Annals of Warsaw University of Life Sciences - SGGW
Forestry and Wood Technology No. 109, 2020: 6-15
(Ann. WULS - SGGW, For. and Wood Technol. 109, 2020)

Review of the industrial applications of bacterial cellulose

MICHAŁ MICHAŁOWSKI, BŁAŻEJ WACIKOWSKI
Faculty of Wood Technology, Warsaw University of Life Sciences - SGGW, 159 Nowoursynowska St., 02-776 Warsaw, Poland

Abstract: *Review of the industrial applications of bacterial cellulose.* Bacterial cellulose (BC) differs from plant cellulose in fibre diameter, which for BC is between 20 and 100 nm. Literature data indicates that BC has a crystalline level of 90% and is thermally stable and has higher mechanical properties than plant cellulose. The purity of BC is estimated in the range of 98% because it is not contaminated with lignin, pectin and hemicelluloses like plant cellulose. The BC is used in medicine, cosmetics, electronics, food, paper and packaging industries. So far, bacterial cellulose has not been implemented for technological applications in the wood-based panels industry. Current research and development trends in the wood-based panels industry include the use of plant-based nanocellulose to improve selected properties of wood-based panels of various types. It should be assumed that BC may be a full value material ingredient in the production of wood-based panels, simultaneously improving mechanical and physical parameters of composites manufactured with its participation.

Keywords: bacterial cellulose, wood based panels industry, application of bacterial cellulose, properties

INTRODUCTION

Contemporary trends in research and implementation activities of various industries focus on developing environmentally friendly solutions. This leads to an increased interest in the use of materials from renewable sources to implement efficient and ecological industrial processes. The global goal assumes full substitution of synthetic polymers, fully biodegradable natural polymers, produced with the use of known transformations and processes taking place in the natural environment (Kim *et al.* 2006).

Poland is one of the European leaders in the production of wood-based panels, producing about 11 million m^3 of fibrous, chipboard and layered panels per year, with a steady production growth rate. The largest part of production is made up of particle boards, which are produced in the amount of about 6,5 million m^3 per year. The plant's production is strictly dependent on constant supplies of increasingly deficient wood. Already in 2006, the wood deficit for the panel industry was estimated at 20%. This situation is directly influenced by economic conditions, increase in technological innovation, processing capacity through modernization of existing and construction of new production lines. In order to reduce emerging risks, the expert community has formulated predicted development scenarios for the entire wood industry based on foresight data. Among the five identified research areas with the highest level of innovativeness for the wood composite industry, a research direction has been identified which provides, among other things, for the need to modify the raw material structure, including the substitution of wood, especially in the case of materials with new properties. Scientific issues concerning the search for complementary raw material substitutes (in relation to wood) for the wood composite industry in order to develop materials with new, better physical and mechanical properties are currently the highest scientific priority in the engineering of wood materials (P7), characterized by high implementation potential, evaluated at 4.7 points (on a scale of 5.0 points), while at the same time the demand for research results is constantly growing. The effects of the undertaken activities may significantly contribute to inhibiting or reducing the growing material deficit and will allow to maintain the production dynamics at a constantly growing level. Natural biopolymers, in particular cellulose (Fig.2) and its derivatives are promising materials. Cellulose is the most common biopolymer, it is mainly derived from plants and is used most in paper production (Vela´squez-Rian˜o and Vivian Bojaca 2017). However, obtaining cellulose from plants requires large financial and energy expenditure in order to separate it from the strongly bound lignin. In recent decades, there has been a lot of research of the production of cellulose from microorganisms. Bacterial cellulose (BC) does not contain lignin or hemicelluloses and is the purest form of cellulose. It can be a renewable source of biomass with unique chemical and physical properties, high purity, high crystalline, chemical intensity and polymerization possibilities, as well as biodegradability and biocompatibility (Betlej 2019; Ludwicka et.al 2019, Siro´ and Plackett 2010). Bacterial cellulose has a significantly higher degree of crystalline than plant cellulose (60% vs. 90%). It forms characteristic fibrous ribbons (Shaghaleh *et al.* 2018), which connect to other elementary fibbers in 3D network (Klemm *et al.* 2005). For this reason, the evolution of materials containing among other things, cellulose synthesized under laboratory conditions has become an object of interest for the field of material engineering sciences, with the aim of producing environmentally friendly products, created using fully eco-friendly technological processes (Bajpai *et al.* 2013).

