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Bacterial Cellulose - Properties and Its Potential Application

(Bakteria Selulosa - Sifat dan Keupayaan Aplikasi)

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ABSTRACT

This review paper is related to the utilization on bacterial cellulose in many applications. The polymer produced from bacterial cellulose possessed a very good physical and mechanical properties, such as high tensile strength, elasticity, absorbency. The polymer from bacterial cellulose has a significantly higher degree of polymerization and crystallinity compared to those derived from plant. The collection of selected literature review shown that bacterial cellulose produced are in the form pure cellulose and can be used in many of applications. These include application in various industries and sectors of the economy, from medicine to paper or electronic industry.

Keywords: Acetobacter xylinum*; biocomposites; culturing; properties of bacterial cellulose*

ABSTRAK

Ulasan kepustakaan ini adalah mengenai bakteria selulosa yang digunakan dalam banyak aplikasi. Bahan polimer yang terhasil daripada bakteria selulosa mempunyai sifat fizikal dan mekanikal yang sangat baik seperti sifat kekuatan regangan, kelenturan dan serapan. Bahan polimer terhasil daripada selulosa bakteria mempunyai darjah pempolimeran dan kehabluran yang tinggi berbanding daripada sumber tumbuhan. Suntingan kajian daripada beberapa koleksi ulasan kepustakaan menunjukkan bakteria selulosa terhasil adalah selulosa tulen yang boleh digunakan untuk banyak kegunaan. Antaranya adalah untuk pelbagai industri dan sektor ekonomi seperti perubatan atau industri elektronik.

Kata kunci: Acetobacter xylinum*; komposit-bio; pengkulturan; sifat bakteria selulosa*

Introduction

Cellulose is the most common polymer found in nature. It's a component of the cell wall of plants, fungi, and some algae. In plant cells, together with lignin and hemicellulose, it performs structural functions, giving them adequate rigidity and strength (Ye et al. 2019). The possibilities of technological use of cellulose are enormous, however, obtaining pure cellulose, i.e. separating it from the encrusting components requires a chemical treatment that can cause permanent changes in the structure, affecting its physical and mechanical properties.

Therefore, it is interesting to be able to use cellulose of bacterial origin, which is chemically similar polymer as plant cellulose, but unlike it is free of other polymers such as lignin, hemicellulose, and extractives materials and cross-linked in a different way.

Bacterial cellulose is an exopolymer made of β-1,4 D glucopyranose units, produced by aerobic microorganisms, mainly belonging to *Komagataeibacter, Aerobacter, Achromobacter, Agrobacterium, Psedomonas, Sarcina zooglea* i *Rhizobium* (Jung et al. 2007; Lee et al. 2014; Ross et al. 1991; Shoda & Sugano 2005; Skocaj 2019; Yamada et al. 2012). The first reports on the synthesis of cellulose by microorganisms were published in 1886 - by Brown, who indicated the *Acetobacter xylinum* species as capable of synthesizing cellulose (Brown 1889; Skocaj 2019). It is now known that this polymer can be produced by several microorganisms, including Gram positive bacteria, Gram negative bacteria and fungi, including yeast-like fungi.

As reported by Wang et al. (2019), polymers produced by different microorganisms have different morphology, structure, and even properties. *A. xylinum, A. hansenii,* and *A. pasteurianus* are mentioned among the microorganisms that have the ability to intensively synthesize cellulose (Toyosaki et al. 1995). Wang et al. (2019) indicated that *A. xylinum* is characterized by the highest efficiency of cellulose synthesis. Within one hour, this bacterium converts 108 glucose molecules into cellulose chain. The intensity of synthesized bacterial cellulose is not only a species feature, but also depends on many other factors, such as the availability of nutrient components (Zhao et al. 2018), the culture method, the pH of the medium (Chwala et al. 2009), or the coexistence of other microorganisms (Liu & Catchmark 2019). The Polish patent specification PL216180 presented a method of producing bacterial cellulose on a medium containing 2% glucose, 0.90% ethanol, 0.10% citric acid, 0.50% yeast extract and mineral salts: 0.05% $MgSO_4x7H_2O$, 0.30% Na_2HPO_4. Betlej et al. (2020) obtained bacterial cellulose on a medium containing saccharose, peptone, and tea extract. Lu et al. (2020) used eight different carbon sources in the culture of *Komagataeibacter* sp. nov. CGMCC 17276, indicating that in the presence of glycerol polymer synthesis is the most efficient. Vigentini et al. (2019) indicated that, above all, the source of nitrogen and the type of microorganisms, and to a lesser extent the source of carbon has an impact on the quality of synthesized cellulose. In their research, they also indicated differences in productivity between two strains of *K. rhaeticus* LMG 22126T and *K. swingsii* LMG 22125T. Differences in the synthesis of bacterial cellulose between strains result from the number of cellulose synthase operons, however, the influence and function of operon copy in polymer production is not fully been explained (Lu et al. 2020).

