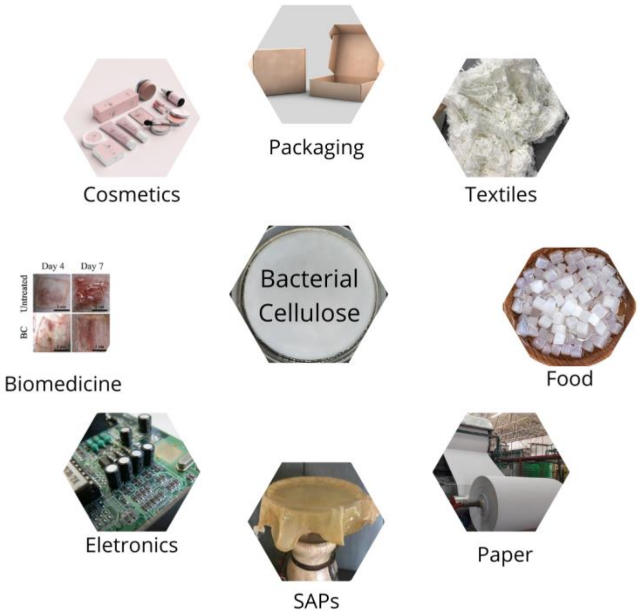

Figure 2: Applications of Bacterial Cellulose. Images sources: (8; 9) and Tehran Times.

5. CONCLUSIONS AND CHALLENGES

BC has been receiving a lot of interest due to the increasing number of applications (2). Biomedicine, environmental engineering, biosensing, food design, sustainable packaging, and electronic devices are some of the possibilities (7). However, BC production is limited and the bioprocess is full of challenges (1).

Unfortunately, BC's large-scale production implementation still faces difficulties (11). The production process demands a high cost due to the expensive culture media, the heterogeneity in the amounts of interesting compounds, discrepancies between strains' growth rates, and low productivity, depending on culture conditions (4; 11). Some of these limitations can be overcome by the use of unconventional and waste materials as subtracts, developing modified strains, using fermentation reactors, and optimizing the fermentation conditions (4; 8; 11).

More than the traditional applications of cellulose, BC offers a broad spectrum of applications (9). Furthermore, the possibility of controlling the fermentation pathways and properties, such as crystallinity, pore size, internal structure, morphology, and others, would expand this material's uses as a resource for many applications and the production of value-added products (1; 3).

In conclusion, BC is a highly versatile green material with huge potential (2). Making good use of the unique properties of BC for the development of important materials and technologies will allow the creation of non-toxic and eco-friendly opportunities for the future (2; 8).

REFERENCES

1. **Singhania, R. R., Patel, A. K., Tseng, Y. S., Kumar, V., Chen, C. W., Haldar, D., Saini, J. K., & Dong, C. Di.** Developments in bioprocess for bacterial cellulose production. *Bioresource Technology.* 344, 2022, Vol. 126343, https://doi.org/10.1016/j.biortech.2021.126343.

2. **Gregory, D. A., Tripathi, L., Fricker, A. T. R., Asare, E., Orlando, I., Raghavendran, V., & Roy, I.** Bacterial cellulose: A smart biomaterial with diverse applications. *Materials Science and Engineering R.* 145, 2021, Vol. 100623, https://doi.org/10.1016/j.mser.2021.100623.

3. **Kosseva, M. R., Zhong, S., Li, M., Zhang, J., & Tjutju, N. A. S.** Biopolymers produced from food wastes: A case study on biosynthesis of bacterial cellulose from fruit juices. *Food Industry Wastes: Assessment and Recuperation of Commodities.* 225–254, 2020, https://doi.org/10.1016/B978-0-12-817121-9.00011-5.

4. **Manan, S., Wajid Ullah, M., Ul-Islam, M., Shi, Z., Gauthier, M., & Yang, G.** Bacterial cellulose: Molecular regulation of biosynthesis, supramolecular assembly, and tailored structural and functional properties. *Progress in Materials Science.* 129, 2022, Vol. 100972, https://doi.org/10.1016/j.pmatsci.2022.100972.

5. **Konopacki, M., Grygorcewicz, B., Kordas, M., Ossowicz-Rupniewska, P., Nowak, A., Perużyńska, M., & Rakoczy, R.** Intensification of bacterial cellulose production process with sequential electromagnetic field exposure aided by dynamic modelling. *Biochemical Engineering Journal.* 182, 2022, Vol. 108432, https://doi.org/10.1016/j.bej.2022.108432.

6. **Esa, F., Tasirin, S. M., & Rahman, N. A.** Overview of Bacterial Cellulose Production and Application. *Agriculture and Agricultural Science Procedia.* 2, 2014, Vols. 113–119, https://doi.org/10.1016/j.aaspro.2014.11.017.

7. **Jin, K., Jin, C., & Wu, Y.** Synthetic biology-powered microbial co-culture strategy and application of bacterial cellulose-based composite materials. *Carbohydrate Polymers.* 283, 2022, Vol. 119171, https://doi.org/10.1016/j.carbpol.2022.119171.

8. **Zhong, C.** Industrial-Scale Production and Applications of Bacterial Cellulose. *Frontiers in Bioengineering and Biotechnology.* 8, 2020, Vols. 1–19, https://doi.org/10.3389/fbioe.2020.605374.

9. **Chen, C., Ding, W., Zhang, H., Zhang, L., Huang, Y., Fan, M., Yang, J., & Sun, D.** Bacterial cellulose-based biomaterials: From fabrication to application. *Carbohydrate Polymers.* 278, 2022, Vol. 118995, https://doi.org/10.1016/j.carbpol.2021.118995.

10. **Szymańska, M., Hoppe, J., Dutkiewicz, M., Sobolewski, P., Palacz, M., Janus, E., Zielińska, B., & Drozd, R.** Silicone polyether surfactant enhances bacterial cellulose synthesis and water holding capacity. *International Journal of Biological Macromolecules.* 208, 2022, Vols. 642–653, https://doi.org/10.1016/j.ijbiomac.2022.03.124.

11. **Fernandes, I. de A. A., Pedro, A. C., Ribeiro, V. R., Bortolini, D. G., Ozaki, M. S. C., Maciel, G. M., & Haminiuk, C. W. I.** Bacterial cellulose: From production optimization to new applications. *International Journal of Biological Macromolecules.* 164, 2020, Vols. 2598–2611, https://doi.org/10.1016/j.ijbiomac.2020.07.255.

12. **Raghavendran, V., Asare, E., & Roy, I.** Bacterial cellulose: Biosynthesis, production, and applications. *In Advances in Microbial Physiology.* 1, 2020, Vol. 77, https://doi.org/10.1016/bs.ampbs.2020.07.002.