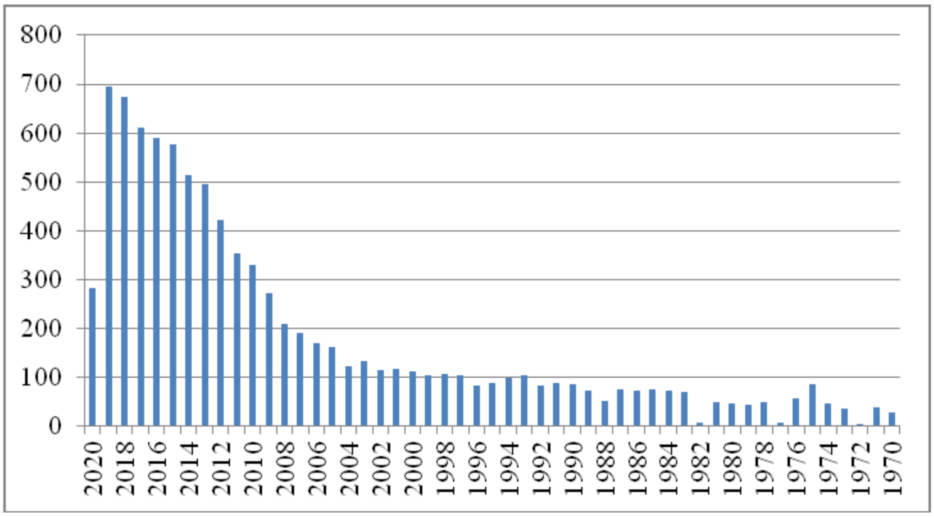

Fig.1. The number of publications with the tag "Bacterial Cellulose" in the years 1970 to 2020 The source: https://pubmed.ncbi.nlm.nih.gov/

Many studies on the use of BC are currently being conducted. This is evidenced by the constantly increasing number of published results over the past years (Fig.1). This paper presents information on the use of bacterial cellulose in various industries. The paper is divided into five parts: the first part provides information on the properties of bacterial cellulose and shows its differences from plant cellulose; the second part refers to the manufacturing processes of bacterial cellulose; the third part describes the existing application possibilities of bacterial cellulose in different industries; the fourth part describes the possibilities of direct use of bacterial cellulose in the wood-based panels industry, the whole is summarised in part five.

PROPERTIES OF BACTERIAL CELULOSE

Cellulose chains with a length of several micrometers are polysaccharides composed of 3000 to 14000 glucose particles connected by β - 1.4 - glycoside bonds. Plant-based cellulose as well as bacterial cellulose is characterized by the occurrence of free hydroxyl groups, which are easily substituted (Skocˇaj 2019). Cellulose is produced by plants but can also be synthesized by bacterial such as *Agrobacterium*, *Aerobacter*, *Azotobacter*, *Rhizobium*, *Sarcin*, *Salmonella* and *Gluconacetobacter*. The BC is a straight chain polysaccharide (Fig.2), with the same chemical structure as cellulose that is derived from plants (Torgbo *et al.* 2018). The BC has the advantage of being devoid of lignin, pectin, hemicelluloses, and other biogenic products that are normally associated with plant cell wall structures (Jonas and Farah 1998; Gallagos *et al.* 2016; Betlej and Krajewski 2019). The amount of synthesised plant cellulose is estimated to be between 100 and 150 billion tonnes per year (Skocˇaj 2019). For research purposes, bacterial cellulose is most often produced by the *Acetobacter Xylinus* strain (Aitoma¨ki and Oksman 2014, Skocˇaj 2019), which can synthesise cellulose into two structural types. The first type is characterized by glucose molecules connected by β - 1.4 bonds which are arranged linearly, in the second type of cellulose the bonds are arranged non-linearly (Skocˇaj 2019; Yu X *et al.* 1996). Although the structure of bacterial cellulose is chemically identical to that of plant-based cellulose, they differ, for example, in fibre diameter, which for BC is between 20 and 100 nm. Bacterial cellulose is thermally stable and purity estimates at 98% because it does not contain lignin, pectin or hemicelluloses (Jonas Farah 1998; Nguyen et al 2008). Bacterial cellulose has a very high level of absorbability (at least 200 times the dry matter of cellulose) (Evans *et al.* 2003).