However, disturbances in individual operons may reduce cellulose synthesis or irregular packing of fibre (Nakai et al. 2013). Genetic modifications regarding the intensification of cellulose synthesis by microorganisms are not the subject of frequent analyzes, but the genomes of several species, such as *K. xylinus* E25 (Kubiak et al. 2014) and *K. xylinus* CGMCC 2955 (Liu et al. 2018) have been completely sequenced. The effect of *E. coli* interaction on cellulose production by *G. hansenii* was analyzed by Liu and Catchmark (2019). They have proven that the co-culture of microorganisms contributes to better cellulose properties, which was explained by the inclusion of mannose-rich exopolysaccharide synthesized by *E. coli* into the structure of the cellulose network. The method of culturing microorganisms is a very important factor influencing the polymer properties. Undoubtedly, the method of culturing cellulose synthesizing microorganisms affects its potential application (Wang et al. 2019).

PROPERTIES OF BACTERIAL CELLULOSE AND ITS POTENTIAL APPLICATION USE

Bacterial cellulose is completely biodegradable, ecological, non-toxic, chemically stable, and biocompatible material. Unlike plant cellulose, it is characterized by high crystallinity, higher degree of polymerization, higher tensile strength and Young's modulus. In addition, bacterial cellulose, unlike vegetable cellulose, has a smaller diameter of fibres and hence possesses higher hydrophilicity (Ye et al. 2019). Bacterial cellulose fibre has the length of about 10 µm and a diameter of about 10-20 nm (Krystynowicz et al. 1999) form a 3D network structure (Illa et al. 2019; Sederavičiūtė et al. 2019). In its natural state, this fibre network is swollen in water. These unique features of cellulose make it a potentially promising biomaterial in the context of applications in various areas of life and industries.

The properties of bacterial cellulose depend on multiple factors - culture conditions, the type of microorganisms, and nutrients present in the growth medium. These factors have a huge impact on the properties of the polymer, such as strength, crystallinity, degree of polymerization or hygroscopicity (Kiziltas et al. 2015; Skvortsova et al. 2019; Yim et al. 2017). Stanisławska et al. (2020) proved that the drying temperature of a polymer has a significant impact on its strength. They compared the quality of the polymer dried at 25 °C and 105 °C, found that the tensile strength of cellulose dried at 25 °C was 17.5 MPa and was 15 times higher than the strength of cellulose dried at higher temperature. These results confirm previous studies presented by Domskiene et al. (2019). Indriyati et al. (2019) obtained a polymer, the tensile strength of which was as much as 448.86 MPa. They suggested that the method of handling the polymer after the completed cultivation period, in particular, treatment with alkali, improves its mechanical properties. Completely different results were obtained by Betlej et al. (2020). The low strength of cellulose, at the level of about 0.05 N/mm^2, was associated with the cultivation of microorganisms synthesizing the polymer on a very poor culture medium containing only sucrose. The influence of the components of the culture medium on the strength properties and modulus of elasticity of biocellulose was also reported by Amorim et al. (2019). Illa et al. (2019) indicated that the type of cellulose synthesizing microorganisms and the method of drying it affect the Young's modulus result. They obtained the value of Young's modulus within the range from 0.18 to 10.2G Pa.

The treatment of cellulose with NaOH and NaClO increases its Young's modulus even up to 30 GPa (Skvortsova et al. 2019). Table 1 presents selected mechanical properties of bacterial cellulose, which were related to the properties of other utility materials. The composition of the culture medium and its pH also significantly affect the degree of crystallinity (Abdelraof et al. 2019; Kiziltas et al. 2015) and cellulose polymerization (Tahara et al. 1997). The degree of crystallinity of cellulose obtained from waste of potato peelings was as high as 82.5% (Abdelraof et al. 2019). Yim et al. (2017) proved that, depending on the type of carbon source, the degree of crystallinity of bacterial cellulose can range from 13 to 74%. Stanisławska et al. (2020) indicated that the method of drying the polymer influences changes in intra- and extra-molecular hydrogen bonds, and consequently on the Iα/Iβ ratio of cellulose. They obtained a very high degree of cellulose crystallinity, amounting to 91.6%, using the lyophilization method as a method of drying the polymer.

TABLE 1. Mechanical properties bacterial cellulose and others materials

Material	Tensile strength (MPa)	Young Modulus (GPa)	Elongtion (%)	References
Bacterial cellulose	200-300	15-35	1.5-2.0	
Cellophane	20-100	2-3	15-40	Stanisławska (2016)
Polypropylene	30-40	1.0-1.5	100-600	

Bacterial cellulose fibres are arranged in space in the form of a three-dimensional network. Depending on the growing conditions, the size and diameter of the monofilament will change. Kiziltas et al. (2015) presented that cellulose obtained on a substrate containing wood sugars is made of fibres with a smaller diameter than cellulose fibres obtained on a standard Hestrin-Schramm medium. Chen et al. (2019) showed that there is a relationship between the number of cellulose layers and the size of the fibre. Betlej (2019) proved that cellulose obtained on a substrate rich in nitrogen is characterized by multilayers and greater corrugation of the surface, in contrast to the polymer obtained on a culture medium, poor in nutrients (Figure 1). Literature data show that the size of cellulose fibres may range from 20 nm (Gündüz et al. 2015) to 58 nm (Illa et al. 2019), which makes it clear that these structures are 100-200 times thinner than plant cellulose fibres (Skvortsova et al. 2019).

The water content of bacterial cellulose is defined as water holding capacity and water absorption capacity. This feature is of great importance in the case of potential applications of cellulose as a carrier of water-soluble substances. Research indicates that the water absorption in native cellulose is around 90-350% (Amorim et al. 2019; Mohammadkazemi et al. 2019).

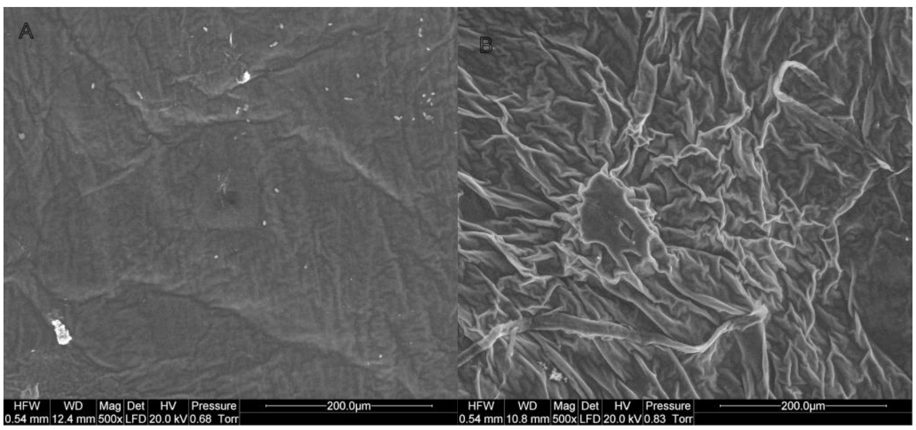

FIGURE 1. Surface morphology of bacterial cellulose from medium containing A- sucrose, B- sucrose and peptone (Betlej 2019)