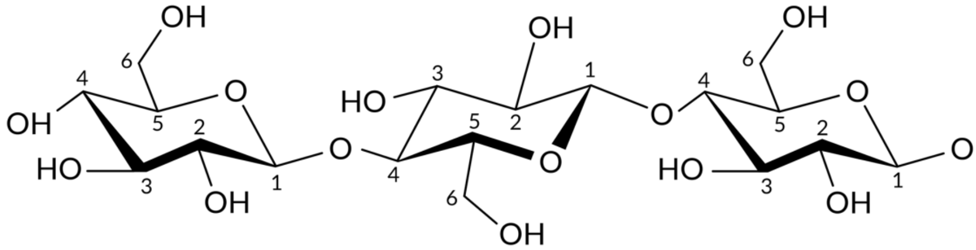

Fig.2 Chemical structure of cellulose

PRODUCTION OF BACTERIAL CELULOSE

The first synthesis of bacterial cellulose was performed by Brown *et al.* (1886) over 130 years ago. *Komagataeibacter* (now known as *Gluconacetobacter*) is the most common bacterium capable of producing cellulose in the temperature range 25 to 30°C and the pH range 4.5 to 7.5 (Son *et al.* 2001). Optimal conditions for the synthesis of BC by *Gluconacetobacter* are 28 to 30°C (Budhiono *et al.* 1999; Gomes *et al.*2013; Kurosumi *et al.* 2009; Vela´squez-Rian˜o and Bojaca 2017). Bacteria capable of synthesising cellulose can use a variety of carbon sources, usually glucose and sucrose. However, there are many potential substrates that bacteria can use as a source of carbon. These include monosaccharide, disaccharides, polysaccharides, organic acids, alcohols (Jonas and Farah 1998; Igbal 2014). There are many studies proving that bacteria can produce BC using other carbon sources (Mikkelsen *et al.* 2009). In the studies Abdelraof *et al.* (2019) demonstrated that waste products from the food industry can be used for cellulose synthesis. Bacterial cellulose produced from food industry waste (e.g. potato peelings) characterized a high degree of cross-linking and a crystalline level of 82.5%.

USE OF BACTERIAL CELLULOSE

Due to its physical and chemical properties, bacterial cellulose is used in many industries such as medicine, cosmetics, electronics, food and paper (Gray et.al 2013). There are many studies showing that the addition of BC to various materials improves their rheological and strength properties. BC as a resource is low-cost, environmentally friendly source, can be produced on industrial scales via the microbial fermentation process (Chen *et al.* 2013).

FOOD INDUSTRY

Bacterial cellulose has been classified in GRAS (Generally Recognized As Safe) because of its health benefits. In the food industry, it can be used for a variety of purposes due to its ability to obtain a different of shapes, textures, colours and flavours (Badel *et al.* 2011, Gallegos *et al.* 2016, Ullach *et al.* 2016). Today, bacterial cellulose is used in the food industry to produce the Philippine dessert *nata-de-coco*, *nata-de-pina* and *kombucha tea*. *Nata-de-coco* is produced by the fermentation of coconut water in which BC synthesis takes place. BC is then soaked in carbohydrate and amino acid syrup (Iguchi *et al.* 2000, Ullach *et al.* 2016). BC is also the product of a process that takes place during the fermentation process of *kombucha tea* - sweet tea with the addition of symbiotic bacteria and yeast cultures (Iguchi *et al.* 2000, Gallegos *et al.* 2016). Due to its hydrophilic and emulsifying properties, research is being conducted into the addition of bacterial cellulose to many food products. Published research results indicate that BC can be used as a filling material for brittle food hydro gels (Okiyama *et al.* 1993). Huang *et al.* (2014) states that adding BC to selected food products can improve their firmness, texture and sensory quality, e.g. in the case of tofu or kamaboko (processed Japanese seafood). Bacterial cellulose is also used as a fat substitute in meatballs production. While in the production of ice cream, BC has replaced cream, which could reduce the calorific value of this type of product. The addition of BC to ice cream also keeps the ice cream in its original shape for 60 minutes after it is removed from the cold store (Guo *et al.* 2018, Lin *et al.* 2020).