The improvement in water holding capacity was analyzed by Sulaev et al. (2020). By introducing alginate into the cellulose structures, they found that the addition of a hydrophilic component, which is also capable of forming hydrogen bonds with water molecules, improves the water retention capacity of the material. Muñoz-García et al. (2019) showed that the addition of arabinoxylan and xyloglucan to the growth medium of *Gluconacetobacter xylinus* does not change the water content in cellulose, but affects the thickness of the film and the ability to completely rehydrate it. Oxidizing agents such as $KMnO_4$ and H_2O_2 can increase the absorption and retention of water up to three times compared to native cellulose (Mohammadkazemi et al. 2019). Chaiyasat at al. (2018) showed that the ability of a biopolymer to more or less water absorption depends on its degree of cross-linking. Modification of the cellulose film by adding beeswax increases the hydrophobicity of the film, which was confirmed by a significant increase in the contact angle from 53° for native bacterial cellulose to 124° for modified cellulose (Indriyati et al. 2019). In turn, the addition of guar gum to the film based on bacterial cellulose and polyvinyl pyrrolidone - carboxymethyl cellulose not only increased the hydrophobicity of the composite, but also contributed to increasing the tensile strength.

So far, the most work has been devoted to the possibilities of using bacterial cellulose in medicine, tissue engineering, cosmetics, papermaking, footwear, and food industry (Antolak & Kręgiel 2015; Kołaczkowska et al. 2019; Skocaj 2019; Sutherland 1998). In other areas of the economy, such as the wood industry, electronics and packaging, the use of bacterial cellulose can have potentially high application significance. The way of growing is very important in the potential use of cellulose. Cellulose produced under dynamic conditions is in the form of spherical balls, it is characterized by a much larger surface, porosity and hydrophilicity compared to cellulose synthesized under static conditions, which is produced in the form of a flap. The larger active surface of the spherical cellulose and its higher absorbency facilitates the adsorption of many chemicals. Attempts to adsorb and cross-link in the structure of bacterial cellulose such compounds as enzymes, antibiotics, as well as heavy metal ions or substances with antibacterial properties have been conducted by numerous researchers (Berndt et al. 2013; Karimian et al. 2019; Sunasee et al. 2016; Yang et al. 2012).

Attempts to modify bacterial cellulose with carbon nanotubes and carboxyl nanotubes have been conducted by Nie et al. (2019). Through the modifications process they managed to reduce the hydrophilicity of the polymer, in which the modified cellulose gel composite obtained perform better absorption properties of hydrophobic compounds. Another type of bacterial cellulose modification was carried out by Dai et al. (2019). By introducing collagen between cellulose fibres, they did not change their structure, but increased thermal stability and improved the adhesion of fibroblast cells. Modifications of cellulose, gelatin, agar, and chitosan are also reported by many researchers (Bae et al. 2004; Chang et al. 2012; Ciechańska 2004). In each of these cases, the improvement in the mechanical properties and hydration capacity were obtained.

METHODS OF CULTURING MICROORGANISMS AND NUTRIENTS IN THE SYNTHESIS OF BACTERIAL CELLULOSE

The method of culturing cellulose producing microorganisms determines the efficiency of polymer synthesis. In static culture, it is very important to control the correct pH. The accumulation of acids as products of the metabolism of microorganisms can reduce the efficiency of synthesis (Chawla et al. 2009). In static culture, in contrast to dynamic culture, a smaller distribution of oxygen, necessary for the growth of microorganisms, is also observed.

As reported by Watanabe et al. (1998), cellulose produced under static and dynamic conditions differs in crystallinity. In dynamic culture, the biggest difficulty is the conversion of cellulose-producing strains into mutants unable to synthesize it (Kim et al. 2007). In dynamic culture, aeration of the medium, thus, the availability of oxygen for microorganisms can be very high. With easier availability of oxygen, the intensity of cellulose synthesis is higher. According to Kim et al. (2007), at an aeration rate of 1.25 vvm, the bacterial cellulose synthesis was 5.67 g/L. Methods for the synthesis of bacterial cellulose have been described in many patents such as US5846213, US4891317, and EP0197748.

Despite enormous possibilities of using bacterial cellulose, the industrial production is still small. There are several reasons for this. The most important is being the method of culturing the microorganisms and the appropriate composition of the medium. Skocaj (2019) reported that the intensification of cellulose synthesis can be achieved by proper selection of substrate components, and these constitute 30% of the total cost of bacterial cellulose production. The source of synthesis is determined by the source of carbon and nitrogen. According to Embuscado et al. (1994), the use of yeast and peptone extract in culture determines the very high efficiency of cellulose synthesis. The carbon source is also important. In EP0318543 it was indicated that the best yield of cellulose synthesis by *A. xylinum* is obtained on a medium with fructose and sucrose. The search for cheap sources of carbon and nitrogen in the production of bacterial cellulose is one of the many topics undertaken by researchers.

Attempts to obtain cellulose on a substrate derived from wastewater from fermentation of pullulan have been conducted by Zhao et al. (2018). They showed that the components present in wastewater affect the microstructure and mechanical properties of cellulose. In turn, Fan et al. (2016) obtained cellulose on a skin-containing medium and citrus pomace. The properties of cellulose obtained in such conditions did not differ from that obtained on a synthetic substrate. As well as rich in simple sugars, fruit extracts were analyzed for use as components of the substrate for the synthesis of bacterial cellulose (Castro et al. 2011; Karahan et al. 2011; Yang et al. 2016). Fan et al. (2016) indicated the possibility of using food production waste as growth media in the production of bacterial cellulose. An interesting issue was developed by Kiziltas et al. (2015) using substrates for *A. xylinum* culture, obtained from wood extraction with hot water. They indicated that extracts from cellulose and biorefineries of lignocellulosic materials are rich source of monosaccharides, organic acids and other important substances that affect the efficiency of cellulose synthesis. At the same time, wastewater from lipid fermentation containing low-grade carbohydrate polymers may be useful for bacterial cellulose dynamics (Huang et al. 2016).

THE USE OF BACTERIAL CELLULOSE IN THE MEDICAL AREA, VETERINARY AREA, AND COSMETICS INDUSTRY

Bacterial cellulose that has not undergone a drying process is characterized by mechanical properties in which stresses and deformations correspond to the characteristics of soft tissues (Wang et al. 2019). Additionally, in a properly established culture process, it can be formed to any shape, size, and thickness (Chwala et al. 2009), which is of great importance in its use, e.g. as a cartilage implant in reconstructive surgery. High *in vivo* biocompatibility and very good physical and mechanical parameters allow it to be used as biomedical material in the form of artificial skin, implants, artificial blood vessels or wound healing dressings and severe burns (Chantereau et al. 2019). Ullah et al. 2016 indicated that bacterial cellulose membranes accelerate tissue regeneration after surgery compared to conventional synthetic materials. In addition, membranes made of bacterial cellulose are characterized by excellent gas exchange, constitute a barrier against the penetration of infectious agents into wounds and allow the transfer of drugs to the affected tissue (Czaja et al. 2006; Fontana et al. 1990). In the study carried out by Juncu et al. (2016), they reported that bacterial cellulose containing cross-linked carboxymethyl cellulose has a higher ibuprofen uptake capacity than unmodified cellulose.

Undoubtedly, an interesting issue is the possibility of using bacterial cellulose in ophthalmology. Several bacterial cellulose biocomposites supporting the growth of corneal stromal cells have been described (Dutton 1991). Bacterial cellulose has also been studied for the use as contact lens containing ciprofloxacin as a dressing after eye surgery (Cavicchioli et al. 2015). Such a modification of cellulose allowed to discontinue the use of a conventional antibiotic in the form of drops.

The most discussed issue in the medical literature regarding bacterial cellulose is the possibility of its use in bone regeneration. Bone grafts based on bacterial cellulose scaffolds have been the research focus of Torgbo and Sukyai (2018). However, the use of bacterial cellulose as implants in cardiac and vascular surgery was analyzed by Kołaczkowska et al. (2019).