PAPER AND PACKAGING INDUSTRY

Continuous economic development is causing a significant increase in demand for paper. The paper industry, in order to maintain its growth dynamics, is constantly looking for alternative materials for production (Singh *et al.* 2012). EU Directive 2018/852 of 30 May 2018 specifies the use of packaging materials that do not adversely affect the environment. At the same time, European Union Member States are encouraged to make greater use of bio-based materials that are easily recyclable. Studies by Urbina et. al. (2019) have shown that stiff nano-paper, which is entirely derived from bacterial cellulose, can be produced and used as environmentally friendly packaging. Stiff nanopolymers are obtained by infiltrating bacterial cellulose nanocrystals into bacterial cellulose membranes. The combination of nanocrystals with membranes results in a denser and more cross-linked structure with a smoother surface. Another example is the use of bacterial nanocellulose (BCN). In a study by George et. al. (2014), authors have shown that the addition of BCN to fibrous materials improves their quality and strength (especially in terms of static bending strength and modulus of elasticity in static bending). Bacterial cellulose is also used in the production of PVA film (George et. al. 2011) and corn starch film (Fabra et. al. 2016). In the case addition of BC to PVA film significantly improves the physical properties of the film, such as tensile strength, modulus of elasticity and thermal stability. On the other hand cornstarch films, BC improve tensile strength by up to 50%. The films tested were characterized by better stiffness and lower extensibility.

ELECTRONICAL INDUSTRY

The continuous progress and development of the electronics industry has a negative impact on environmental pollution. Bacterial cellulose turns out to be a valuable material in the production of lithium-ion batteries. Unlike plant cellulose, it has been discovered that bacterial cellulose catalyzes the deposition of metals in the structure to produce a thin layer of catalyst. Research suggests that BC has reducing groups capable of precipitating heavy metals from an aqueous solution (Evans *et al.* 2003). Studies by Huang *et al.* (2019) have shown that BC membrane combined with Hallo site cellulose membranes (HNT) has excellent heat resistance and high porosity (83%). The interaction between the electrolyte and the electrodes was extremely good and the high ionic conductivity was observed, more than 2.5 times higher than the commercially available PP-PE-PP membranes. BC/HNTs membranes can achieve better battery capacity and better cyclic properties. These properties can make BC/HNTs membranes and ultimately compete with products available on the market for the production of high-performance lithium-ion batteries. The BC membrane manufacturing properties are also confirmed by Evans *et al.* (2003) and Yang *et al.* (2009). BC can be used to create an efficient capacitor where MnO_2cellulose acts as a positive electrode, while Nitrogen BC acts as a negative electrode. The capacitor has a high cyclic stability of 96% after 100 cycles (Chen *et al.* 2013).

MEDICINE

Scientists presented the use of bacterial cellulose in medicine as a material for the production of implants for transplantation, artificial blood vessels and dressings (Mohite *et al.* 2014, Stanislawska 2016, Ullah *et al.* 2016, and Picheth *et al.* 2017). Stanislawska (2016) states that by combining bacterial cellulose with collagen, a bioactive nasal or ear cartilage implant may be formed, which is characterized by good mechanical properties and high compatibility with living tissues. Therefore, bacterial cellulose is tested for its use as artificial blood vessels, which are highly susceptible to formation (Stanislawska 2016, Picheth *et al.* 2017). Membranes made of bacterial cellulose are used to treat epidermal burns. They are characterized by: keeping wounds moist, soothing pain, helping to regenerate the epidermis and minimizing scars. Additionally, BC membranes can be soaked with substances such as analgesics or antibacterial (Czaja 2006, Kawecki *et al.* 2004, Mohite 2014, Stanisławska 2016). Burn dressings based on BC are characterized by similar properties to cosmetic masks, it means they are able to pass through air.

COSMETICAL INDUSTRY

The problem of frequent allergic reactions among users of cosmetics results in increasing interest in cosmetics made of natural ingredients (Hasan *et al.* 2012). Bacterial cellulose has the ability to stabilize oil in water without the addition of a surfactant, therefore BC-based products can be used by people with sensitive skin prone to allergic reactions (Hasan *et al.* 2012, Mohite *et al.* 2014). In addition, bacterial cellulose is a good carrier of cosmetic active ingredients (e.g. hyaluronic acid, salicylic acid) due to its good gas permeability and high water content (Lin *et al.* 2015). Bacterial cellulose is increasingly becoming more common in the composition of products such as face masks, scrubs, nail polishes and artificial nails. Due to the high level of hydration, bacterial cellulose is used to produce moisturizing creams. (Czaja *et al.* 2006, Mohite *et al.* 2014, Ullah *et al.* 2016). It has been proven that people using masks with bacterial cellulose membrane have noticed an improvement in facial skin hydration (Amnuaikit *et al.* 2011, Thanaporn *et al.* 2011).