There are attempts to use bacterial cellulose in veterinary medicine. Saska et al. (2011) evaluated the effectiveness of rat tibial bone regeneration using a composite of bacterial cellulose and hydroxyapatite. Researchers observed complete regeneration of the tissue defect 16 weeks after the transplant was performed. An interesting solution is also the use of cellulose as an absorbent material in the treatment of a root canal in premolars in dogs (Bodea et al. 2019; Yoshino et al. 2013). Perforated bacterial cellulose can also be used as a material for prosthetic abdominal wall (Silveira et al. 2016), as a material that replaces the meniscus in the knee joint (Tanaka et al. 2014), or a material helpful in the regeneration of the tympanic membrane (Kim et al. 2013). Undoubtedly, an interesting issue is the possibility of using bacterial cellulose in cosmetology. There are many interesting applications works on the use of cellulose in the form of a shhet mask soaked with moisturizing or anti-inflammatory substances (Amorim et al. 2020a, 2019; Pacheco et al. 2018). Bacterial cellulose impregnated with 1,3-dihydroxy-2-propanone as a cosmetic product in the form of a self-tanning agent was tested by Stasiak-Różańska and Płoska (2018). After 30 minutes of skin exposure to the cellulose patch, the desired effect of a natural tan was obtained. Effective skin care effect was achieved by Pacheco et al. (2017) in skin moisturizing tests using a cellulose mask soaked with plant extracts.

The preparation of a hydrogel composite of bacterial cellulose and polyvinyl alcohol as a material for potential applications in personal care, as cleansing and moisturizing masks was the subject of studies by Chunshom et al. (2018). The researchers showed that the obtained hydrogel showed very good swelling properties in various types of chemicals, which suggests that it can be a carrier of many valuable active ingredients used in cosmetic care.

BACTERIAL CELLULOSE IN THE LEATHER INDUSTRY

The use of bacterial cellulose as a skin substitute is undoubtedly an innovative idea. Elastic cellulose of the desired thickness has characteristics similar to animal skins used in the footwear industry. According to Garcia and Pieto (2018), cellulose properties, i.e. its stretchiness and softness are an important attribute in the production of footwear, in which the comfort of using the product determines customer satisfaction. They particularly noted the need for high-quality footwear for people with diabetic foot syndrome, who require footwear made of a material that limits the risk of foot infection. Undoubtedly, an important factor in the functionality of footwear is its waterproofness. Thus, the use of bacterial cellulose in the production of footwear seems to be possible, but after prior modification with hydrophobic substances. Attempts to modify bacterial cellulose with a hydrophobizer based on a perfluorocarbon and plasticizer based on polydimethylsiloxane for use in footwear products were conducted by Fernandes et al. (2019a). In the experiment, the researchers obtained a water-impermeable cellulose composite with high plasticity. Analyzes of a similar modification were conducted by Fernandes et al. (2019b) to obtain a highly hydrophobic bacterial cellulose composite, but with reduced tensile strength and increased elongation at break. The costs of using the raw material for the production of footwear, which are skins, and in addition the use of often toxic substances in the tanning process, may result in greater demand for footwear from organic and biodegradable bacterial cellulose.

BACTERIAL CELLULOSE IN ENVIRONMENTAL PROTECTION

Water, soil, and air pollution is a huge problem for many countries in the world. Heavy metals, polycyclic aromatic hydrocarbons, antibiotic residues, solid particles suspended in the air, can contribute not only to numerous health problems in humans, but above all, disturb the ecosystem and lead to progressive and visible climate changes. An attempt to use bacterial cellulose as a membrane in wastewater treatment technology was the subject of studies by Urbin et al. (2018). Researchers have shown that the cellulose-chitosan biocomposite is characterized by a high efficiency in eliminating copper ions from water. In assessing the possibility of multiple use of such a membrane, they obtained good results, indicating slight changes in the efficiency of copper removal in the second filtration cycle. In the work presented by Liu et al. (2017), they analyzed a composite based on bacterial cellulose and proteins isolated from soy as a highly efficient air filtering material. Researchers found that the composite was highly effective at removing dust pollution across a wide range of sizes. They proved that the three-dimensional structure of cellulose contributes to the initial, physical capture of dust particles, and that the functional groups of soybean proteins bind dust particles through non-covalent interactions. Another interesting issue related to the use of bacterial cellulose as a material for purifying water from oily substances was presented by Galdino Jr. et al. (2020). They not only obtained positive results of the effectiveness of water purification from oily substances, but also confirmed that the polymer used is highly durable, which suggests very promising possibilities of its potential use in environmental protection.

A very important issue related to the synthesis of cellulose by microorganisms are the methods of its efficient and economic extraction. This issue involves works on the possibility of managing industrial waste, mainly from the food industry (Sijabat et al. 2020), as well as from paper and textile waste (Hussain et al. 2018), as nutrients for cellulose-synthesizing microorganisms. Waste products from the brewing industry were assessed as a potential nutrient medium for the cultivation of *G. hansenii* CGMCC 3917 (Hyun et al. 2014). They showed that the cellulose synthesis efficiency was 6 times higher than that of the traditional HS medium, and the polymer structure was looser, with lots of voids. Similar observations were confirmed by Vazquez et al. (2013) in a study of the efficiency of bacterial cellulose synthesis on a substrate of citrus pomace. Cotton-based textile wastes, given enzymatic hydrolysis as a source of sugars in the culture of cellulose-synthesizing bacteria, were the subject of studies by Pensupa et al. (2017). They concluded that cellulose produced on waste from the textile industry is characterized by much better mechanical properties than the polymer synthesized on the basis of glucose. The possibility of using bagasse - the dry residue after crushing sugar cane - as a source of nutrients for cellulose-synthesizing microorganisms is also promising (Qi et al. 2017).

THE USE OF BIOCELLULOSE IN BIOTECHNOLOGICAL PROCESSES

Bacterial cellulose can be a very good carrier for various catalytic systems. Especially in enzymatic catalysis, where the reaction rate depends on the stability of the enzyme, the use of a bacterial polymer may show promise. Liu et al. (2019) immobilized catalase on a support based on bacterial cellulose and poly (glycidyl methacrylate). They obtained not only high stability of the immobilized enzyme, but also its high activity, even after 10 cycles of catalysis, which means that the used carrier may have future applications in biocatalysis. The use of bacterial cellulose in the preparation of the catalyst used in the synthesis of biphenyl-4-amine and 4’-fluorobiphenyl-4-amine was presented in the research of Jeremic et al.

(2019). An interesting description of the use of bacterial cellulose hydrogel as a nanoreactor in the production of iron oxide nanoparticles was presented by Andarini et al. (2017). They produced iron oxide nanoparticles by adding ferrocenium salt to the hyrogel-cellulose system. Qualitative analysis of the obtained nanoparticles made it possible to state that hydrogel bacterial cellulose is a promising nanoreactor in the production of iron oxide nanoparticles. Hydrogel cellulose composites can also be an excellent absorbent for medicinal substances (Amin et al. 2012), dyes (Lazim et al. 2018) or many other chemicals (Abeer et al. 2014).

BACTERIAL NANOCELLULOSE AND ITS APPLICATION PROPERTIES

Bacterial cellulose fibres, unlike their plant counterparts, are nanoscale. These fibres are characterized by a small diameter, very high crystallinity and the presence of numerous hydroxyl groups, which give them strong hydrophilic properties. These features of bacterial nanocellulose, different from plant cellulose, make it an excellent raw material for the production of new composites with changed properties (Amorim et al. 2020b). Modification of the nanocellulose surface by attaching aliphatic and aromatic substituents allows to obtain a material with very good mechanical properties (Abushammala & Mao 2019). An interesting method of producing medical sensors on ultra-thin sheets of bacterial nanocellulose was presented by Yuen et al. (2020). They installed electronic sensors on the nanocellulose to monitor the heart rate and measure temperature. Interesting solutions for the paper industry were described in the studies by Urbin et al. (2019), in which they demonstrated how to make rigid nanopapers. They introduced nanocrystals into the structure of bacterial cellulose, obtained a material with a higher density, smoother surface and lower oxygen permeability.

Torres et al. (2019) reviewed various materials that, in combination with bacterial cellulose, make it possible to create innovative biocomposites. Examples of such materials are: graphene, carbon nanotubes, polyaniline, hydroxyapatite, metals, and silica. Bacterial cellulose and graphene nanocomposite, developed by Lou et al. (2018) showed a 91% improvement in tensile strength and a 279% improvement in elastic modulus, compared to pure bacterial nanocellulose. In turn, the addition of carbon nanotubes to biocellulose not only increased its mechanical properties, but also improved its thermal properties and electrical conductivity (Torres et al. 2019). A flexible nanocomposite with magnetic properties, obtained by introducing magnetite particles into the cellulose structure, was developed by Zhang et al. (2011). Another example of a nanocomposite based on biocellulose and silica for use as an absorbent for water purification was presented in their research by Maeda et al. (2006).