WOOD-BASED PANELS INDUSTRY

The demand for wood-based materials (plywood, particleboard, fibreboard) is constantly growing. Solid wood is gradually being displaced from furniture production in favour of particleboard. Although the use of material is improving in the production of wood-based boards, unfortunately, the technology also requires the use of synthetic materials which are harmful to the environment and not biodegradable. The literature review conducted so far does not indicate any research on the use of BC in the production of wood-based panels. Instead, there are papers describing the use of cellulose nanofiber in the field of wood-based materials engineering sciences. Yoichi Kojima *et al.* (2018) have developed three-layer particle boards in which chips are sealed exclusively with cellulose nanofiber. The addition of cellulose nanofiber was in the range of 3, 5, 10, 20% by weight of the board. As the participation of cellulose nanofiber increased, the bending strength of the boards increased. Moreover, in the case of the boards where the participation of cellulose nanofiber was higher, the surface absorption of the boards was reduced. The addition of 20% by weight of cellulose nanofiber to the boards resulted in similar strength properties to traditional particleboards with 10% urea formaldehyde adhesive (UF). However, from an economic point of view, this production is unprofitable. Hansted *et al.* (2019) presents the results of a study on the effect of cellulose nanofiber instead of water on the UF glue. With different proportions of cellulose nanofiber (0.25, 0.5, 1 %) in the adhesive, the board did not differ in terms of absorbability. On the other hand, the higher the participation of cellulose nanofiber in the board, its surface was characterized by significantly lower roughness. The low level of surface roughness is a desirable feature in the production of wood-based panels because the surface is then better prepared for finishing. The constantly tightening requirements for the emission of formaldehyde in relation to wood-based panels force the development of new solutions. In the case of particleboards, the addition of 1.5 % nanofiber cellulose to the UF adhesive results in a significant reduction of formaldehyde emissions while at the same time positively affecting the mechanical properties of the boards (Zhang *et al.* 2011). Studies by Lee *et al.* (2013) have shown that synthetic cellulose by microorganisms on natural fibres grows them superficially, acting as a nano-disarmament. Natural fibers coated with BC had better tensile strength and modulus of elasticity.

CONCLUSION

The basis of the current situation in the wood-based panel industry, including nowadays literature reports, in order to maintain the dynamics of production development at the actual level, it is necessary to strive for modification of the material structure, including substitution of wood. The implementation of cellulose synthesized by microorganisms in the production of wood-based panels may prove to be a promising direction of research. The introduction of innovative products containing components enabling full biodegradability of these products on the market will positively affect the level of competitiveness of the wood-based panel industry.

The basis of the properties of bacterial cellulose, as defined so far, it can be assumed that it may constitute a fully-valued raw material ingredient in the technology of wood-based materials (mainly of the particleboard and fibreboard), significantly improving selected properties of the panels manufactured.

ACKNOWLEDGEMENTS

The authors would like to thank P. Boruszewski and I. Betlej for their support during the writing process. The authors also thank Warsaw University of Life Sciences - SGGW for their financial support.

REFERENCES:

1. Abdelraof M., Hasaninb M. S., El -Saied H. (2019). Ecofriendly green conversion of potato peel wastes to high productivity. Carbohydrate Polymers 211: 75-83
2. Aitoma¨ki Y., Oksman K. (2014). Reinforcing efficiency of nanocellulose in polymers. React Funct Polym 85: 151-156
3. Amnuaikit T., Chusuit T., Raknam P., Boonme P. (2011). Effects of a cellulose mask synthesized by a bacterium on facial skin characteristics and user satisfaction. Med Devices 4: 77-81
   bacterial nanocellulose and perforated polypropylene mesh for biomedical applications.

4. Badel S., Bernardi T., and Michaud P. (2011). New perspectives for Lactobacilliexopolysaccharides. Biotechnology Advances 29(1): 54-66
5. Bajpai S. K., Bajpai M., Gautam D. (2013). In situ Formation of Silver Nanoparticles in Regenerated Cellulose-Polyacrylic Acid (RC-PAAc) Hydrogels for Antibacterial Application. Journal of Macromolecular Science, Part A, 50(1): 46-54
6. Betlej I. (2019). Studies on the diversity of substrate composition in the culture medium of Kombucha microorganisms and its influence on the quality of synthesized cellulose, Annals of Warsaw University of Life Sciences Forestry and Wood Technology 108: 21-25
7. Betlej I., Krajewski K., (2019). Bacterial cellulose synthesis by Kombucha microorganisms on a medium with a variable composition of nutrients, Annals of Warsaw University of Life Sciences Forestry and Wood Technology 108: 53-57
8. Brown A. J. (1886). The chemical action of pure cultivations of bacterium aceti. J. Chem. Soc., Trans., 49: 172-187
9. Budhiono A., Rosidi B., Taher H., Iguchi M. (1999). Kineticaspects of bacterial cellulose formation in nata-de-coco culture system. Carbohydr Polym 40:137-143
10. Chen L.-F., Huang Z.-H., Liang H.-W., Guan Q.-F., Yu, S.-H. (2013). Bacterial-Cellulose-Derived Carbon Nanofiber MnO2 and Nitrogen-Doped Carbon Nanofiber Electrode Materials: An Asymmetric Supercapacitor with High Energy and Power Density. Advanced Materials, 25(34): 4746-4752
11. Czaja W., Krystynowicz A., Bielecki S., Brown R.M. (2006). Microbial cellulose—the natural power to heal wounds. Biomaterials 27:145-151
12. Directive (EU) 2018/852 of the European Parliament and of the Council of 30 May 2018 amending Directive 94/62/EC on packaging and packaging waste (Text with EEA relevance) PE/12/2018/REV/2
13. Evans B. R., O'Neill H. M., Malyvanh V. P., Lee I., Woodward J. (2003). Palladium-bacterial cellulose membranes for fuel cells. Biosensors and Bioelectronics 18(7): 917-923
14. Fabra M. J., López-Rubio A., Ambrosio-Martín J., Lagaron J. M. (2016). Improving the barrier properties of thermoplastic corn starch-based films containing bacterial cellulose nanowhiskers by means of PHA electrospun coatings of interest in food packaging. Food Hydrocolloids, 61: 261-268
15. Gallegos A., Carrera A. M., Parra S. H., Keshavarz, T., Iqbal, H. M. N. (2016). Bacterial cellulose: A sustainable source to develop value-added products - A review. BioRes. 11(2): 5641-5655
16. George J., Kumar R., Sajeevkumar V. A., Ramana K. V., Rajamanickam R., Abhishek V., Siddaramaiah (2014). Hybrid HPMC nanocomposites containing bacterial cellulose nanocrystals and silver nanoparticles. Carbohydrate Polymers, 105: 285-292
17. George J., Ramana K. V., Bawa A. S. (2011). Bacterial cellulose nanocrystals exhibiting high thermal stability and their polymer nanocomposites. Int. J. Biol. Macromol. 48: 50-57
18. Gomes F.P., Silva N.H.C.S., Trovatti E., Serafim L.S., Duarte M.F., Silvestre A.J.D., Neto C.P., Freire C.S.R. (2013). Production of bacterial cellulose by Gluconacetobacter sacchari using dry olive mill residue. Biomass Bioenerg 55:205-211
19. Gray D. 2013. Nanocellulose: from nature to high performance tailored material. Holzforschung, 67: 353
20. Guo Y., Zhang X., Hao W., Xie Y., Chen L., Li Z., Zhu B., Feng X. 2018. Nano-bacterial cellulose/soy protein isolate complex gel as fat substitutes in ice cream model. Carbohydr. Polym. 198:620-630