OTHER POSSIBILITIES OF USING BACTERIAL CELLULOSE

Like plant cellulose, bacterial cellulose also has many free hydroxyl groups. Hence, like other hydroxyl functional materials, it can easily undergo substitution reactions. Cellulose derivatives with improved properties can be obtained, which can be particularly useful in the paper industry. Materials produced from modified bacterial cellulose exhibited greater mechanical strength, which is especially important when it is used in the case of reinforcing recycled paper, but above all, acquire special features that allow it to be used in the production of fireproof or specialized papers (Skocaj 2019). Attempts to determine the usefulness of bacterial cellulose in papermaking were conducted towards the application in the production of paper with high bending strength (Campano et al. 2018a, 2018b, 2018c), banknote paper, fireproof paper (Basta & El-Saied 2009), and magnetic paper (Lim et al. 2016). A method of producing white magnetic paper from bacterial cellulose by incorporating $CoFe_2O_4$ nanoparticles and impregnating with ZnO was presented by Sriplai et al. (2018). They obtained flexible white paper with magnetic properties, with higher reflection coefficient of over 70% in the visible spectral range. A very important research issue is the possibility of using bacterial cellulose to strengthen the strength of paper made from recycled material. After four times of recycling process have taken placed, the individual fibre strength will be reduced. This will result in lower binding capacity between fibres hence, worse strength of recycled paper will be produced. The introduction of bacterial cellulose fibres can assist and improved the properties of recycle paper (Skocaj 2019). The use of bacterial cellulose in paper production improves the quality of the paper surface (Presler & Surma-Ślusarska 2006) and increases moisture resistance and permeability (Gao et al. 2010; Santos et al. 2017; Xiang et al. 2017b). The addition of 1% bacterial cellulose to low-quality fibres dramatically improves the mechanical properties (Xiang et al. 2017a).

Undoubtedly, the use of bacterial cellulose in 3D printing technology is an innovative solution. Schaffner et al. (2017) have added microorganism to the hydrogel and they created printed, living material in which it became a scaffold for the cellulose forming on it. This innovative approach to 3D printing technology has allowed the creation of a new generation of innovative materials with complex shapes, designed for a variety of applications.

Bacterial cellulose can also have potential applications in the electronics industry. Jiang et al.

(2015) have developed a lithium-ion battery separator whose membrane is bacterial cellulose. The cellulose membrane had thermal stability up to 200 °C and high ionic conductivity. Halloysite cellulose membranes (HNTs), developed by Huang et al. (2019) were characterized by high tear strength (84.4 MPa), and batteries containing cellulose-HNTs separator with higher ionic conductivity and good cycling property.

Undoubtedly, a prospective solution would be the possibility of using bacterial cellulose in wood industry. The fusion of wood particles with bacterial cellulose can be the concept of a new composite, important in the production of chipboard. An attempt to modify the panels, e.g. by reducing the content of lignin and hemicelluloses, due to the introduction of cellulose of bacterial origin, allows not only to obtain materials with useful physical and mechanical properties, but also to reduce the share and consumption of the basic raw material which is wood. Due to the economic problem, which is the deficit of wood raw material for the plate industry, the important argument is the fact that new solutions are proposed and an attempt to find new sources of raw material, and such a solution may be the introduction of alternative bacterial cellulose into lignocellulose chips with different physical and mechanical properties, than plant cellulose. The first research works on the production of a lignocellulosic complex combined with bacterial cellulose are described in the patent application P.433630 (2020) and the publication Wacikowski and Michałowski (2020).

Conclusion

In the presented stage of literature, it has been shown that bacterial cellulose, due to its unique properties, can be of great application importance in various areas of life. Additional potential attention is drawn to the fact that it is a natural, non-toxic and biodegradable polymer, which makes it environmentally friendly. It seems that the most important aspect of its technological use is to develop an effective method of its synthesis, preferably using appropriate but also cheap waste materials rich in nitrogen and carbon to reduce the high costs of using standard microbiological reagents.

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