21. Hansted F. A. S., Hansted A. L. S., Padilha E. R. D., Caraschi J. C., Goveia, D., Inácio de Campos, C. (2019). The use of nanocellulose in the production of medium density particleboard panels and the modification of its physical properties. BioRes. 14(3): 5071-5079
22. Hasan N., Biak D.R.A., Kamarudin S. (2012). Application of bacterial cellulose (BC) in natural facial scrub. IJASEIT 2:1-4
23. Huang Y.C., Zhu J., Yang Y., Nie C., Sun C.D. (2014). Recent advances in bacterial cellulose. Cellulose 21(1): 1-30
24. Huang C., Ji H., Guo B., Luo L., Xu W., Li J., Xu J. (2019). Composite nanofiber membranes of bacterial cellulose/ halloysite nanotubes as lithium ion battery separators. Cellulose 26: 6669–6681
25. Igbal H.M.N., Kyazze G., Tron., Keshavarz T. (2014). Laccase-Assisted grafting of poly(3-hydroxybutyrate) onto the bacterial cellulose as backbone polymer: Development and characterization. Carnohydrate Polymers 113: 131-137
26. Iguchi M., Yamanaka S., Budhiono A. (2000). Bacterial cellulose - A masterpiece of nature's arts. Journal of Materials Science 35(2): 261-270
27. Jonas R., Farah L. F. (1998). Production and application of microbial cellulose. Polymer Degradation and Stability 59: 1-3
28. Kawecki M., Krystynowicz A., Wysota K., Czaja W., Sakiel S., Wróblewski P., Glik J., Bielecki S. (2004). Bacterial Cellulose-Biosynthesis, Properties and Applications. Presented at the International Review Conference Biotechnology: Vienna, Austria, November, 14- 18
29. Kim C.W., Kim D.S., Kang S.Y. (2006). Structural studies of electrospun cellulose nanofibers. Polymer 14: 5097-5107
30. Klemm D., Heublein B., Fink H.-P., Bohn A. (2005). Cellulose: Fascinating Biopolymer and Sustainable Raw Material. Angewandte Chemie International Edition 44(22): 3358-3393.
31. Kurosumi A., Sasaki C., Yamashita Y., Nakamura Y. (2009). Utilization of various fruit juices as carbon source for production of bacterial cellulose by Acetobacter xylinum NBRC 13693. Carbohydr Polym 76: 333-335
32. Kojima Y., Kato N., Ota K., Kobori H., Suzuki S., Aoki K., Ito H. (2018). Cellulose Nanofiber as Complete Natural Binder for Particleboard. Forest Products Journal. 3(68): 203-210
33. Lee, K.-Y., Buldum, G., Mantalaris, A., Bismarck, A. (2013). More Than Meets the Eye in Bacterial Cellulose: Biosynthesis, Bioprocessing, and Applications in Advanced Fiber Composites. Macromolecular Bioscience, 14(1), 10-32.
34. Lin D., Liu Z., Shen R., Chen S., Yang, X. (2020). Bacterial cellulose in food industry: Current research and future prospects. International Journal of Biological Macromolecules 158: 1007-1019
35. Ludwicka, K., Kolodziejczyk, M., Gendaszewska-Darmach, E., Chrzanowski, M., Jedrzejczak-Krzepkowska, M., Rytczak, P., Bielecki, S. (2018). Stable composite of bacterial nanocellulose and perforated polypropylene mesh for biomedical applications. Journal of Biomedical Materials Research Part B: Applied Biomaterials
36. Mikkelsen, D., Flanagan, B. M., Dykes, G. A., Gidley, M. J. (2009). Influence of different carbon sources on bacterial cellulose production by Gluconacetobacter xylinus strain ATCC 53524. Journal of Applied Microbiology 107(2): 576-583
37. Mohite B. V., Patil S. V. (2014). A novel biomaterial: bacterial cellulose and its new era applications. Biotechnology and Applied Biochemistry 61(2): 101-110

38. Nguyen V. T., Flanagan B., Gidley M. J., Dykes G. A. (2008). Characterization of Cellulose Production by a Gluconacetobacter xylinus Strain from Kombucha. Current Microbiology 57(5): 449-453
39. Okiyama A Motoki M. Yamanaka S. (1993). Bacterial cellulose IV. Application to processed foods. Food Hydrocoll 6 (6): 503-511
40. Okiyama, A., Motoki M., Yamanaka S. (1992). Bacterial cellulose II. Processing of the gelatinous cellulose for food materials. Food Hydrocoll 6(5): 479-487
41. Picheth G. F., Pirich C. L., Sierakowski M. R., Woehl M. A., Sakakibara C. N., de Souza C. F., de Freitas R. A. (2017). Bacterial cellulose in biomedical applications: A review. International Journal of Biological Macromolecules 104: 97-106
42. Shaghaleh H., Xu X., Wang, S. (2018). Current progress in production of biopolymeric materials based on cellulose, cellulose nanofibers, and cellulose derivatives. RSC Advances 8(2): 825-842
43. Singh P., Sulaiman O., Hashim R., Peng L. C., Singh R. P. (2012). Using biomass residues from oil palm industry as a raw material for pulp and paper industry: potential benefits and threat to the environment. Environment, Development and Sustainability 15(2): 367-383
44. Siro´ I., Plackett D. (2010). Microfibrillated cellulose and new nanocomposite materials: a review. Cellulose 17: 459-494
45. Skocˇaj M. (2019). Bacterial nanocellulose in papermaking. Cellulose 26: 6477-6488
46. Stanisławska A.. (2016). Bacterial nanocellulose as a microbiological derived nanomaterial. Advances in materials science 4(16): 45-57
47. Son H.-J., Heo M.-S., Kim Y.-G., Lee S.-J. (2001). Optimization of fermentation conditions for the production of bacterial cellulose by a newly isolated Acetobacter sp.A9 in shaking cultures. Biotechnology and Applied Biochemistry 33(1): 1-5
48. Thanaporn A., Toon C., Panithi R., Prapaporn B. (2011). Effects of a cellulose mask synthesized by a bacterium on facial skin characteristics and user satisfaction. Medical Devices: Evidence and Research 4: 77-81
49. Torgbo S., Sukyai P. (2018). Bacterial cellulose-based scaffold materials for bone tissue engineering. Applied Materials Today 11: 34-49
50. Ullah H., Santos H. A., Khan T. (2016). Applications of bacterial cellulose in food, cosmetics and drug delivery. Cellulose 23(4): 2291-2314
51. Urbina L., Corcuera M.A., Eceiza A., Retegi A. (2019). Stiff all-bacterial cellulose nanopaper with enhanced mechanical and barrier properties. Materials Letters 246: 67-70
52. Lin Y.C., Wey Y.C., Lee M.L., Lin P.C. (2015). Cosmetic composition containing fragments of bacterial cellulose film and method for manufacturing thereof. US patent, US 20150216784 A1
53. Velásquez-Riaño M., Bojacá V. (2017). Production of bacterial cellulose from alternative low-cost substrates. Cellulose 24(7): 2677-2698
54. Wu Z.-Y. , Li C., Liang H. W., Chen J. F., Yu S. H. 2013. Ultralight, Flexible, and Fire-Resistant Carbon Nanofiber Aerogels from Bacterial Cellulose. Angew. Chem. Int. Ed. 2013 , 52: 2925 -2929
55. Yang J., Sun D., Li J., Yang X., Yu J., Hao Q., Liu W., Liu J., Zou Z., Gu, J. (2009). In situ deposition of platinum nanoparticles on bacterial cellulose membranes and evaluation of PEM fuel cell performance. Electrochimica Acta, 54(26), 6300-6305
56. Yu X., Atalla R. H. (1996). Production of cellulose II by Acetobacter xylinum in the presence of 2,6-dichlorobenzonitrile. International Journal of Biological Macromolecules. 19(2): 145-146

57. Zhang H., Zhang J., Shong S., Wu G., Pu J. (2011). Modified nanocrystalline cellulose from two kinds of modifiers used for improving formaldehyde emission and bonding strength of urea-formaldehyde resin adhesive. BioResources 6(4): 4430 - 4438

Streszczenie: *Przegląd przemysłowych możliwości zastosowania celulozy bakteryjnej*. Celuloza bakteryjna (BC) różni się od celulozy roślinnej średnicą włókna, która w przypadku BC wynosi od 20 do 100 nm. Dane literaturowe wskazują, że stopień krystaliczności BC kształtuje się na poziomie 90%, ponadto jest ona stabilna termicznie oraz odznacza się wyższymi wartościami właściwości mechanicznych od celulozy roślinnej. Czystość BC szacuje się w przedziale 98%, ponieważ nie jest ona zanieczyszczona ligniną, pektynami oraz hemicelulozami, jak celuloza pochodzenia roślinnego. BC wykorzystuje się w medycynie, przemyśle kosmetycznym, elektronicznym, spożywczym, papierniczym czy opakowaniowym. Dotychczas celuloza bakteryjna nie jest implementowana do technologicznych zastosowań w przemyśle tworzyw drewnopochodnych. Aktualne trendy badawczo - rozwojowe w przemyśle tworzyw drewnopochodnych obejmują m.in. zastosowanie nanocelulozy pochodzenia roślinnego celem poprawy wybranych właściwości płyt drewnopochodnych różnego typu. Należy przypuszczać, że BC może stanowić pełnowartościowy ingredient surowcowy w produkcji tworzyw drewnopochodnych, wpływający jednocześnie na poprawę parametrów mechanicznych i fizycznych kompozytów wytwarzanych z jego udziałem.

Corresponding author:

Michał Michałowski
Faculty of Wood Technology
Warsaw University of Life Sciences - SGGW
159 Nowoursynowska St., 02-776 Warsaw, Poland
email: michalowski.michal12@gmail.com